CLIMATE CHANGE AND WATER

IPCC Technical Paper VI

WMO

Intergovernmental Panel on Climate Change

UNEP

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

WMO

UNEP

Climate Change and Water

Edited by

Bryson Bates
CSIRO
Australia

Zbigniew W. Kundzewicz
Polish Academy of Sciences, Poland
and Potsdam Institute for Climate
Impact Research, Germany

Shaohong Wu
Chinese Academy of Sciences
China

Jean Palutikof
Met Office Hadley Centre
United Kingdom

This is a Technical Paper of the Intergovernmental Panel on Climate Change prepared in response to a decision of the Panel. The material herein has undergone expert and government review, but has not been considered by the Panel for possible acceptance or approval.

June 2008

This paper was prepared under the management of the IPCC Working Group II
Technical Support Unit

Please cite this Technical Paper as:

Bates, B.C., Z.W. Kundzewicz, S. Wu and J.P. Palutikof, Eds., 2008: Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

ISBN: 978-92-9169-123-4

Contents

Preface

The Intergovernmental Panel on Climate Change (IPCC) Technical Paper on Climate Change and Water is the sixth paper in the IPCC Technical Paper series and was produced in response to a proposal by the Secretariat of the World Climate Programme – Water (WCP-Water) and the International Steering Committee of the Dialogue on Water and Climate at the 19th Plenary Session of the IPCC which took place in Geneva in April 2002. A consultative meeting on Climate Change and Water was held in Geneva in November 2002 and recommended the preparation of a Technical Paper on Climate Change and Water instead of preparing a Special Report to address this subject. Such a document was to be based primarily on the findings of the Fourth Assessment Report of the IPCC, but also earlier IPCC publications. The Panel also decided that water should be treated as cross cutting theme in the Fourth Assessment Report.

The Technical Paper addresses the issue of freshwater. Sea-level rise is dealt with only insofar as it can lead to impacts on freshwater in coastal areas and beyond. Climate, freshwater, biophysical and socio-economic systems are interconnected in complex ways. Hence, a change in any one of these can induce a change in any other. Freshwater-related issues are critical in determining key regional and sectoral vulnerabilities. Therefore, the relationship between climate change and freshwater resources is of primary concern to human society and also has implications for all living species.

An interdisciplinary writing team of Lead Authors was selected by the three IPCC Working Group Bureaus with the aim of achieving a regional and topical balance. Like all IPCC Technical Papers, this product too is based on the material of previously approved/accepted/adopted IPCC reports and underwent a simultaneous expert and Government review, followed by a final Government review. The Bureau of the IPCC acted in the capacity of an editorial board to ensure that the review comments were adequately addressed by the Lead Authors in the finalisation of the Technical Paper.

The Bureau met in its 37th Session in Budapest in April 2008 and considered the major comments received during the final Government review. In the light of its observations and requests, the Lead Authors finalised the Technical Paper, after which the Bureau authorised its release to the public.

We owe a large debt of gratitude to the Lead Authors (listed in the Paper) who gave of their time very generously and who completed the Technical Paper according to schedule. We would like to thank Dr. Jean Palutikof, Head of the Technical Support Unit of IPCC Working Group II, for her skilful leadership through the production of this Paper.

Rajendra K. Pachauri
Chairman of the IPCC

Renate Christ
Secretary of the IPCC

Osvaldo Canziani
Co-Chair IPCC Working Group II

Martin Parry
Co-Chair IPCC Working Group II

Acknowledgments

We thank the Working Group II Technical Support Unit, especially Norah Pritchard and Clair Hanson, for their hard work in the preparation of this Technical Paper.

The Government of Canada kindly agreed to host the second Lead Author meeting, and we thank Terry Prowse for undertaking the hard work of organisation in Victoria, British Columbia.

Maurice Roos, from the State of California Department of Water Resources, and Bill Girling, from Manitoba Hydro, attended the second Lead Author meeting to provide advice and suggestions from a user perspective.

Marilyn Anderson prepared the Index and Nancy Boston copy edited the text.

Thanks go to all the authors, their families, institutions and governments, for making this paper possible.

Bryson Bates
Zbyszek Kundzewicz
Shaohong Wu
Jean Palutikof

23 June 2008

Climate Change and Water

This Technical Paper was requested by IPCC Plenary in response to suggestions by the World Climate Programme - Water, the Dialogue on Water and other organisations concerned with the provision of water. It was prepared under the auspices of the IPCC Chair, Dr. R.K. Pachauri.

Coordinating Lead Authors
Bryson Bates (Australia), Zbigniew W. Kundzewicz (Poland) and Shaohong Wu (China)

Lead Authors
Nigel Arnell (UK), Virginia Burkett (USA), Petra Döll (Germany), Daniel Gwary (Nigeria), Clair Hanson (UK), BertJan Heij (The Netherlands), Blanca Elena Jiménez (Mexico), Georg Kaser (Austria), Akio Kitoh (Japan), Sari Kovats (UK), Pushpam Kumar (UK), Christopher H.D. Magadza (Zimbabwe), Daniel Martino (Uruguay), Luis José Mata (Germany/Venezuela), Mahmoud Medany (Egypt), Kathleen Miller (USA), Taikan Oki (Japan), Balgis Osman (Sudan), Jean Palutikof (UK), Terry Prowse (Canada), Roger Pulwarty (USA/ Trinidad and Tobago), Jouni Räisänen (Finland), James Renwick (New Zealand), Francesco Nicola Tubiello (USA/IIASA/Italy), Richard Wood (UK) and Zong-Ci Zhao (China)

Contributing Authors
Julie Arblaster (Australia), Richard Betts (UK), Aiguo Dai (USA), Christopher Milly (USA), Linda Mortsch (Canada), Leonard Nurse (Barbados), Richard Payne (Australia), Iwona Pinskwar (Poland) and Tom Wilbanks (USA)

Executive Summary

Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems.

Observed warming over several decades has been linked to changes in the large-scale hydrological cycle such as: increasing atmospheric water vapour content; changing precipitation patterns, intensity and extremes; reduced snow cover and widespread melting of ice; and changes in soil moisture and runoff. Precipitation changes show substantial spatial and inter-decadal variability. Over the 20th century, precipitation has mostly increased over land in high northern latitudes, while decreases have dominated from 10°S to 30°N since the 1970s. The frequency of heavy precipitation events (or proportion of total rainfall from heavy falls) has increased over most areas (*likely*[1]). Globally, the area of land classified as very dry has more than doubled since the 1970s (*likely*). There have been significant decreases in water storage in mountain glaciers and Northern Hemisphere snow cover. Shifts in the amplitude and timing of runoff in glacier- and snowmelt-fed rivers, and in ice-related phenomena in rivers and lakes, have been observed (*high confidence*). [2.1[2]]

Climate model simulations for the 21st century are consistent in projecting precipitation increases in high latitudes (*very likely*) and parts of the tropics, and decreases in some sub-tropical and lower mid-latitude regions (*likely*). Outside these areas, the sign and magnitude of projected changes varies between models, leading to substantial uncertainty in precipitation projections.[3] Thus projections of future precipitation changes are more robust for some regions than for others. Projections become less consistent between models as spatial scales decrease. [2.3.1]

By the middle of the 21st century, annual average river runoff and water availability are projected to increase as a result of climate change[4] at high latitudes and in some wet tropical areas, and decrease over some dry regions at mid-latitudes and in the dry tropics.[5] Many semi-arid and arid areas (e.g., the Mediterranean Basin, western USA, southern Africa and north-eastern Brazil) are particularly exposed to the impacts of climate change and are projected to suffer a decrease of water resources due to climate change (*high confidence*). [2.3.6]

Increased precipitation intensity and variability are projected to increase the risks of flooding and drought in many areas. The frequency of heavy precipitation events (or proportion of total rainfall from heavy falls) will be *very likely* to increase over most areas during the 21st century, with consequences for the risk of rain-generated floods. At the same time, the proportion of land surface in extreme drought at any one time is projected to increase (*likely*), in addition to a tendency for drying in continental interiors during summer, especially in the sub-tropics, low and mid-latitudes. [2.3.1, 3.2.1]

Water supplies stored in glaciers and snow cover are projected to decline in the course of the century, thus reducing water availability during warm and dry periods (through a seasonal shift in streamflow, an increase in the ratio of winter to annual flows, and reductions in low flows) in regions supplied by melt water from major mountain ranges, where more than one-sixth of the world's population currently live (*high confidence*). [2.1.2, 2.3.2, 2.3.6]

Higher water temperatures and changes in extremes, including floods and droughts, are projected to affect water quality and exacerbate many forms of water pollution – from sediments, nutrients, dissolved organic carbon, pathogens, pesticides and salt, as well as thermal pollution, with possible negative impacts on ecosystems, human health, and water system reliability and operating costs (*high confidence*). In addition, sea-level rise is projected to extend areas of salinisation of groundwater and estuaries, resulting in a decrease of freshwater availability for humans and ecosystems in coastal areas. [3.2.1.4, 4.4.3]

Globally, the negative impacts of future climate change on freshwater systems are expected to outweigh the benefits (*high confidence*). By the 2050s, the area of land subject to increasing water stress due to climate change is projected to be more than double that with decreasing water stress. Areas in which runoff is projected to decline face a clear reduction in the value of the services provided by water resources. Increased annual runoff in some areas is projected to lead to increased total water supply. However, in many regions, this benefit is likely to be counterbalanced by the negative effects of increased precipitation variability and seasonal runoff shifts in water supply, water quality and flood risks (*high confidence*). [3.2.5]

Changes in water quantity and quality due to climate change are expected to affect food availability, stability, access and utilisation. This is expected to lead to decreased food security and increased vulnerability of poor rural farmers, especially in the arid and semi-arid tropics and Asian and African megadeltas. [4.2]

[1] See Box 1.1.

[2] Numbers inside square brackets relate to sections in the main body of the Technical Paper.

[3] Projections considered are based on the range of non-mitigation scenarios developed by the IPCC Special Report on Emissions Scenarios (SRES).

[4] This statement excludes changes in non-climatic factors, such as irrigation.

[5] These projections are based on an ensemble of climate models using the mid-range SRES A1B non-mitigation emissions scenario. Consideration of the range of climate responses across SRES scenarios in the mid-21st century suggests that this conclusion is applicable across a wider range of scenarios.

Climate change affects the function and operation of existing water infrastructure – including hydropower, structural flood defences, drainage and irrigation systems – as well as water management practices. Adverse effects of climate change on freshwater systems aggravate the impacts of other stresses, such as population growth, changing economic activity, land-use change and urbanisation (*very high confidence*). Globally, water demand will grow in the coming decades, primarily due to population growth and increasing affluence; regionally, large changes in irrigation water demand as a result of climate change are expected (*high confidence*). [1.3, 4.4, 4.5, 4.6]

Current water management practices may not be robust enough to cope with the impacts of climate change on water supply reliability, flood risk, health, agriculture, energy and aquatic ecosystems. In many locations, water management cannot satisfactorily cope even with current climate variability, so that large flood and drought damages occur. As a first step, improved incorporation of information about current climate variability into water-related management would assist adaptation to longer-term climate change impacts. Climatic and non-climatic factors, such as growth of population and damage potential, would exacerbate problems in the future (*very high confidence*). [3.3]

Climate change challenges the traditional assumption that past hydrological experience provides a good guide to future conditions. The consequences of climate change may alter the reliability of current water management systems and water-related infrastructure. While quantitative projections of changes in precipitation, river flows and water levels at the river-basin scale are uncertain, it is *very likely* that hydrological characteristics will change in the future. Adaptation procedures and risk management practices that incorporate projected hydrological changes with related uncertainties are being developed in some countries and regions. [3.3]

Adaptation options designed to ensure water supply during average and drought conditions require integrated demand-side as well as supply-side strategies. The former improve water-use efficiency, e.g., by recycling water. An expanded use of economic incentives, including metering and pricing, to encourage water conservation and development of water markets and implementation of virtual water trade, holds considerable promise for water savings and the reallocation of water to highly valued uses. Supply-side strategies generally involve increases in storage capacity, abstraction from water courses, and water transfers. Integrated water resources management provides an important framework to achieve adaptation measures across socio-economic, environmental and administrative systems. To be effective, integrated approaches must occur at the appropriate scales. [3.3]

Mitigation measures can reduce the magnitude of impacts of global warming on water resources, in turn reducing adaptation needs. However, they can have considerable negative side effects, such as increased water requirements for afforestation/reforestation activities or bio-energy crops, if projects are not sustainably located, designed and managed. On the other hand, water management policy measures, e.g., hydrodams, can influence greenhouse gas emissions. Hydrodams are a source of renewable energy. Nevertheless, they produce greenhouse gas emissions themselves. The magnitude of these emissions depends on specific circumstance and mode of operation. [Section 6]

Water resources management clearly impacts on many other policy areas, e.g., energy, health, food security and nature conservation. Thus, the appraisal of adaptation and mitigation options needs to be conducted across multiple water-dependent sectors. Low-income countries and regions are *likely* to remain vulnerable over the medium term, with fewer options than high-income countries for adapting to climate change. Therefore, adaptation strategies should be designed in the context of development, environment and health policies. [Section 7]

Several gaps in knowledge exist in terms of observations and research needs related to climate change and water. Observational data and data access are prerequisites for adaptive management, yet many observational networks are shrinking. There is a need to improve understanding and modelling of climate changes related to the hydrological cycle at scales relevant to decision making. Information about the water-related impacts of climate change is inadequate – especially with respect to water quality, aquatic ecosystems and groundwater – including their socio-economic dimensions. Finally, current tools to facilitate integrated appraisals of adaptation and mitigation options across multiple water-dependent sectors are inadequate. [Section 8]

1

Introduction to climate change and water

1.1 Background

The idea of a special IPCC publication dedicated to water and climate change dates back to the 19th IPCC Session held in Geneva in April 2002, when the Secretariat of the World Climate Programme – Water and the International Steering Committee of the Dialogue on Water and Climate requested that the IPCC prepare a Special Report on Water and Climate. A consultative meeting on Climate Change and Water held in Geneva in November 2002 concluded that the development of such a report in 2005 or 2006 would have little value, as it would quickly be superseded by the Fourth Assessment Report (AR4), which was planned for completion in 2007. Instead, the meeting recommended the preparation of a Technical Paper on Climate Change and Water that would be based primarily on AR4 but would also include material from earlier IPCC publications.

An interdisciplinary writing team was selected by the three IPCC Working Group Bureaux with the aim of achieving regional and topical balance, and with multiple relevant disciplines being represented. United Nations (UN) agencies, non-governmental organisations (NGOs) and representatives from relevant stakeholder communities, including the private sector, have been involved in the preparation of this Technical Paper and the associated review process.

IPCC guidelines require that Technical Papers are derived from:

(a) the text of IPCC Assessment Reports and Special Reports and the portions of material in cited studies that were relied upon in these reports;
(b) relevant models with their assumptions, and scenarios based on socio-economic assumptions, as they were used to provide information in those IPCC Reports.

These guidelines are adhered to in this Technical Paper.

1.2 Scope

This Technical Paper deals only with freshwater. Sea-level rise is dealt with only insofar as it can lead to impacts on freshwater in the coastal zone; for example, salinisation of groundwater. Reflecting the focus of the literature, it deals mainly with climate change through the 21st century whilst recognising that, even if greenhouse gas concentrations were to be stabilised, warming and sea-level rise would continue for centuries. [WGI SPM]

The importance of freshwater to our life support system is widely recognised, as can be seen clearly in the international context (e.g., Agenda 21, World Water Fora, the Millennium Ecosystem Assessment and the World Water Development Report). Freshwater is indispensable for all forms of life and is needed, in large quantities, in almost all human activities. Climate, freshwater, biophysical and socio-economic systems are interconnected in complex ways, so a change in any one of these induces a change in another. Anthropogenic climate change adds a major pressure to nations that are already confronting the issue of sustainable freshwater use. The challenges related to freshwater are: having too much water, having too little water, and having too much pollution. Each of these problems may be exacerbated by climate change. Freshwater-related issues play a pivotal role among the key regional and sectoral vulnerabilities. Therefore, the relationship between climate change and freshwater resources is of primary concern and interest.

So far, water resource issues have not been adequately addressed in climate change analyses and climate policy formulations. Likewise, in most cases, climate change problems have not been adequately dealt with in water resources analyses, management and policy formulation. According to many experts, water and its availability and quality will be the main pressures on, and issues for, societies and the environment under climate change; hence it is necessary to improve our understanding of the problems involved.

The objectives of this Technical Paper, as set out in IPCC-XXI – Doc. 9[6], are summarised below:

- to improve our understanding of the links between both natural and anthropogenically induced climate change, its impacts, and adaptation and mitigation response options, on the one hand, and water-related issues, on the other;
- to inform policymakers and stakeholders about the implications of climate change and climate change response options for water resources, as well as the implications for water resources of various climate change scenarios and climate change response options, including associated synergies and trade-offs.

The scope of this Technical Paper, as outlined in IPCC-XXI – Doc. 9, is to evaluate the impacts of climate change on hydrological processes and regimes, and on freshwater resources – their availability, quality, uses and management. The Technical Paper takes into account current and projected regional key vulnerabilities and prospects for adaptation.

The Technical Paper is addressed primarily to policymakers engaged in all areas relevant to freshwater resource management, climate change, strategic studies, spatial planning and socio-economic development. However, it is also addressed to the scientific community working in the area of water and climate change, and to a broader audience, including NGOs and the media.

Since material on water and climate change is scattered throughout the IPCC's Fourth Assessment and Synthesis Reports, it is useful to have a compact and integrated publication focused on water and climate change. The present Technical Paper also refers to earlier IPCC Assessment and Special Reports, where necessary. The added value of this Technical Paper lies in the distillation, prioritisation, synthesis and interpretation of those materials.

[6] 'Scoping Paper for a possible Technical Paper on Climate Change and Water'. Available at: http://www.ipcc.ch/meetings/session21.htm.

Text in the Technical Paper carefully follows the text of the underlying IPCC Reports. It reflects the balance and objectivity of those Reports and, where the text differs, this is with the purpose of supporting and/or explaining further the Reports' conclusions. Every substantive paragraph is sourced back to an IPCC Report. The source is provided within square brackets, generally at the end of the paragraph (except where parts of a paragraph are sourced from more than one IPCC document, in which case the relevant IPCC source is located after the appropriate entry). The following conventions have been used.

- The Fourth Assessment Report (AR4) is the most frequently cited IPCC publication and is represented by, for example, [WGII 3.5], which refers to AR4 Working Group II Chapter 3 Section 3.5. See IPCC (2007a, b, c, d).
- Where material is taken from other IPCC sources, the following acronyms are used: TAR (Third Assessment Report: IPCC 2001a, b, c), RICC (Special Report on Regional Impacts of Climate Change: Watson et al., 1997), LULUCF (Special Report on Land Use, Land-Use Change and Forestry: IPCC, 2000), SRES (Special Report on Emissions Scenarios: Nakićenović and Swart, 2000), CCB (Technical Paper V – Climate Change and Biodiversity: Gitay et al., 2002) and CCS (Special Report on Carbon Dioxide Capture and Storage: Metz et al., 2005). Thus, [WGII TAR 5.8.3] refers to Section 5.8.3 of Chapter 5 in the Working Group II Third Assessment Report.
- Additional sourcing acronyms include ES (Executive Summary), SPM (Summary for Policymakers), TS (Technical Summary) and SYR (Synthesis Report), which all refer to the AR4 unless otherwise indicated.

References to original sources (journals, books and reports) are placed after the relevant sentence, within round brackets.

1.3 The context of the Technical Paper: socio-economic and environmental conditions

This Technical Paper explores the relationships between climate change and freshwater, as set out in IPCC Assessment and Special Reports. These relationships do not exist in isolation, but in the context of, and interacting with, socio-economic and environmental conditions. In this section, we describe the major features of these conditions as they relate to freshwater, both observed and projected.

Many non-climatic drivers affect freshwater resources at all scales, including the global scale (UN, 2003). Water resources, both in terms of quantity and quality, are critically influenced by human activity, including agriculture and land-use change, construction and management of reservoirs, pollutant emissions, and water and wastewater treatment. Water use is linked primarily to changes in population, food consumption (including type of diet), economic policy (including water pricing), technology, lifestyle[7] and society's views about the value of freshwater ecosystems. In order to assess the relationship between climate change and freshwater, it is necessary to consider how freshwater has been, and will be, affected by changes in these non-climatic drivers. [WGII 3.3.2]

1.3.1 Observed changes

In global-scale assessments, basins are defined as being water-stressed[8] if they have either a per capita water availability below 1,000 m^3 per year (based on long-term average runoff) or a ratio of withdrawals to long-term average annual runoff above 0.4. A water volume of 1,000 m^3 per capita per year is typically more than is required for domestic, industrial and agricultural water uses. Such water-stressed basins are located in northern Africa, the Mediterranean region, the Middle East, the Near East, southern Asia, northern China, Australia, the USA, Mexico, north-eastern Brazil and the west coast of South America (Figure 1.1). The estimates for the population living in such water-stressed basins range between 1.4 billion and 2.1 billion (Vörösmarty et al., 2000; Alcamo et al., 2003a, b; Oki et al., 2003; Arnell, 2004). [WGII 3.2]

Water use, in particular that for irrigation, generally increases with temperature and decreases with precipitation; however, there is no evidence for a climate-related long-term trend of water use in the past. This is due, in part, to the fact that water use is mainly driven by non-climatic factors, and is also due to the poor quality of water-use data in general, and of time-series data in particular. [WGII 3.2]

Water availability from surface water sources or shallow groundwater wells depends on the seasonality and interannual variability of streamflow, and a secured water supply is determined by seasonal low flows. In snow-dominated basins, higher temperatures lead to reduced streamflow and thus decreased water supply in summer (Barnett et al., 2005). [WGII 3.2]

In water-stressed areas, people and ecosystems are particularly vulnerable to decreasing and more variable precipitation due to climate change. Examples are given in Section 5.

In most countries, except for a few industrialised nations, water use has increased over recent decades, due to population and economic growth, changes in lifestyle, and expanded water supply systems, with irrigation water use being by far the most important cause. Irrigation accounts for about 70% of total water withdrawals worldwide and for more than 90% of consumptive water use (i.e., the water volume that is not available for reuse downstream). [WGII 3.2] Irrigation generates about 40% of total agricultural output (Fischer et al., 2006). The area of global irrigated land has increased approximately linearly since

[7] In this context use of water-hungry appliances such as dishwashers, washing machines, lawn sprinklers etc.

[8] Water stress is a concept describing how people are exposed to the risk of water shortage.

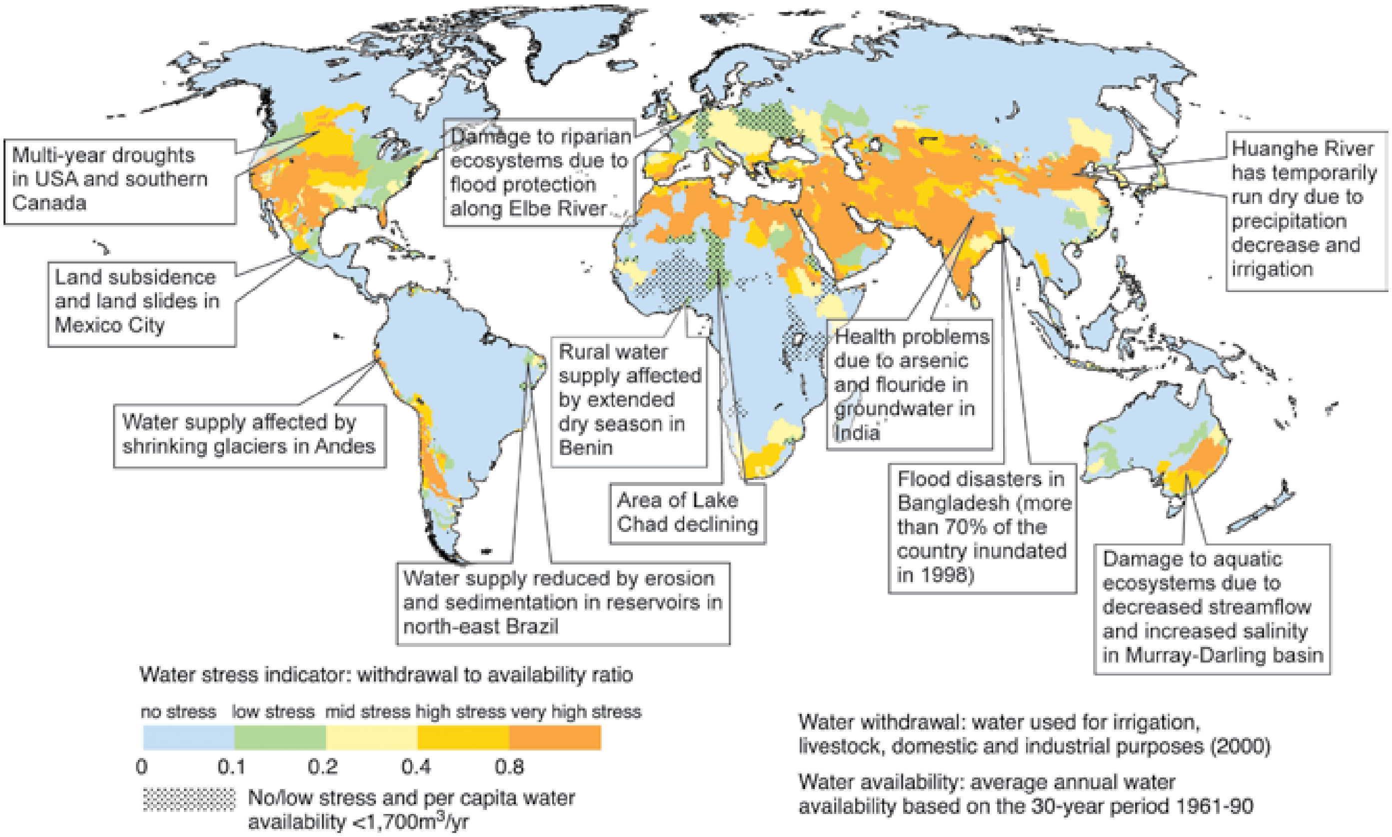


Figure 1.1: *Examples of current vulnerabilities of freshwater resources and their management; in the background, a water stress map based on WaterGAP (Alcamo et al., 2003a). See text for relation to climate change. [WGII Figure 3.2]*

1960, at a rate of roughly 2% *per annum*, from 140 million ha in 1961/63 to 270 million ha in 1997/99, representing about 18% of today's total cultivated land (Bruinsma, 2003).

Although the rates of regional population change differ widely from the global average, the rate of global population increase is already declining. Global water use is probably increasing due to economic growth in developing countries, but there are no reliable data with respect to the rate of increase. [WGII 3.2, 5.3]

The quality of surface water and groundwater has generally declined in recent decades due principally to growth in agricultural and industrial activities (UN, 2006). To counter this problem, many countries (e.g., in the European Union and Canada) have established or enforced effluent water standards and have rehabilitated wastewater treatment facilities (GEO-3, 2003). [WGII 3.3.2, Table 8.1]

1.3.2 Projected changes

1.3.2.1 General background

The four IPCC SRES (Special Report on Emissions Scenarios: Nakićenović and Swart, 2000) storylines, which form the basis for many studies of projected climate change and water resources, consider a range of plausible changes in population and economic activity over the 21st century (see Figure 1.2). Among the scenarios that assume a world economy dominated by global trade and alliances (A1 and B1), global population is expected to increase from today's 6.6 billion and peak at 8.7 billion in 2050, while in the scenarios with less globalisation and co-operation (A2 and B2), global population is expected to increase until 2100, reaching 10.4 billion (B2) and 15 billion (A2) by the end of the century. In general, all SRES scenarios depict a society that is more affluent than today, with world gross domestic product (GDP) rising to 10–26 times today's levels by 2100. A narrowing of income differences between world regions is assumed in all SRES scenarios – with technology representing a driving force as important as demographic change and economic development. [SRES SPM]

1.3.2.2 Water resources

Of particular interest for projections of water resources, with or without climate change, are possible changes in dam construction and decommissioning, water supply infrastructure, wastewater treatment and reuse, desalination, pollutant emissions and land use, particularly with regard to irrigation. Irrespective of climate change, new dams are expected to be built in developing countries for hydropower generation as well as water supply, even though their number is *likely* to be small compared to the existing 45,000 large dams. However, the impacts of a possible future increase in hydropower demand have not been taken into account (World Commission on Dams,

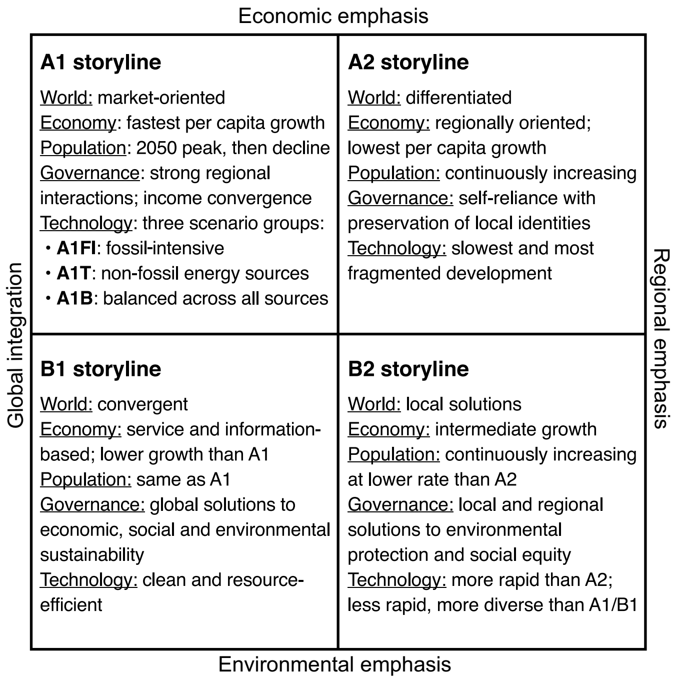


Figure 1.2: *Summary characteristics of the four SRES storylines (based on Nakićenović and Swart, 2000). [WGII Figure 2.5]*

2000; Scudder, 2005). In developed countries, the number of dams is *very likely* to remain stable, and some dams will be decommissioned. With increased temporal runoff variability due to climate change, increased water storage behind dams may be beneficial, especially where annual runoff does not decrease significantly. Consideration of environmental flow requirements may lead to further modification of reservoir operations so that the human use of water resources might be restricted. Efforts to reach the Millennium Development Goals (MDGs, see Table 7.1) should lead to improved water sources and sanitation. In the future, wastewater reuse and desalination will possibly become important sources of water supply in semi-arid and arid regions. However, there are unresolved concerns regarding their environmental impacts, including those related to the high energy use of desalination. Other options, such as effective water pricing policies and cost-effective water demand management strategies, need to be considered first. [WGII 3.3.2, 3.4.1, 3.7]

An increase in wastewater treatment in both developed and developing countries is expected in the future, but point-source discharges of nutrients, heavy metals and organic substances are *likely* to increase in developing countries. In both developed and developing countries, emissions of organic micro-pollutants (e.g., endocrine substances) to surface waters and groundwater may increase, given that the production and consumption of chemicals, with the exception of a few highly toxic substances, is *likely* to increase. Several of these pollutants are not removed by current wastewater treatment technology. Modifications of water quality may be caused by the impact of sea-level rise on storm-water drainage operations and sewage disposal in coastal areas. [WGII 3.2.2, 3.4.4]

Diffuse emissions of nutrients and pesticides from agriculture are *likely* to continue to be important in developed countries and are *very likely* to increase in developing countries, thus critically affecting water quality. According to the four scenarios of the Millennium Ecosystem Assessment (2005a) (‘Global orchestration’, ‘Order from strength’, ‘Adapting mosaic’ and ‘TechnoGarden’), global nitrogen fertiliser use will reach 110–140 Mt by 2050, compared with 90 Mt in 2000. Under three of the scenarios, there is an increase in nitrogen transport in rivers by 2050, while under the ‘TechnoGarden’ scenario (similar to the IPCC SRES scenario B1) there is a reduction (Millennium Ecosystem Assessment, 2005b). [WGII 3.3.2]

Among the most important drivers of water use are population and economic development, but also changing societal views on the value of water. The latter refers to the prioritisation of domestic and industrial water supply over irrigation water supply and the efficient use of water, including the extended application of water-saving technologies and water pricing. In all four Millennium Ecosystem Assessment scenarios, per capita domestic water use in 2050 is broadly similar in all world regions, at around 100 m^3/yr, i.e., the European average in 2000 (Millennium Ecosystem Assessment, 2005b). [WGII 3.3.2]

The dominant non-climate-change-related drivers of future irrigation water use are: the extent of irrigated area, crop type, cropping intensity and irrigation water-use efficiency. According to FAO (UN Food and Agriculture Organization) projections, developing countries, with 75% of the global irrigated area, are *likely* to expand their irrigated areas by 0.6% per year until 2030, while the cropping intensity of irrigated land is projected to increase from 1.27 to 1.41 crops per year and irrigation water-use efficiency will increase slightly (Bruinsma, 2003). These estimates exclude climate change, which is not expected by Bruinsma to affect agriculture before 2030. Most of the expansion is projected to occur in already water-stressed areas such as southern Asia, northern China, the Near East and northern Africa. However, a much smaller expansion of irrigated area is assumed under all four scenarios of the Millennium Ecosystem Assessment, with global growth rates of only 0–0.18% per year until 2050. After 2050, the irrigated area is assumed to stabilise or slightly decline under all scenarios except ‘Global orchestration’ (similar to the IPCC SRES A1 scenario) (Millennium Ecosystem Assessment, 2005a). In another study, using a revised A2 population scenario and FAO long-term projections, increases in global irrigated land of over 40% by 2080 are projected to occur mainly in southern Asia, Africa and Latin America, corresponding to an average increase of 0.4% per year (Fischer et al., 2006). [WGII 3.3.2]

1.4 Outline

This Technical Paper consists of eight sections. Following the introduction to the Paper (Section 1), Section 2 is based primarily on the assessments of Working Group I, and looks at the science of climate change, both observed and projected, as it relates to hydrological variables. Section 3 presents a general overview of observed and projected water-related impacts of climate change, and possible adaptation strategies, drawn principally from the Working Group II assessments. Section 4 then looks at systems and sectors in detail, and Section 5 takes a regional approach. Section 6, based on Working Group III assessments, covers water-related aspects of mitigation. Section 7 looks at the implications for policy and sustainable development, followed by the final section (Section 8) on gaps in knowledge and suggestions for future work. The Technical Paper uses the standard uncertainty language of the Fourth Assessment (see Box 1.1).

Box 1.1: Uncertainties in current knowledge: their treatment in the Technical Paper [SYR]

The IPCC Uncertainty Guidance Note[9] defines a framework for the treatment of uncertainties across all Working Groups and in this Technical Paper. This framework is broad because the Working Groups assess material from different disciplines and cover a diversity of approaches to the treatment of uncertainty drawn from the literature. The nature of data, indicators and analyses used in the natural sciences is generally different from that used in assessing technology development or in the social sciences. WGI focuses on the former, WGIII on the latter, and WGII covers aspects of both.

Three different approaches are used to describe uncertainties, each with a distinct form of language. Choices among and within these three approaches depend on both the nature of the information available and the authors' expert judgement of the correctness and completeness of current scientific understanding.

Where uncertainty is assessed qualitatively, it is characterised by providing a relative sense of the amount and quality of evidence (that is, information from theory, observations or models, indicating whether a belief or proposition is true or valid) and the degree of agreement (that is, the level of concurrence in the literature on a particular finding). This approach is used by WGIII through a series of self-explanatory terms such as: *high agreement, much evidence*; *high agreement, medium evidence*; *medium agreement, medium evidence*; etc.

Where uncertainty is assessed more quantitatively using expert judgement of the correctness of the underlying data, models or analyses, then the following scale of confidence levels is used to express the assessed chance of a finding being correct: *very high confidence* at least 9 out of 10; *high confidence* about 8 out of 10; *medium confidence* about 5 out of 10; *low confidence* about 2 out of 10; and *very low confidence* less than 1 out of 10.

Where uncertainty in specific outcomes is assessed using expert judgement and statistical analysis of a body of evidence (e.g., observations or model results), then the following likelihood ranges are used to express the assessed probability of occurrence: *virtually certain* >99%; *extremely likely* >95%; *very likely* >90%; *likely* >66%; *more likely than not* >50%; *about as likely as not* 33% to 66%; *unlikely* <33%; *very unlikely* <10%; *extremely unlikely* <5%; *exceptionally unlikely* <1%.

WGII has used a combination of confidence and likelihood assessments, and WGI has predominantly used likelihood assessments.

This Technical Paper follows the uncertainty assessment of the underlying Working Groups. Where synthesised findings are based on information from more than one Working Group, the description of uncertainty used is consistent with that for the components drawn from the respective Reports.

[9] See http://www.ipcc.ch/meetings/ar4-workshops-express-meetings/uncertainty-guidance-note.pdf.

2

Observed and projected changes in climate as they relate to water

Water is involved in all components of the climate system (atmosphere, hydrosphere, cryosphere, land surface and biosphere). Therefore, climate change affects water through a number of mechanisms. This section discusses observations of recent changes in water-related variables, and projections of future changes.

2.1 Observed changes in climate as they relate to water

The hydrological cycle is intimately linked with changes in atmospheric temperature and radiation balance. Warming of the climate system in recent decades is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global sea level. Net anthropogenic radiative forcing of the climate is estimated to be positive (warming effect), with a best estimate of 1.6 Wm^{-2} for 2005 (relative to 1750 pre-industrial values). The best-estimate linear trend in global surface temperature from 1906 to 2005 is a warming of 0.74°C (*likely* range 0.56 to 0.92°C), with a more rapid warming trend over the past 50 years. New analyses show warming rates in the lower- and mid-troposphere that are similar to rates at the surface. Attribution studies show that most of the observed increase in global temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations. At the continental scale, it is *likely* that there has been significant anthropogenic warming over the past 50 years averaged over each of the continents except Antarctica. For widespread regions, cold days, cold nights and frost have become less frequent, while hot days, hot nights and heatwaves have become more frequent over the past 50 years. [WGI SPM]

Climate warming observed over the past several decades is consistently associated with changes in a number of components of the hydrological cycle and hydrological systems such as: changing precipitation patterns, intensity and extremes; widespread melting of snow and ice; increasing atmospheric water vapour; increasing evaporation; and changes in soil moisture and runoff. There is significant natural variability – on interannual to decadal time-scales – in all components of the hydrological cycle, often masking long-term trends. There is still substantial uncertainty in trends of hydrological variables because of large regional differences, and because of limitations in the spatial and temporal coverage of monitoring networks (Huntington, 2006). At present, documenting interannual variations and trends in precipitation over the oceans remains a challenge. [WGI 3.3]

Understanding and attribution of observed changes also presents a challenge. For hydrological variables such as runoff, non-climate-related factors may play an important role locally (e.g., changes in extraction). The climate response to forcing agents is also complex. For example, one effect of absorbing aerosols (e.g., black carbon) is to intercept heat in the aerosol layer which would otherwise reach the surface, driving evaporation and subsequent latent heat release above the surface. Hence, absorbing aerosols may locally reduce evaporation and precipitation. Many aerosol processes are omitted or included in somewhat simple ways in climate models, and the local magnitude of their effects on precipitation is in some cases poorly known. Despite the above uncertainties, a number of statements can be made on the attribution of observed hydrological changes, and these are included in the discussion of individual variables in this section, based on the assessments in AR4. [WGI 3.3, 7.5.2, 8.2.1, 8.2.5, 9.5.4; WGII 3.1, 3.2]

2.1.1 Precipitation (including extremes) and water vapour

Trends in land precipitation have been analysed using a number of data sets; notably the Global Historical Climatology Network (GHCN: Peterson and Vose, 1997), but also the Precipitation Reconstruction over Land (PREC/L: Chen et al., 2002), the Global Precipitation Climatology Project (GPCP: Adler et al., 2003), the Global Precipitation Climatology Centre (GPCC: Beck et al., 2005) and the Climatic Research Unit (CRU: Mitchell and Jones, 2005). Precipitation over land generally increased over the 20th century between 30°N and 85°N, but notable decreases have occurred in the past 30–40 years from 10°S to 30°N (Figure 2.1). Salinity decreases in the North Atlantic and south of 25°S suggest similar precipitation changes over the ocean. From 10°N to 30°N, precipitation increased markedly from 1900 to the 1950s, but declined after about 1970. There are no strong hemispheric-scale trends over Southern Hemisphere extra-tropical land masses. At the time of writing, the attribution of changes in global precipitation is uncertain, since precipitation is strongly influenced by large-scale patterns of natural variability. [WGI 3.3.2.1]

The linear trend for the global average from GHCN during 1901–2005 is statistically insignificant (Figure 2.2). None of the trend estimates for 1951–2005 are significant, with many discrepancies between data sets, demonstrating the difficulty of monitoring a quantity such as precipitation, which has large variability in both space and time. Global changes are not linear in time, showing significant decadal variability, with a relatively wet period from the 1950s to the 1970s, followed by a decline in precipitation. Global averages are dominated by tropical and sub-tropical precipitation. [WGI 3.3.2.1]

Spatial patterns of trends in annual precipitation are shown in Figure 2.3, using GHCN station data interpolated to a 5° × 5° latitude/longitude grid. Over much of North America and Eurasia, annual precipitation has increased during the 105 years from 1901, consistent with Figure 2.1. The period since 1979 shows a more complex pattern, with regional drying evident (e.g., south-west North America). Over most of Eurasia, the number of grid-boxes showing increases in precipitation is greater than the number showing decreases, for both periods. There is a tendency for inverse variations between northern Europe and the Mediterranean, associated with changes in the North Atlantic Oscillation teleconnection (see also Section 2.1.7). [WGI 3.3.2.2]

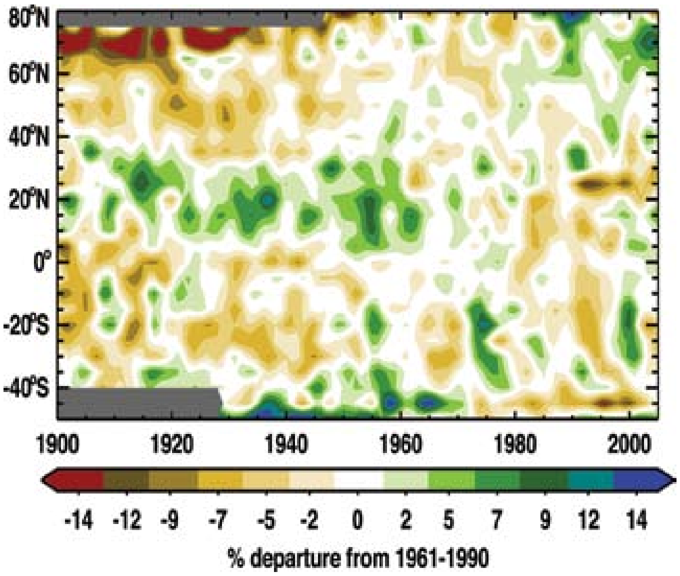


Figure 2.1: *Latitude–time section of average annual anomalies for precipitation (%) over land from 1900 to 2005, relative to their 1961–1990 means. Values are averaged across all longitudes and are smoothed with a filter to remove fluctuations less than about 6 years. The colour scale is non-linear and grey areas indicate missing data. [WGI Figure 3.15]*

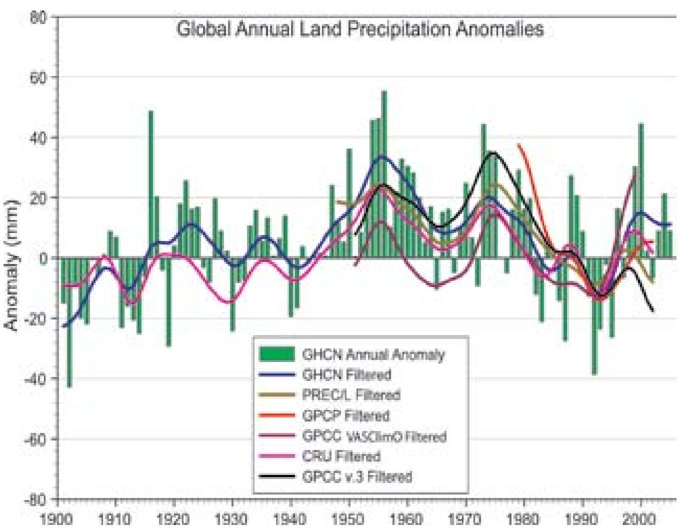


Figure 2.2: *Time-series for 1900–2005 of annual global land precipitation anomalies (mm) from GHCN with respect to the 1981–2000 base period. Smoothed decadal-scale values are also given for the GHCN, PREC/L, GPCP, GPCC and CRU data sets. [WGI Figure 3.12]*

Across South America, increasingly wet conditions have been observed over the Amazon Basin and south-eastern South America, including Patagonia, while negative trends in annual precipitation have been observed over Chile and parts of the western coast of the continent. Variations over Amazonia, Central America and western North America are suggestive of latitudinal changes in monsoon features. [WGI 3.3.2.2]

The largest negative trends since 1901 in annual precipitation are observed over western Africa and the Sahel (see also Section 5.1), although there were downward trends in many other parts of Africa, and in south Asia. Since 1979, precipitation has increased in the Sahel region and in other parts of tropical Africa, related in part to variations associated with teleconnection patterns (see also Section 2.1.7). Over much of north-western India the 1901–2005 period shows increases of more than 20% per century`, but the same area shows a strong decrease in annual precipitation since 1979. North-western Australia shows areas with moderate to strong increases in annual precipitation over both periods. Conditions have become wetter over north-west Australia, but there has been a marked downward trend in the far south-west, characterised by a downward shift around 1975. [WGI 3.3.2.2]

A number of model studies suggest that changes in radiative forcing (from combined anthropogenic, volcanic and solar sources) have played a part in observed trends in mean precipitation. However, climate models appear to underestimate the variance of land mean precipitation compared to observational estimates. It is not clear whether this discrepancy results from an underestimated response to shortwave forcing, underestimated internal climate variability, observational errors, or some combination of these. Theoretical considerations suggest that the influence of increasing greenhouse gases on mean precipitation may be difficult to detect. [WGI 9.5.4]

Widespread increases in heavy precipitation events (e.g., above the 95th percentile) have been observed, even in places where total amounts have decreased. These increases are associated with increased atmospheric water vapour and are consistent with observed warming (Figure 2.4). However, rainfall statistics are dominated by interannual to decadal-scale variations, and trend estimates are spatially incoherent (e.g., Peterson et al., 2002; Griffiths et al., 2003; Herath and Ratnayake, 2004). Moreover, only a few regions have data series of sufficient quality and length to assess trends in extremes reliably. Statistically significant increases in the occurrence of heavy precipitation have been observed across Europe and North America (Klein Tank and Können, 2003; Kunkel et al., 2003; Groisman et al., 2004; Haylock and Goodess, 2004). Seasonality of changes varies with location: increases are strongest in the warm season in the USA, while in Europe changes were most notable in the cool season (Groisman et al., 2004; Haylock and Goodess, 2004). Further discussion of regional changes is presented in Section 5. [WGI 3.8.2.2]

Theoretical and climate model studies suggest that, in a climate that is warming due to increasing greenhouse gases, a greater increase is expected in extreme precipitation, as compared to the mean. Hence, anthropogenic influence may be easier to detect in extreme precipitation than in the mean. This is because extreme precipitation is controlled by the availability of water vapour, while mean precipitation is controlled by the ability of the atmosphere to radiate long-wave energy (released as latent heat by condensation) to space, and the latter is restricted by increasing greenhouse gases. Taken together, the observational

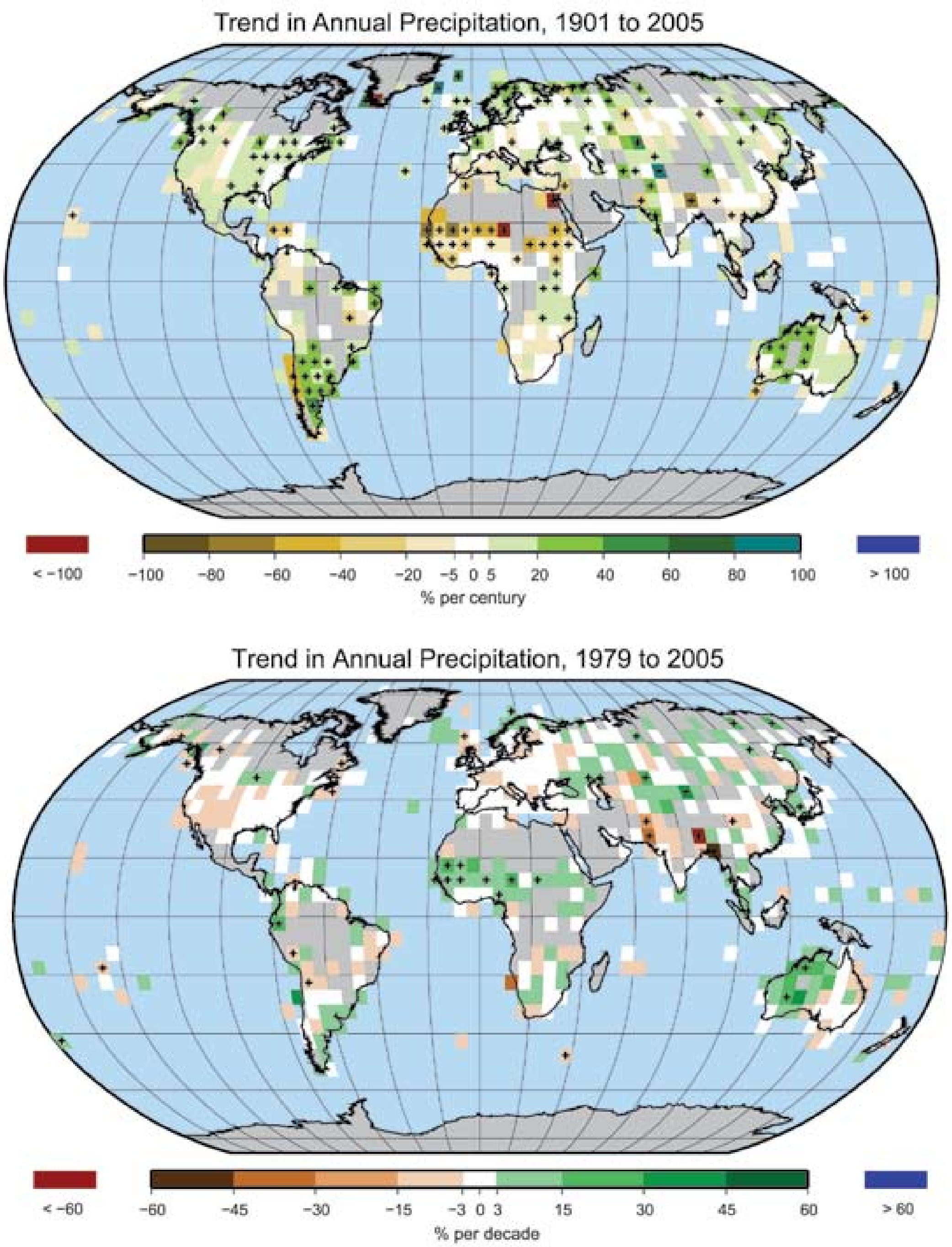


Figure 2.3: *Trend of annual precipitation amounts, 1901–2005 (upper, % per century) and 1979–2005 (lower, % per decade), as a percentage of the 1961–1990 average, from GHCN station data. Grey areas have insufficient data to produce reliable trends. [WGI Figure 3.13]*

and modelling studies lead to an overall conclusion that an increase in the frequency of heavy precipitation events (or in the proportion of total rainfall from heavy falls) is *likely* to have occurred over most land areas over the late 20th century, and that this trend is *more likely than not* to include an anthropogenic contribution. The magnitude of the anthropogenic contribution cannot be assessed at this stage. [WGI SPM, 9.5.4, 10.3.6, FAQ10.1]

There is observational evidence for an increase in intense tropical cyclone activity in the North Atlantic since about 1970, correlated with increases in tropical sea surface temperatures (SSTs). There are also suggestions of increased intense tropical cyclone activity in some other regions, but in these regions concerns over data quality are greater. Multi-decadal variability and the quality of the tropical cyclone records prior to routine satellite observations in about 1970 complicate the detection of

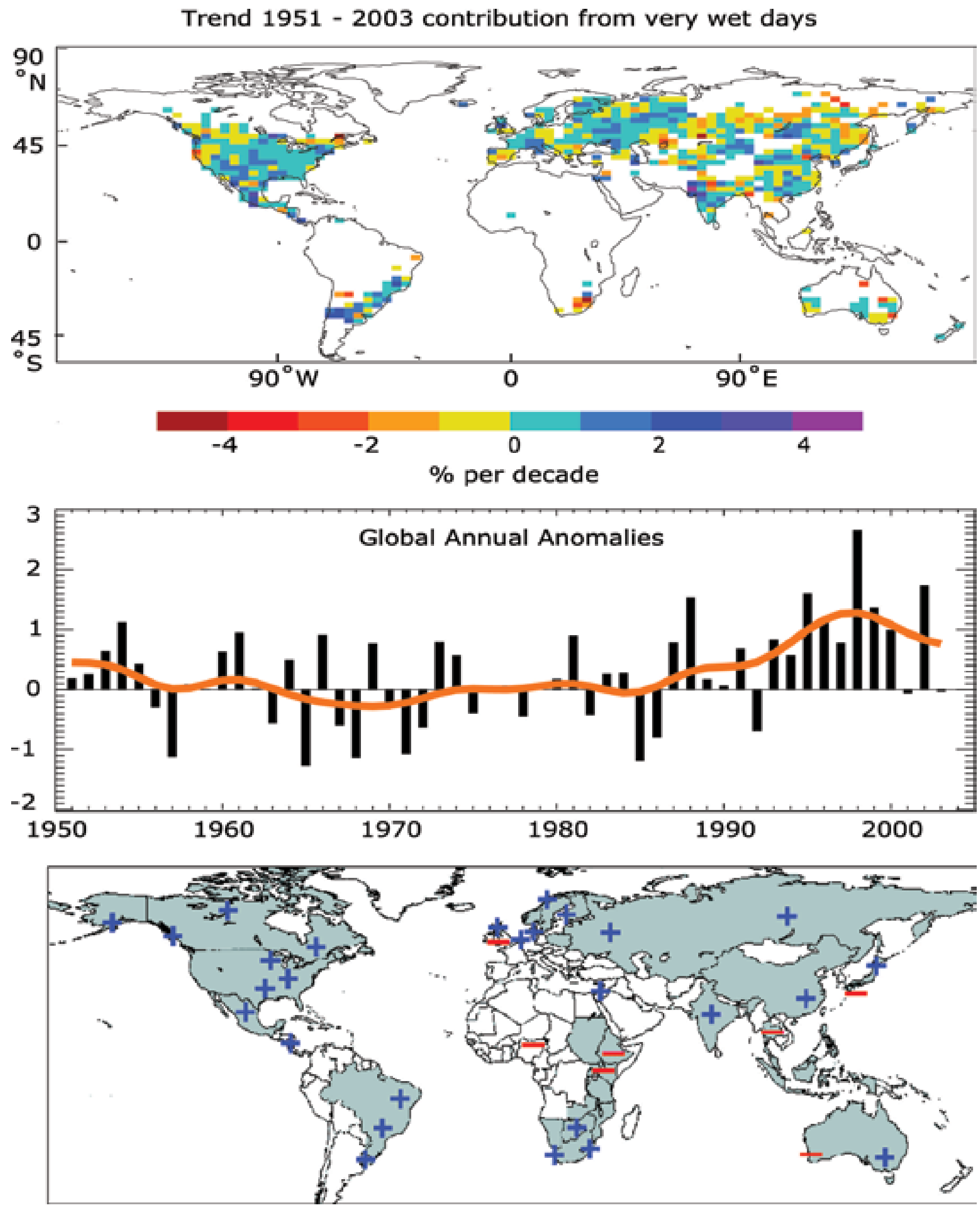


Figure 2.4: Upper panel shows observed trends (% per decade) for 1951–2003 in the contribution to total annual precipitation from very wet days (95th percentile and above). Middle panel shows, for global annual precipitation, the change in the contribution of very wet days to the total (%, compared to the 1961–1990 average of 22.5%) (after Alexander et al., 2006). Lower panel shows regions where disproportionate changes in heavy and very heavy precipitation were documented as either an increase (+) or decrease (–) compared to the change in annual and/or seasonal precipitation (updated from Groisman et al., 2005). [WGI Figure 3.39]

long-term trends in tropical cyclone activity. There is no clear trend in the annual numbers of tropical cyclones. Anthropogenic factors have *more likely than not* contributed to observed increases in intense tropical cyclone activity. However, the apparent increase in the proportion of very intense storms since 1970 in some regions is much larger than simulated by current models for that period. [WGI SPM]

The water vapour content of the troposphere has been observed to increase in recent decades, consistent with observed warming and near-constant relative humidity. Total column water vapour has increased over the global oceans by 1.2 ± 0.3% per decade from 1988 to 2004, in a pattern consistent with changes in sea surface temperature. Many studies show increases in near-surface atmospheric moisture, but there are regional differences and differences between day and night. As with other components of the hydrological cycle, interannual to decadal-scale variations are substantial, but a significant upward trend has been observed over the global oceans and over some land areas in the Northern Hemisphere. Since observed warming of SST is *likely* to be largely anthropogenic, this suggests that anthropogenic influence has contributed to the observed increase in atmospheric water vapour over the oceans. However, at the time of writing of the AR4, no formal attribution study was available. [WGI 3.4.2, 9.5.4]

2.1.2 Snow and land ice

The cryosphere (consisting of snow, ice and frozen ground) on land stores about 75% of the world's freshwater. In the climate system, the cryosphere and its changes are intricately linked to the surface energy budget, the water cycle and sea-level change. More than one-sixth of the world's population lives in glacier- or snowmelt-fed river basins (Stern, 2007). [WGII 3.4.1] Figure 2.5 shows cryosphere trends, indicating significant decreases in ice storage in many components. [WGI Chapter 4]

2.1.2.1 Snow cover, frozen ground, lake and river ice

Snow cover has decreased in most regions, especially in spring and summer. Northern Hemisphere snow cover observed by satellites over the 1966–2005 period decreased in every month except November and December, with a stepwise drop of 5% in the annual mean in the late 1980s. Declines in the mountains of western North America and in the Swiss Alps have been largest at lower elevations. In the Southern Hemisphere, the few long records or proxies available mostly show either decreases or no change in the past 40 years or more. [WGI 4.2.2]

Degradation of permafrost and seasonally frozen ground is leading to changes in land surface characteristics and drainage systems. Seasonally frozen ground includes both seasonal soil freeze–thaw in non-permafrost regions and the active layer over permafrost that thaws in summer and freezes in winter. The estimated maximum extent of seasonally frozen ground in non-permafrost areas has decreased by about 7% in the Northern Hemisphere from 1901 to 2002, with a decrease of up to 15% in spring. Its maximum depth has decreased by about 0.3 m in Eurasia since the mid-20th century in response to winter warming and increases in snow depth. Over the period 1956 to 1990, the active layer measured at 31 stations in Russia exhibited a statistically significant deepening of about 21 cm. Records from other regions are too short for trend analyses. Temperature at the top of the permafrost layer has increased by up to 3°C since the 1980s in the Arctic. Permafrost warming and degradation of frozen ground appear to be the result of increased summer air temperatures and changes in the depth and duration of snow cover. [WGI 4.7, Chapter 9]

Freeze-up and break-up dates for river and lake ice exhibit considerable spatial variability. Averaged over available data for the Northern Hemisphere spanning the past 150 years, freeze-up has been delayed at a rate of 5.8 ± 1.6 days per century, while the break-up date has occurred earlier at a rate of 6.5 ± 1.2 days per century. There are insufficient published data on river and lake ice thickness to allow the assessment of trends. Modelling studies (e.g., Duguay et al., 2003) indicate that much of the variability in maximum ice thickness and break-up date is driven by variations in snowfall. [WGI 4.3]

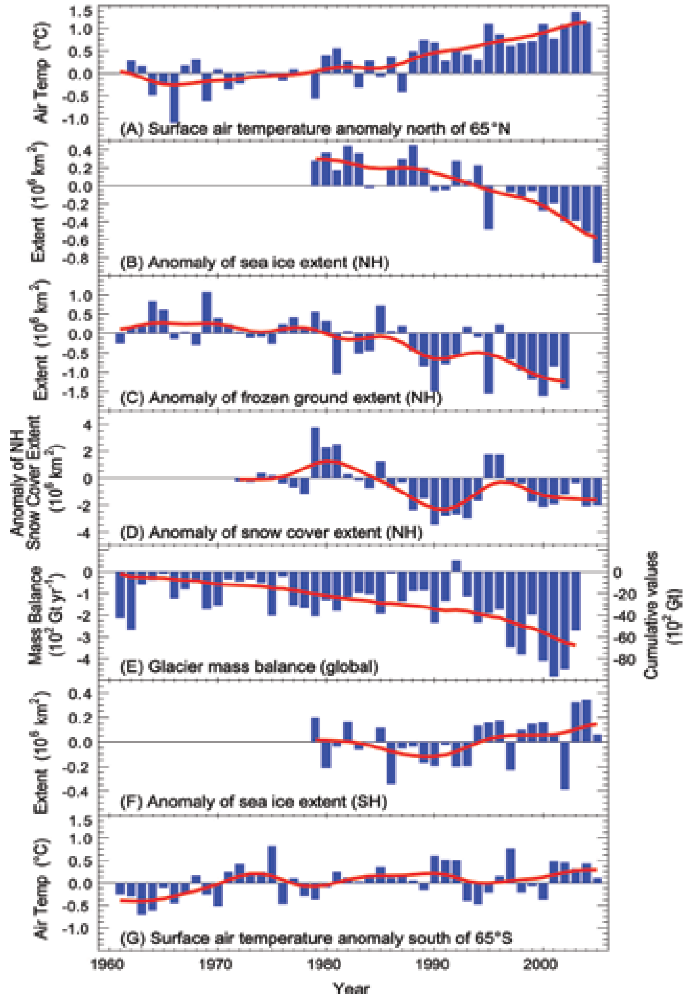


Figure 2.5: *Anomaly time-series (departure from the long-term mean) of polar surface air temperature (A and E), Northern Hemisphere (NH) seasonally frozen ground extent (B), NH snow cover extent for March–April (C), and global glacier mass balance (D). The solid red line in D denotes the cumulative global glacier mass balance; otherwise it represents the smoothed time-series. [Adapted from WGI FAQ 4.1]*

2.1.2.2 Glaciers and ice caps

On average, glaciers and ice caps in the Northern Hemisphere and Patagonia show a moderate but rather consistent increase in mass turnover over the last half-century, and substantially increased melting. [WGI 4.5.2, 4.6.2.2.1] As a result, considerable mass loss occurred on the majority of glaciers and ice caps worldwide (Figure 2.6) with increasing rates: from 1960/61 to 1989/90 the loss was 136 ± 57 Gt/yr (0.37 ± 0.16 mm/yr sea-level equivalent, SLE), and between 1990/91 and 2003/04 it was 280 ± 79 Gt/yr (0.77 ± 0.22 mm/yr SLE). The widespread 20th-century shrinkage appears to imply widespread warming as the primary cause although, in the tropics, changes in atmospheric moisture might be contributing. There is evidence that this melting has *very likely* contributed to observed sea-level rise. [WGI 4.5 Table 4.4, 9.5]

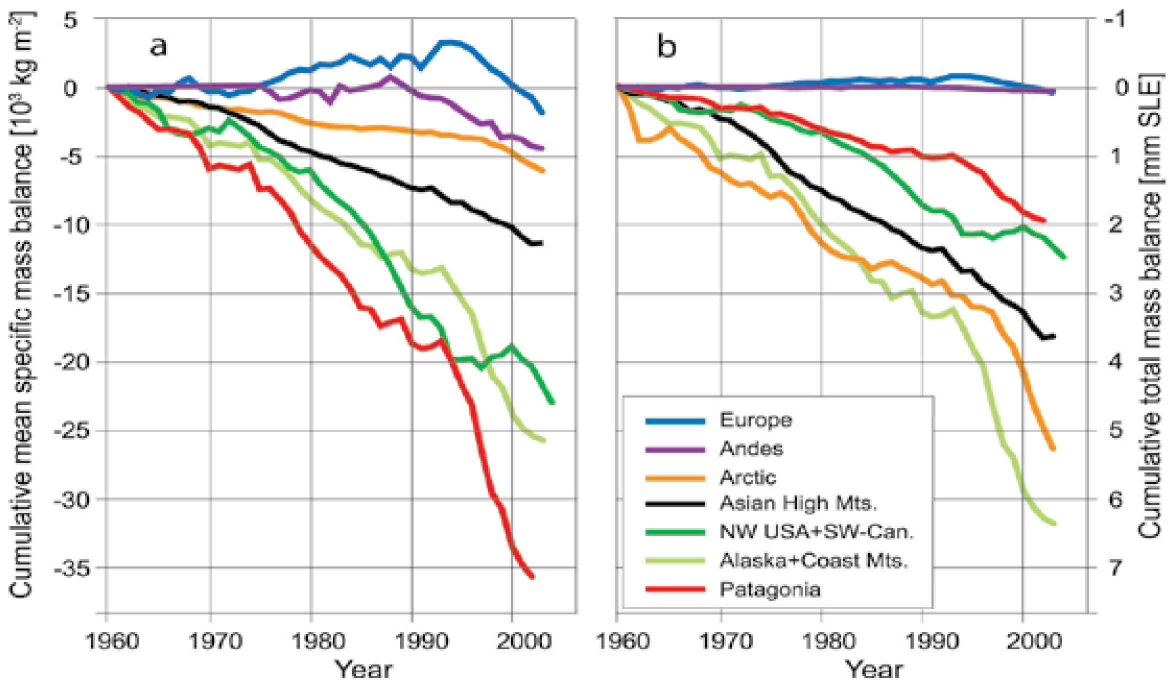


Figure 2.6: *Cumulative mean specific mass balances (a) and cumulative total mass balances (b) of glaciers and ice caps, calculated for large regions (Dyurgerov and Meier, 2005). The mass balance of a glacier is the sum of all mass gains and losses during a hydrological year. Mean specific mass balance is the total mass balance divided by the total surface area of all glaciers and ice caps of a region, and it shows the strength of change in the respective region. Total mass balance is presented as the contribution from each region to sea-level rise. [WGI 4.5.2, Figure 4.15]*

Formation of lakes is occurring as glacier tongues retreat from prominent Little Ice Age (LIA) moraines in several steep mountain ranges, including the Himalayas, the Andes, and the Alps. These lakes have a high potential for glacial lake outburst floods. [WGII 1.3.1.1, Table 1.2]

2.1.3 Sea level

Global mean sea level has been rising and there is *high confidence* that the rate of rise has increased between the mid-19th and the mid-20th centuries. The average rate was 1.7 ± 0.5 mm/yr for the 20th century, 1.8 ± 0.5 mm/yr for 1961–2003, and 3.1 ± 0.7 mm/yr for 1993–2003. It is not known whether the higher rate in 1993–2003 is due to decadal variability or to an increase in the longer-term trend. Spatially, the change is highly non-uniform; e.g., over the period 1993 to 2003, rates in some regions were up to several times the global mean rise while, in other regions, sea levels fell. [WGI 5.ES]

There are uncertainties in the estimates of the contributions to the long-term sea-level change. For the period 1993–2003, the contributions from thermal expansion (1.6 ± 0.5 mm/yr), mass loss from glaciers and ice caps (0.77 ± 0.22 mm/yr) and mass loss from the Greenland (0.21 ± 0.07 mm/yr) and Antarctic (0.21 ± 0.35 mm/yr) ice sheets totalled 2.8 ± 0.7 mm/yr. For this period, the sum of these climate contributions is consistent with the directly observed sea-level rise given above, within the observational uncertainties. For the longer period 1961–2003, the sum of the climate contributions is estimated to be smaller than the observed total sea-level rise; however, the observing system was less reliable prior to 1993. For both periods, the estimated contributions from thermal expansion and from glaciers/ice caps are larger than the contributions from the Greenland and Antarctic ice sheets. The large error bars for Antarctica mean that it is uncertain whether Antarctica has contributed positively or negatively to sea level. Increases in sea level are consistent with warming, and modelling studies suggest that overall it is *very likely* that the response to anthropogenic forcing contributed to sea-level rise during the latter half of the 20th century; however, the observational uncertainties, combined with a lack of suitable studies, mean that it is difficult to quantify the anthropogenic contribution. [WGI SPM, 5.5, 9.5.2]

Rising sea level potentially affects coastal regions, but attribution is not always clear. Global increases in extreme high water levels since 1975 are related to both mean sea-level rise and large-scale inter-decadal climate variability (Woodworth and Blackman, 2004). [WGII 1.3.3]

2.1.4 Evapotranspiration

There are very limited direct measurements of actual evapotranspiration over global land areas, while global analysis products[10] are sensitive to the type of analysis and can contain large errors, and thus are not suitable for trend analysis. Therefore, there is little literature on observed trends in evapotranspiration, whether actual or potential. [WGI 3.3.3]

2.1.4.1 Pan evaporation

Decreasing trends during recent decades are found in sparse records of pan evaporation (measured evaporation from an open water surface in a pan, a proxy for potential evapotranspiration) over the USA (Peterson et al., 1995; Golubev et al., 2001; Hobbins et al., 2004), India (Chattopadhyay and Hulme, 1997), Australia (Roderick and Farquhar, 2004), New Zealand (Roderick and Farquhar, 2005), China (Liu et al., 2004; Qian et al., 2006b) and Thailand (Tebakari et al., 2005). Pan measurements do not represent actual evaporation (Brutsaert and Parlange, 1998), and trends may be caused by decreasing surface solar radiation (over the USA and parts of Europe and Russia) and decreased sunshine duration over China that may be related to increases in air pollution and atmospheric aerosols and increases in cloud cover. [WGI 3.3.3, Box 3.2]

2.1.4.2 Actual evapotranspiration

The TAR reported that actual evapotranspiration increased during the second half of the 20th century over most dry regions of the USA and Russia (Golubev et al., 2001), resulting from greater availability of surface moisture due to increased precipitation and larger atmospheric moisture demand due to higher temperature. Using observations of precipitation, temperature, cloudiness-based surface solar radiation and a comprehensive land surface model, Qian et al. (2006a) found that global land evapotranspiration closely follows variations in land precipitation. Global precipitation values peaked in the early 1970s and then decreased somewhat, but reflect mainly tropical values, and precipitation has increased more generally over land at higher latitudes. Changes in evapotranspiration depend not only on moisture supply but also on energy availability and surface wind. [WGI 3.3.3]

Other factors affecting actual evapotranspiration include the direct effects of atmospheric CO_2 enrichment on plant physiology. The literature on these direct effects, with respect to observed evapotranspiration trends, is non-existent, although effects on runoff have been seen. [WGI 9.5.4]

Annual amounts of evapotranspiration depend, in part, on the length of the growing season. The AR4 presents evidence for observed increases in growing season length. These increases, associated with earlier last spring frost and delayed autumn frost dates, are clearly apparent in temperate regions of Eurasia (Moonen et al., 2002; Menzel et al., 2003; Genovese et al., 2005; Semenov et al., 2006) and a major part of North America (Robeson, 2002; Feng and Hu, 2004). [WGII 1.3.6.1]

2.1.5 Soil moisture

Historical records of soil moisture content measured *in situ* are available for only a few regions and are often very short in duration. [WGI 3.3.4] Among more than 600 stations from a large variety of climates, Robock et al. (2000) identified an increasing long-term trend in surface (top 1 m) soil moisture content during summer for the stations with the longest records, mostly located in the former Soviet Union, China, and central USA. The longest records available, from the Ukraine, show overall increases in surface soil moisture, although increases are less marked in recent decades (Robock et al., 2005). The initial approach to estimating soil moisture has been to calculate Palmer Drought Severity Index (PDSI) values from observed precipitation and temperature. PDSI changes are discussed in Section 3.1.2.4. [WGI Box 3.1, 3.3.4]

2.1.6 Runoff and river discharge

A large number of studies have examined potential trends in measures of river discharge during the 20th century, at scales ranging from catchment to global. Some have detected significant trends in some indicators of flow, and some have demonstrated statistically significant links with trends in temperature or precipitation. Many studies, however, have found no trends or have been unable to separate out the effects of variations in temperature and precipitation from the effects of human interventions in the catchment. The methodology used to search for trends can also influence results. For example, different statistical tests can give different indications of significance; different periods of record (particularly start and end dates) can suggest different rates of change; failing to allow for cross-correlation between catchments can lead to an overestimation of the numbers of catchments showing significant change. Another limitation of trend analysis is the availability of consistent, quality-controlled data. Available streamflow gauge records cover only about two-thirds of the global actively drained land area and often contain gaps and vary in record length (Dai and Trenberth, 2002). Finally, human interventions have affected flow regimes in many catchments. [WGI 3.3.4, 9.1, 9.5.1; WGII 1.3.2]

At the global scale, there is evidence of a broadly coherent pattern of change in annual runoff, with some regions experiencing an increase in runoff (e.g., high latitudes and large parts of the USA) and others (such as parts of West Africa, southern Europe and southernmost South America) experiencing a decrease in

[10] 'Analysis products' refers to estimates of past climate variations produced by assimilating a range of observations into a weather forecasting or climate model, in the way that is done routinely to initialise daily weather forecasts. Because operational weather analysis/forecasting systems are developed over time, a number of 'reanalysis' exercises have been carried out in which the available observations are assimilated into a single system, eliminating any spurious jumps or trends due to changes in the underlying system. An advantage of analysis systems is that they produce global fields that include many quantities that are not directly observed. A potential disadvantage is that all fields are a mixture of observations and models, and for regions/variables for which there are few observations, may represent largely the climatology of the underlying model.

runoff (Milly et al., 2005, and many catchment-scale studies). Variations in flow from year to year are also influenced in many parts of the world by large-scale climatic patterns associated, for example, with ENSO, the NAO and the PNA pattern.[11] One study (Labat et al., 2004) claimed a 4% increase in global total runoff per 1°C rise in temperature during the 20th century, with regional variations around this trend, but debate around this conclusion (Labat et al., 2004; Legates et al., 2005) has focused on the effects of non-climatic drivers on runoff and the influence of a small number of data points on the results. Gedney et al. (2006) attributed widespread increases in runoff during the 20th century largely to the suppression of evapotranspiration by increasing CO_2 concentrations (which affect stomatal conductance), although other evidence for such a relationship is difficult to find and Section 2.1.4 presents evidence for an increase in evapotranspiration. [WGII 1.3.2]

Trends in runoff are not always consistent with changes in precipitation. This may be due to data limitations (in particular the coverage of precipitation data), the effect of human interventions such as reservoir impoundment (as is the case with the major Eurasian rivers), or the competing effects of changes in precipitation and temperature (as in Sweden: see Lindstrom and Bergstrom, 2004).

There is, however, far more robust and widespread evidence that the timing of river flows in many regions where winter precipitation falls as snow has been significantly altered. Higher temperatures mean that a greater proportion of the winter precipitation falls as rain rather than snow, and the snowmelt season begins earlier. Snowmelt in parts of New England shifted forward by 1 to 2 weeks between 1936 and 2000 (Hodgkins et al., 2003), although this has had little discernible effect on summer flows (Hodgkins et al., 2005). [WGII 1.3.2]

2.1.7 Patterns of large-scale variability

The climate system has a number of preferred patterns of variability having a direct influence on elements of the hydrological cycle. Regional climates may vary out of phase, owing to the action of such 'teleconnections'. Teleconnections are often associated with droughts and floods, and with other changes which have significant impacts on humans. A brief overview is given below of the key teleconnection patterns. A more complete discussion is given in Section 3.6 of the WGI AR4.

A teleconnection is defined by a spatial pattern and a time-series describing variations in its magnitude and phase. Spatial patterns may be defined over a grid or by indices based on station observations. For example, the Southern Oscillation Index (SOI) is based solely on differences in mean sea-level pressure anomalies between Tahiti (eastern Pacific) and Darwin (western Pacific), yet it captures much of the variability of large-scale atmospheric circulation throughout the tropical Pacific. Teleconnection patterns tend to be most prominent in winter (especially in the Northern Hemisphere), when the mean circulation is strongest. The strength of teleconnections, and the way in which they influence surface climate, also varies over long time-scales. [WGI 3.6.1]

The SOI describes the atmospheric component of the El Niño–Southern Oscillation (ENSO), the most significant mode of interannual variability of the global climate. ENSO has global impacts on atmospheric circulation, precipitation and temperature (Trenberth and Caron, 2000). ENSO is associated with an east–west shift in tropical Pacific precipitation, and with modulation of the main tropical convergence zones. ENSO is also associated with wave-like disturbances to the atmospheric circulation outside the tropics, such as the Pacific–North American (PNA) and Pacific–South American (PSA) patterns, which have major regional climate effects. The strength and frequency of ENSO events vary on the decadal scale, in association with the Pacific Decadal Oscillation (PDO, also known as the Inter-decadal Pacific Oscillation or IPO), which modulates the mean state of ocean surface temperatures and the tropical atmospheric circulation on time-scales of 20 years and longer. The climate shift in 1976/77 (Trenberth, 1990) was associated with changes in El Niño evolution (Trenberth and Stepaniak, 2001) and a tendency towards more prolonged and stronger El Niños. As yet there is no formally detectable change in ENSO variability in observations. [WGI 3.6.2, 3.6.3]

Outside the tropics, variability of the atmospheric circulation on time-scales of a month or longer is dominated by variations in the strength and locations of the jet streams and associated storm tracks, characterised by the Northern and Southern 'Annular Modes' (NAM and SAM, respectively: Quadrelli and Wallace, 2004; Trenberth et al., 2005). The NAM is closely related to the North Atlantic Oscillation (NAO), although the latter is most strongly associated with the Atlantic storm track and with climate variations over Europe. The NAO is characterised by out-of-phase pressure anomalies between temperate and high latitudes over the Atlantic sector. The NAO has its strongest signature in winter, when its positive (negative) phase exhibits an enhanced (diminished) Iceland Low and Azores High (Hurrell et al., 2003). The closely related NAM has a similar structure over the Atlantic, but is more longitudinally symmetrical. The NAO has a strong influence on wintertime surface temperatures across much of the Northern Hemisphere, and on storminess and precipitation over Europe and North Africa, with a poleward shift in precipitation in the positive phase and an Equatorward shift in the negative phase. There is evidence of prolonged positive and negative NAO periods during the last few centuries (Cook et al., 2002; Jones et al., 2003a). In winter, a reversal occurred from the minimum index values in the late 1960s to strongly positive NAO index values in the mid-1990s. Since then, NAO values have declined to near their long-term mean. Attribution studies suggest that the trend over recent decades in the NAM is *likely* to be related in part to human activity. However, the response to natural and anthropogenic forcings that is simulated by climate models is smaller than the observed trend. [WGI 3.6.4, 9.ES]

[11] Respectively, ENSO = El Niño–Southern Oscillation, NAO = North Atlantic Oscillation, PNA = Pacific–North American; see Section 2.1.7 and Glossary for further explanation.

The Southern Annular Mode (SAM) is associated with synchronous pressure variations of opposite sign in mid- and high latitudes, reflecting changes in the main belt of sub-polar westerly winds. Enhanced Southern Ocean westerlies occur in the positive phase of the SAM, which has become more common in recent decades, leading to more cyclones in the circumpolar trough (Sinclair et al., 1997), a poleward shift in precipitation, and a greater contribution to Antarctic precipitation (Noone and Simmonds, 2002). The SAM also affects spatial patterns of precipitation variability in Antarctica (Genthon et al., 2003) and southern South America (Silvestri and Vera, 2003). Model simulations suggest that the recent trend in the SAM has been affected by increased greenhouse gas concentration and, in particular, by stratospheric ozone depletion. [WGI 3.6.5, 9.5.3.3]

North Atlantic SSTs show about a 70-year variation during the instrumental period (and in proxy reconstructions), termed the Atlantic Multi-decadal Oscillation (AMO: Kerr, 2000). A warm phase occurred during 1930–1960 and cool phases during 1905–1925 and 1970–1990 (Schlesinger and Ramankutty, 1994). The AMO appears to have returned to a warm phase beginning in the mid-1990s. The AMO may be related to changes in the strength of the thermohaline circulation (Delworth and Mann, 2000; Latif, 2001; Sutton and Hodson, 2003; Knight et al., 2005). The AMO has been linked to multi-year precipitation anomalies over North America, appears to modulate ENSO teleconnections (Enfield et al., 2001; McCabe et al., 2004; Shabbar and Skinner, 2004) and also plays a role in Atlantic hurricane formation (Goldenberg et al., 2001). The AMO is believed to be a driver of multi-decadal variations in Sahel drought, precipitation in the Caribbean, summertime climate of both North America and Europe, sea-ice concentration in the Greenland Sea, and sea-level pressure over the southern USA, the North Atlantic and southern Europe (e.g., Venegas and Mysak, 2000; Goldenberg et al., 2001; Sutton and Hodson, 2005; Trenberth and Shea, 2006). [WGI 3.6.6]

2.2 Influences and feedbacks of hydrological changes on climate

Some robust correlations have been observed between temperature and precipitation in many regions. This provides evidence that processes controlling the hydrological cycle and temperature are closely coupled. At a global scale, changes in water vapour, clouds and ice change the radiation balance of the Earth and hence play a major role in determining the climate response to increasing greenhouse gases. The global impact of these processes on temperature response is discussed in WGI AR4 Section 8.6. In this section, we discuss some processes through which changes in hydrological variables can produce feedback effects on regional climate, or on the atmospheric budget of major greenhouse gases. The purpose of this section is not to provide a comprehensive discussion of such processes, but to illustrate the tight coupling of hydrological processes to the rest of the climate system. [WGI 3.3.5, Chapter 7, 8.6]

2.2.1 Land surface effects

Surface water balances reflect the availability of both water and energy. In regions where water availability is high, evapotranspiration is controlled by the properties of both the atmospheric boundary layer and surface vegetation cover. Changes in the surface water balance can feed back on the climate system by recycling water into the boundary layer (instead of allowing it to run off or penetrate to deep soil levels). The sign and magnitude of such effects are often highly variable, depending on the details of the local environment. Hence, while in some cases these feedbacks may be relatively small on a global scale, they may become extremely important at smaller space- or time-scales, leading to regional/local changes in variability or extremes. [WGI 7.2]

The impacts of deforestation on climate illustrate this complexity. Some studies indicate that deforestation could lead to reduced daytime temperatures and increases in boundary layer cloud as a consequence of rising albedo, transpiration and latent heat loss. However, these effects are dependent on the properties of both the replacement vegetation and the underlying soil/snow surface – and in some cases the opposite effects have been suggested. The effects of deforestation on precipitation are likewise complex, with both negative and positive impacts being found, dependent on land surface and vegetation characteristics. [WGI 7.2, 7.5]

A number of studies have suggested that, in semi-arid regions such as the Sahel, the presence of vegetation can enhance conditions for its own growth by recycling soil water into the atmosphere, from where it can be precipitated again. This can result in the possibility of multiple equilibria for such regions, either with or without precipitation and vegetation, and also suggests the possibility of abrupt regime transitions, as may have happened in the change from mid-Holocene to modern conditions. [WGI Chapter 6, 7.2]

Soil moisture is a source of thermal inertia due to its heat capacity and the latent heat required for evaporation. For this reason, soil moisture has been proposed as an important control on, for example, summer temperature and precipitation. Feedbacks between soil moisture, precipitation and temperature are particularly important in transition regions between dry and humid areas, but the strength of the coupling between soil moisture and precipitation varies by an order of magnitude between different climate models, and observational constraints are not currently available to narrow this uncertainty. [WGI 7.2, 8.2]

A further control on precipitation arises through stomatal closure in response to increasing atmospheric CO_2 concentrations. In addition to its tendency to increase runoff through large-scale decreases in total evapotranspiration (Section 2.3.4), this effect may result in substantial reductions in precipitation in some regions. [WGI 7.2]

Changes in snow cover as a result of regional warming feed back on temperature through albedo changes. While the magnitude of this feedback varies substantially between models, recent studies suggest that the rate of spring snowmelt may provide a good, observable estimate of this feedback strength, offering the prospect of reduced uncertainty in future predictions of temperature change in snow-covered regions. [WGI 8.6]

2.2.2 Feedbacks through changes in ocean circulation

Freshwater input to the ocean changes the salinity, and hence the density, of sea water. Thus, changes in the hydrological cycle can change the density-driven ('thermohaline') ocean circulation, and thence feed back on climate. A particular example is the meridional overturning circulation (MOC) in the North Atlantic Ocean. This circulation has a substantial impact on surface temperature, precipitation and sea level in regions around the North Atlantic and beyond. The Atlantic MOC is projected to weaken during the 21st century, and this weakening is important in modulating the overall climate change response. In general, a weakening MOC is expected to moderate the rate of warming at northern mid-latitudes, but some studies suggest that it would also result in an increased rate of warming in the Arctic. These responses also feed back on large-scale precipitation through changes in evaporation from the low- and mid-latitude Atlantic. While in many models the largest driver of MOC weakening is surface warming (rather than freshening), in the deep water source regions, hydrological changes do play an important role, and uncertainty in the freshwater input is a major contribution to the large inter-model spread in projections of MOC response. Observed changes in ocean salinity over recent decades are suggestive of changes in freshwater input. While nearly all atmosphere–ocean general circulation model (AOGCM) integrations show a weakening MOC in the 21st century, none shows an abrupt transition to a different state. Such an event is considered *very unlikely* in the 21st century, but it is not possible to assess the likelihood of such events in the longer term. [WGI 10.3.4]

Changes in precipitation, evaporation and runoff, and their impact on the MOC, are explicitly modelled in current climate projections. However, few climate models include a detailed representation of changes in the mass balance of the Greenland and Antarctic ice sheets, which represent a possible additional source of freshwater to the ocean. The few studies available to date that include detailed modelling of freshwater input from Greenland do not suggest that this extra source will change the broad conclusions presented above. [WGI 5.2, 8.7, 10.3, Box 10.1]

2.2.3 Emissions and sinks affected by hydrological processes or biogeochemical feedbacks

Changes in the hydrological cycle can feed back on climate through changes in the atmospheric budgets of carbon dioxide, methane and other radiatively-active chemical species, often regulated by the biosphere. The processes involved are complex; for example the response of heterotrophic soil respiration, a source of CO_2, to increasing temperature depends strongly on the amount of soil moisture. A new generation of climate models, in which vegetation and the carbon cycle respond to the changing climate, has allowed some of these processes to be explored for the first time. All models suggest that there is a positive feedback of climate change on the global carbon cycle, resulting in a larger proportion of anthropogenic CO_2 emissions remaining in the atmosphere in a warmer climate. However, the magnitude of the overall feedback varies substantially between models; changes in net terrestrial primary productivity are particularly uncertain, reflecting the underlying spread in projections of regional precipitation change. [WGI 7.3]

A number of sources and sinks of methane are sensitive to hydrological change, for example wetlands, permafrost, rice agriculture (sources) and soil oxidation (sink). Other active chemical species such as ozone have also been shown to be sensitive to climate, again typically through complex biogeochemical mechanisms. Atmospheric aerosol budgets are directly sensitive to precipitation (e.g., through damping of terrestrial dust sources and the importance of wet deposition as a sink), and aerosols feed back onto precipitation by acting as condensation nuclei and so influencing the precipitation efficiency of clouds. The magnitude of these feedbacks remains uncertain, and they are generally included only in simple ways, if at all, in the current generation of climate models. [WGI 7.4]

2.3 Projected changes in climate as they relate to water

A major advance in climate change projections, compared with those considered under the TAR, is the large number of simulations available from a broader range of climate models, run for various emissions scenarios. Best-estimate projections from models indicate that decadal average warming over each inhabited continent by 2030 is insensitive to the choice of SRES scenario and is *very likely* to be at least twice as large (around 0.2°C per decade) as the corresponding model-estimated natural variability during the 20th century. Continued greenhouse gas emissions at or above current rates under SRES non-mitigation scenarios would cause further warming and induce many changes in the global climate system during the 21st century, with these changes *very likely* to be larger than those observed during the 20th century. Projected global average temperature change for 2090–2099 (relative to 1980–1999), under the SRES illustrative marker scenarios, ranges from 1.8°C (best estimate, *likely* range 1.1°C to 2.9°C) for scenario B1, to 4.0°C (best estimate, *likely* range 2.4°C to 6.4°C) for scenario A1FI. Warming is projected to be greatest over land and at most high northern latitudes, and least over the Southern Ocean and parts of the North Atlantic Ocean. It is *very likely* that hot extremes and heatwaves will continue to become more frequent. [WGI SPM, Chapter 10]

Uncertainty in hydrological projections

Uncertainties in projected changes in the hydrological system arise from internal variability of the climate system, uncertainty in future greenhouse gas and aerosol emissions, the translation of these emissions into climate change by global climate models, and hydrological model uncertainty. By the late 21st century, under the A1B scenario, differences between climate model precipitation projections are a larger source of uncertainty than internal variability. This also implies that, in many cases, the modelled changes in annual mean precipitation exceed the (modelled) internal variability by this time. Projections become less consistent between models as the spatial scale decreases. [WGI 10.5.4.3] At high latitudes and in parts of the tropics, all or nearly all models project an increase in precipitation, while in some sub-tropical and lower mid-latitude regions precipitation decreases in all or nearly all models. Between these areas of robust increase and decrease, even the sign of precipitation change is inconsistent across the current generation of models. [WGI 10.3.2.3, 10.5.4.3] For other aspects of the hydrological cycle, such as changes in evaporation, soil moisture and runoff, the relative spread in projections is similar to, or larger than, the changes in precipitation. [WGI 10.3.2.3]

Further sources of uncertainty in hydrological projections arise from the structure of current climate models. Some examples of processes that are, at best, only simply represented in climate models are given in Section 2.2. Current models generally exclude some feedbacks from vegetation change to climate change. Most, although not all, of the simulations used for deriving climate projections also exclude anthropogenic changes in land cover. The treatment of anthropogenic aerosol forcing is relatively simple in most climate models. While some models include a wide range of anthropogenic aerosol species, potentially important species, such as black carbon, are lacking from most of the simulations used for the AR4 (see discussion of the attribution of observed changes, in Section 2.1). More than half of the AR4 models also exclude the indirect effects of aerosols on clouds. The resolution of current climate models also limits the proper representation of tropical cyclones and heavy rainfall. [WGI 8.2.1, 8.2.2, 8.5.2, 8.5.3, 10.2.1]

Uncertainties arise from the incorporation of climate model results into freshwater studies for two reasons: the different spatial scales of global climate models and hydrological models, and biases in the long-term mean precipitation as computed by global climate models for the current climate. A number of methods have been used to address the scale differences, ranging from the simple interpolation of climate model results to dynamic or statistical downscaling methods, but all such methods introduce uncertainties into the projection. Biases in simulated mean precipitation are often addressed by adding modelled anomalies to the observed precipitation in order to obtain the driving dataset for hydrological models. Therefore, changes in interannual or day-to-day variability of climate parameters are not taken into account in most hydrological impact studies. This leads to an underestimation of future floods, droughts and irrigation water requirements. [WGII 3.3.1]

The uncertainties in climate change impacts on water resources, droughts and floods arise for various reasons, such as different scenarios of economic development, greenhouse gas emissions, climate modelling and hydrological modelling. However, there has not yet been a study that assesses how different hydrological models react to the same climate change signal. [WGII 3.3.1] Since the TAR, the uncertainty of climate model projections for freshwater assessments is often taken into account by using multi-model ensembles. Formal probabilistic assessments are still rare. [WGII 3.3.1, 3.4]

Despite these uncertainties, some robust results are available. In the sections that follow, uncertainties in projected changes are discussed, based on the assessments in AR4.

2.3.1 Precipitation (including extremes) and water vapour

2.3.1.1 Mean precipitation

Climate projections using multi-model ensembles show increases in globally averaged mean water vapour, evaporation and precipitation over the 21st century. The models suggest that precipitation generally increases in the areas of regional tropical precipitation maxima (such as the monsoon regimes, and the tropical Pacific in particular) and at high latitudes, with general decreases in the sub-tropics. [WGI SPM, 10.ES, 10.3.1, 10.3.2]

Increases in precipitation at high latitudes in both the winter and summer seasons are highly consistent across models (see Figure 2.7). Precipitation increases over the tropical oceans and in some of the monsoon regimes, e.g., the south Asian monsoon in summer (June to August) and the Australian monsoon in summer (December to February), are notable and, while not as consistent locally, considerable agreement is found at the broader scale in the tropics. There are widespread decreases in mid-latitude summer precipitation, except for increases in eastern Asia. Decreases in precipitation over many sub-tropical areas are evident in the multi-model ensemble mean, and consistency in the sign of change among the models is often high – particularly in some regions such as the tropical Central American—Caribbean and the Mediterranean. [WGI 10.3.2] Further discussion of regional changes is presented in Section 5.

The global distribution of the 2080–2099 change in annual mean precipitation for the SRES A1B scenario is shown in Figure 2.8, along with some other hydrological quantities from a 15-model ensemble. Increases in annual precipitation exceeding 20% occur in most high latitudes, as well as in eastern Africa, the northern part of central Asia and the equatorial Pacific Ocean. Substantial decreases of up to 20% occur in the Mediterranean and Caribbean regions and on the sub-tropical western coasts of each continent. Overall, precipitation over land increases some 5%, while precipitation over oceans increases 4%. The net change over land accounts for 24% of the global mean increase in precipitation. [WGI 10.3.2]

In climate model projections for the 21st century, global mean evaporation changes closely balance global precipitation change, but this relationship is not evident at the local scale

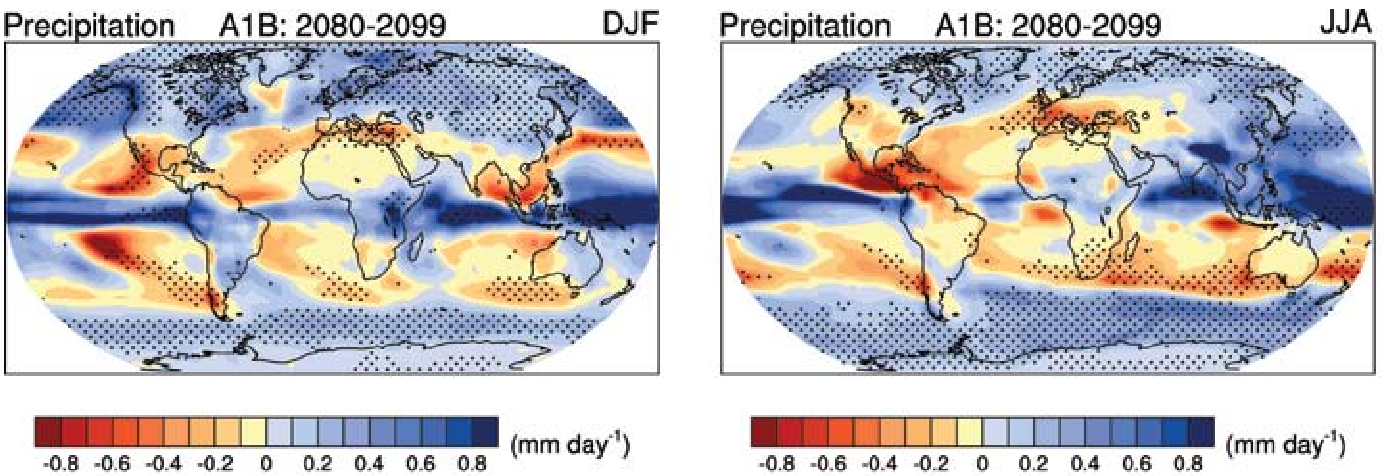


Figure 2.7: *Fifteen-model mean changes in precipitation (unit: mm/day) for DJF (left) and JJA (right). Changes are given for the SRES A1B scenario, for the period 2080–2099 relative to 1980–1999. Stippling denotes areas where the magnitude of the multi-model ensemble mean exceeds the inter-model standard deviation. [WGI Figure 10.9]*

because of changes in the atmospheric transport of water vapour. Annual average evaporation increases over much of the ocean, with spatial variations tending to relate to variations in surface warming. Atmospheric moisture convergence increases over the equatorial oceans and over high latitudes. Over land, rainfall changes tend to be balanced by both evaporation and runoff. On global scales, the water vapour content of the atmosphere is projected to increase in response to warmer temperatures, with relative humidity remaining roughly constant. These water vapour increases provide a positive feedback on climate warming, since water vapour is a greenhouse gas. Associated with this is a change in the vertical profile of atmospheric temperature ('lapse rate'), which partly offsets the positive feedback. Recent evidence from models and observations strongly supports a combined water vapour/lapse rate feedback on climate of a strength comparable with that found in climate general circulation models. [WGI 8.6, 10.ES, 10.3.2]

2.3.1.2 Precipitation extremes

It is *very likely* that heavy precipitation events will become more frequent. Intensity of precipitation events is projected to increase, particularly in tropical and high-latitude areas that experience increases in mean precipitation. There is a tendency for drying in mid-continental areas during summer, indicating a greater risk of droughts in these regions. In most tropical and mid- and high-latitude areas, extreme precipitation increases more than mean precipitation. [WGI 10.3.5, 10.3.6]

A long-standing result from global coupled models noted in the TAR was a projected increased likelihood of summer drying in the mid-latitudes, with an associated increased risk of drought (Figure 2.8). Fifteen recent AOGCM runs for a future warmer climate indicate summer dryness in most parts of the northern sub-tropics and mid-latitudes, but there is a large range in the amplitude of summer dryness across models. Droughts associated with this summer drying could result in regional vegetation die-off and contribute to an increase in the percentage of land area experiencing drought at any one time; for example, extreme drought increasing from 1% of present-day land area (by definition) to 30% by 2100 in the A2 scenario. Drier soil conditions can also contribute to more severe heatwaves. [WGI 10.3.6]

Also associated with the risk of drying is a projected increase in the risk of intense precipitation and flooding. Though somewhat counter-intuitive, this is because precipitation is projected to be concentrated in more intense events, with longer periods of lower precipitation in between (see Section 2.1.1 for further explanation). Therefore, intense and heavy episodic rainfall events with high runoff amounts are interspersed with longer relatively dry periods with increased evapotranspiration, particularly in the sub-tropics. However, depending on the threshold used to define such events, an increase in the frequency of dry days does not necessarily mean a decrease in the frequency of extreme high-rainfall events. Another aspect of these changes has been related to changes in mean precipitation, with wet extremes becoming more severe in many areas where mean precipitation increases, and dry extremes becoming more severe where mean precipitation decreases. [WGI 10.3.6]

Multi-model climate projections for the 21st century show increases in both precipitation intensity and number of consecutive dry days in many regions (Figure 2.9). Precipitation intensity increases almost everywhere, but particularly at mid- and high latitudes where mean precipitation also increases. However, in Figure 2.9 (lower part), there are regions of increased runs of dry days between precipitation events in the sub-tropics and lower mid-latitudes, but decreased runs of dry days at higher mid-latitudes and high latitudes where mean precipitation increases. [WGI 10.3.6.1]

Since there are areas of both increases and decreases in consecutive dry days between precipitation events in the

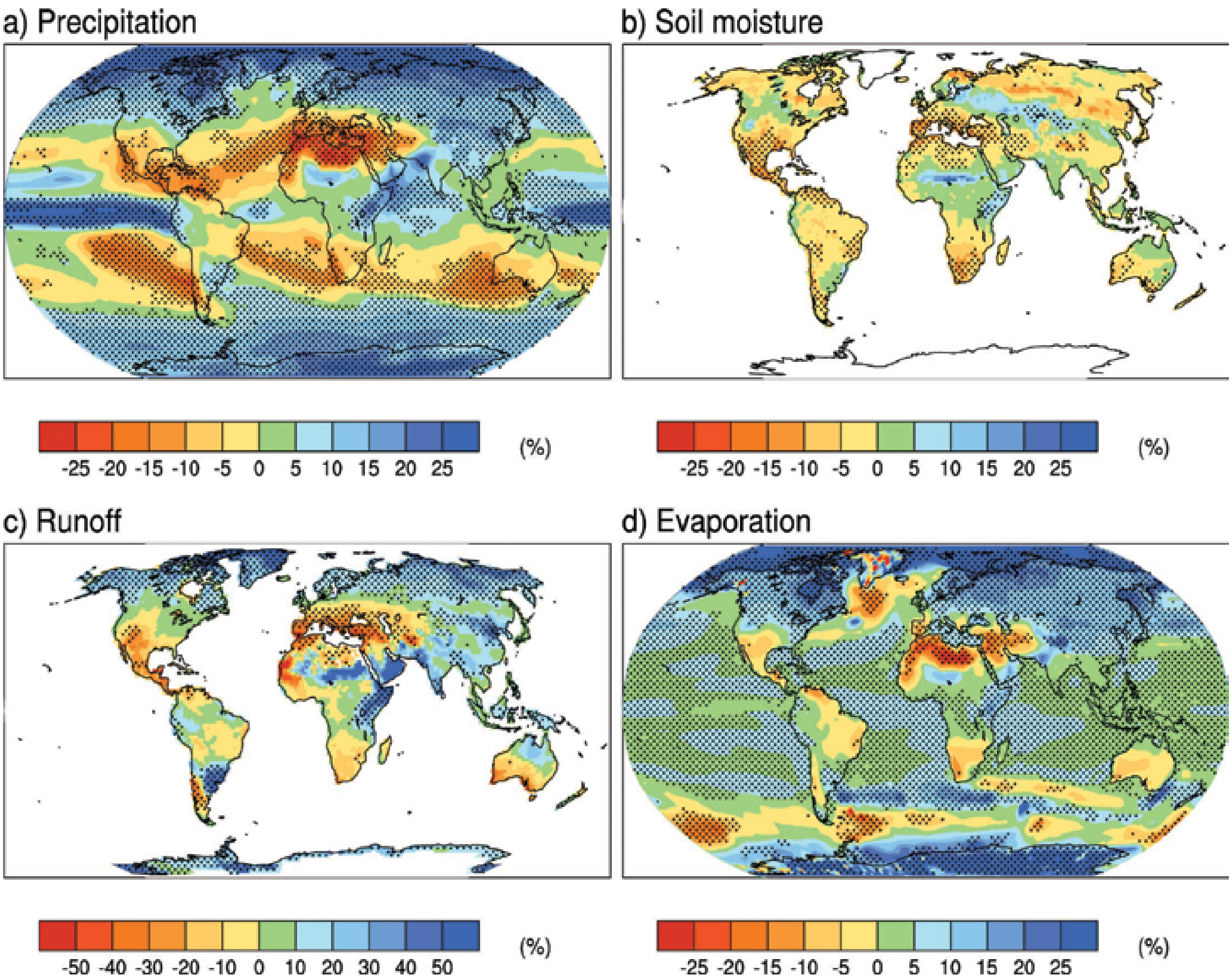


Figure 2.8: *Fifteen-model mean changes in (a) precipitation (%), (b) soil moisture content (%), (c) runoff (%), and (d) evaporation (%). To indicate consistency of sign of change, regions are stippled where at least 80% of models agree on the sign of the mean change. Changes are annual means for the scenario SRES A1B for the period 2080–2099 relative to 1980–1999. Soil moisture and runoff changes are shown at land points with valid data from at least ten models. [Based on WGI Figure 10.12]*

multi-model average (Figure 2.9), the global mean trends are smaller and less consistent across models. A perturbed physics ensemble with one model shows only limited areas of consistently increased frequency of wet days in July. In this ensemble there is a larger range of changes in precipitation extremes relative to the control ensemble mean (comparedwith the more consistent response of temperature extremes). This indicates a less consistent response for precipitation extremes in general, compared with temperature extremes. [WGI 10.3.6, FAQ10.1]

Based on a range of models, it is *likely* that future tropical cyclones will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases in tropical sea surface temperatures. There is less confidence in projections of a global decrease in numbers of tropical cyclones. [WGI SPM]

2.3.2 Snow and land ice

As the climate warms, snow cover is projected to contract and decrease, and glaciers and ice caps to lose mass, as a consequence of the increase in summer melting being greater than the increase in winter snowfall. Widespread increases in thaw depth over much of the permafrost regions are projected to occur in response to warming. [WGI SPM, 10.3.3]

2.3.2.1 Changes in snow cover, frozen ground, lake and river ice

Snow cover is an integrated response to both temperature and precipitation, and it exhibits a strong negative correlation with air temperature in most areas with seasonal snow cover. Because of this temperature association, simulations project widespread reductions in snow cover throughout the 21st century, despite some projected increases at higher altitudes. For example, climate models used in the Arctic Climate Impact Assessment (ACIA) project a 9–17% reduction in the annual mean Northern Hemisphere snow coverage under the B2 scenario by the end of the century. In general, the snow accumulation season is projected to begin later, the melting season to begin earlier, and the fractional snow coverage to decrease during the snow season. [WGI 10.3.3.2, Chapter 11]

Results from models forced with a range of IPCC climate scenarios indicate that by the mid-21st century the permafrost area in the Northern Hemisphere is *likely* to decrease by 20–35%. Projected changes in the depth of seasonal thawing are uniform neither in space nor in time. In the next three decades, active layer depths are *likely* to be within 10–15% of their present values over most of the permafrost area; by the middle of the century, the depth of seasonal thawing may increase on average by 15–25%, and by 50% or more in the northernmost locations; by 2080, it is *likely* to increase by 30–50% or more over all permafrost areas. [WGII 15.3.4]

Warming is forecast to cause reductions in river and lake ice. This effect, however, is expected to be offset on some large northward-flowing rivers because of reduced regional contrasts in south-to-north temperatures and in related hydrological and physical gradients. [WGII 15.4.1.2]

2.3.2.2 Glaciers and ice caps

As the climate warms throughout the 21st century, glaciers and ice caps are projected to lose mass owing to a dominance of summer melting over winter precipitation increases. Based on simulations of 11 glaciers in various regions, a volume loss of 60% of these glaciers is projected by 2050 (Schneeberger et al., 2003). A comparative study including seven GCM simulations at 2 × atmospheric CO_2 conditions inferred that many glaciers may disappear completely due to an increase in the equilibrium-line altitude (Bradley et al., 2004). The disappearance of these ice bodies is much faster than a potential re-glaciation several centuries hence, and may in some areas be irreversible. [WGI 10.7.4.2, Box 10.1] Global 21st-century projections show glacier and ice cap shrinkage of 0.07–0.17 m sea-level equivalent (SLE) out of today's estimated glacier and ice cap mass of 0.15–0.37 m SLE. [WGI Chapter 4, Table 4.1, 10, Table 10.7]

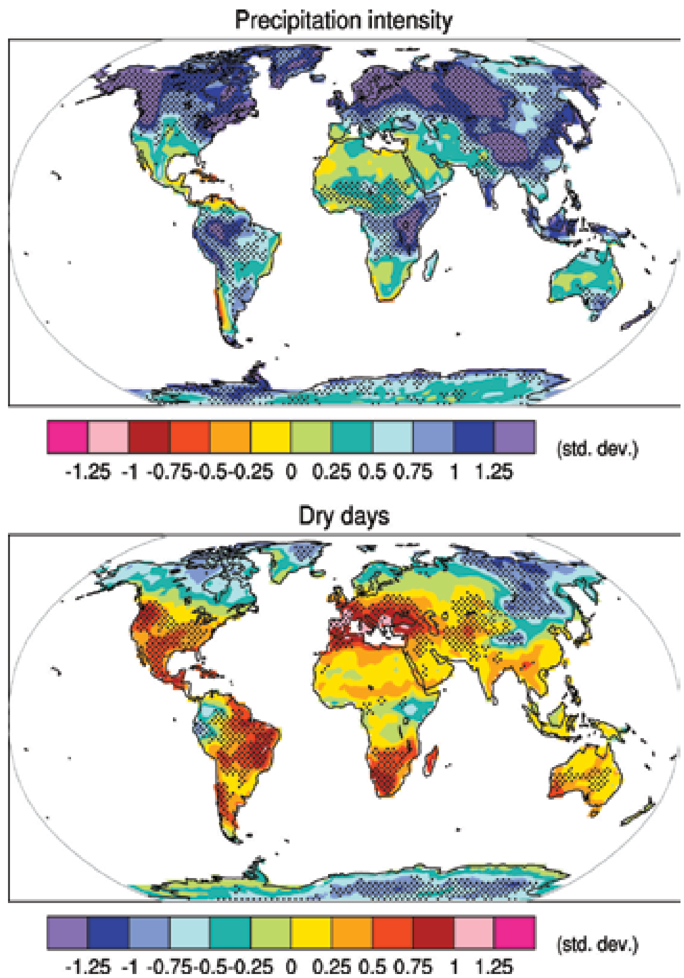


Figure 2.9: *Changes in extremes based on multi-model simulations from nine global coupled climate models in 2080–2099 relative to 1980–1999 for the A1B scenario. Changes in spatial patterns of precipitation intensity (defined as the annual total precipitation divided by the number of wet days) (top); and changes in spatial patterns of dry days (defined as the annual maximum number of consecutive dry days) (bottom). Stippling denotes areas where at least five of the nine models concur in determining that the change is statistically significant. Extreme indices are calculated only over land. The changes are given in units of standard deviations. [WGI Figure 10.18]*

2.3.3 Sea level

Because our present understanding of some important effects driving sea-level rise is too limited, AR4 does not assess the likelihood, nor provide a best estimate or an upper bound for sea-level rise. The projections do not include either uncertainties in climate–carbon cycle feedbacks or the full effects of changes in ice sheet flow; therefore the upper values of the ranges are not to be considered upper bounds for sea-level rise. Model-based projections of global mean sea-level rise between the late 20th century (1980–1999) and the end of this century (2090–2099) are of the order of 0.18 to 0.59 m, based on the spread of AOGCM results and different SRES scenarios, but excluding the uncertainties noted above. In all the SRES marker scenarios except B1, the average rate of sea-level rise during the 21st century is *very likely* to exceed the 1961–2003 average rate (1.8 ± 0.5 mm/yr). Thermal expansion is the largest component, contributing 70–75% of the central estimate in these projections for all scenarios. Glaciers, ice caps and the Greenland ice sheet are also projected to contribute positively to sea level. GCMs indicate that, overall, the Antarctic ice sheet will receive increased snowfall without experiencing substantial surface melting, thus gaining mass and contributing negatively to sea level. Sea-level rise during the 21st century is projected to have substantial geographical variability. [SYR 3.2.1; WGI SPM, 10.6.5, TS 5.2] Partial loss of the Greenland and/or Antarctic ice sheets could imply several metres of sea-level rise, major changes in coastlines and inundation of low-lying areas, with the greatest effects in river deltas and low-lying islands. Current modelling suggests that such changes are possible for Greenland over millennial time-scales, but because dynamic ice flow processes in both ice sheets are currently poorly understood, more rapid sea-level rise on century time-scales cannot be excluded. [WGI SPM; WGII 19.3]

2.3.4 Evapotranspiration

Evaporative demand, or 'potential evaporation', is projected to increase almost everywhere. This is because the water-holding capacity of the atmosphere increases with higher temperatures, but relative humidity is not projected to change markedly. Water vapour deficit in the atmosphere increases as a result, as does the evaporation rate (Trenberth et al., 2003). [WGI Figures 10.9, 10.12; WGII 3.2, 3.3.1] Actual evaporation over open water is projected to increase, e.g., over much of the ocean [WGI Figure 10.12] and lakes, with the spatial variations tending to relate to spatial variations in surface warming. [WGI 10.3.2.3, Figure 10.8] Changes in evapotranspiration over land are controlled by changes in precipitation and radiative forcing, and the changes would, in turn, impact on the water balance of runoff, soil moisture, water in reservoirs, the groundwater table and the salinisation of shallow aquifers. [WGII 3.4.2]

Carbon dioxide enrichment of the atmosphere has two potential competing implications for evapotranspiration from vegetation. On the one hand, higher CO_2 concentrations can reduce transpiration because the stomata of leaves, through which transpiration from plants takes place, need to open less in order to take up the same amount of CO_2 for photosynthesis (see Gedney et al., 2006, although other evidence for such a relationship is difficult to find). Conversely, higher CO_2 concentrations can increase plant growth, resulting in increased leaf area, and thus increased transpiration. The relative magnitudes of these two effects vary between plant types and in response to other influences, such as the availability of nutrients and the effects of changes in temperature and water availability. Accounting for the effects of CO_2 enrichment on evapotranspiration requires the incorporation of a dynamic vegetation model. A small number of models now do this (Rosenberg et al., 2003; Gerten et al., 2004; Gordon and Famiglietti, 2004; Betts et al., 2007), but usually at the global, rather than catchment, scale. Although studies with equilibrium vegetation models suggested that increased leaf area may offset stomatal closure (Betts et al., 1997; Kergoat et al., 2002), studies with dynamic global vegetation models indicate that the effects of stomatal closure exceed those of increasing leaf area. Taking into account CO_2-induced changes in vegetation, global mean runoff under a $2{\times}CO_2$ climate has been simulated to increase by approximately 5% as a result of reduced evapotranspiration due to CO_2 enrichment alone (Leipprand and Gerten, 2006; Betts et al., 2007). [WGII 3.4.1]

2.3.5 Soil moisture

Changes in soil moisture depend on changes in the volume and timing not only of precipitation, but also of evaporation (which may be affected by changes in vegetation). The geographical distribution of changes in soil moisture is therefore slightly different from the distribution of changes in precipitation; higher evaporation can more than offset increases in precipitation. Models simulate the moisture in the upper few metres of the land surface in varying ways, and evaluation of the soil moisture content is still difficult. Projections of annual mean soil moisture content (Figure 2.8b) commonly show decreases in the sub-tropics and the Mediterranean region, but there are increases in East Africa, central Asia and some other regions with increased precipitation. Decreases also occur at high latitudes, where snow cover diminishes (Section 2.3.2). While the magnitude of changes is often uncertain, there is consistency in the sign of change in many of these regions. Similar patterns of change occur in seasonal results. [WGI 10.3.2.3]

2.3.6 Runoff and river discharge

Changes in river flows, as well as lake and wetland levels, due to climate change depend primarily on changes in the volume and timing of precipitation and, crucially, whether precipitation falls as snow or rain. Changes in evaporation also affect river flows. Several hundred studies of the potential effects of climate change on river flows have been published in scientific journals, and many more studies have been presented in internal reports. Studies are heavily focused towards Europe, North America and Australasia, with a small number of studies from Asia. Virtually all studies use a catchment hydrological model driven by scenarios based on climate model simulations, and almost all are at the catchment scale. The few global-scale studies that have been conducted using both runoff simulated directly by climate models [WGI 10.3.2.3] and hydrological models run off-line [WGII 3.4] show that runoff increases in high latitudes and the wet tropics, and decreases in mid-latitudes and some parts of the dry tropics. Figure 2.8c shows the ensemble mean runoff change under the A1B scenario. Runoff is notably reduced in southern Europe and increased in south-east Asia and in high latitudes, where there is consistency among models in the sign of change (although less in the magnitude of change). The larger changes reach 20% or more of the simulated 1980–1999 values, which range from 1 to 5 mm/day in wetter regions to below 0.2 mm/day in deserts. Flows in high-latitude rivers increase, while those from major rivers in the Middle East, Europe and Central America tend to decrease. [WGI 10.3.2.3] The magnitude of change, however, varies between climate models and, in some regions such as southern Asia, runoff could either increase or decrease. As indicated in Section 2.2.1, the effects of CO_2 enrichment may lead to reduced evaporation, and hence either greater increases or smaller decreases in the volume of runoff. [WGI 7.2]

Figure 2.10 shows the change in annual runoff for 2090–2099 compared with 1980–1999. Values represent the median of 12 climate models using the SRES A1B scenario. Hatching and whitening are used to mark areas where models agree or disagree, respectively, on the sign of change: note the large areas where the direction of change is uncertain. This global map of annual runoff illustrates large-scale changes and is not intended to be interpreted at small temporal (e.g., seasonal) and spatial scales. In areas where rainfall and runoff are very low (e.g., desert areas), small changes in runoff can lead to large percentage changes. In some regions, the sign of projected changes in runoff differs from recently observed trends (Section 2.1.6). In some areas with projected increases in runoff, different seasonal effects are expected, such as increased wet-season runoff and decreased dry-season runoff. [WGII 3.4.1]

A very robust finding is that warming would lead to changes in the seasonality of river flows where much winter precipitation currently falls as snow, with spring flows decreasing because of the reduced or earlier snowmelt, and winter flows increasing. This has been found in the European Alps, Scandinavia and around the Baltic, Russia, the Himalayas, and western, central and eastern North America. The effect is greatest at lower elevations, where snowfall is more marginal, and in many cases peak flows by the middle of the 21st century would occur at least a month earlier. In regions with little or no snowfall, changes in runoff are much more dependent on changes in rainfall than on changes in temperature. Most studies in such regions project an increase in the seasonality of flows, often with higher flows in the peak flow season and either lower flows during the low-flow season or extended dry periods. [WGII 3.4.1]

Many rivers draining glaciated regions, particularly in the Asian high mountain ranges and the South American Andes, are sustained by glacier melt during warm and dry periods. Retreat of these glaciers due to global warming would lead to increased river flows in the short term, but the contribution of glacier melt would gradually fall over the next few decades. [WGII 3.4.1]

Changes in lake levels reflect changes in the seasonal distribution of river inflows, precipitation and evaporation, in some cases integrated over many years. Lakes may therefore respond in a very non-linear way to a linear change in inputs. Studies of the Great Lakes of North America and the Caspian Sea suggest changes in water levels of the order of several tens of centimetres, and sometimes metres, by the end of the century. [WGII 3.4.1]

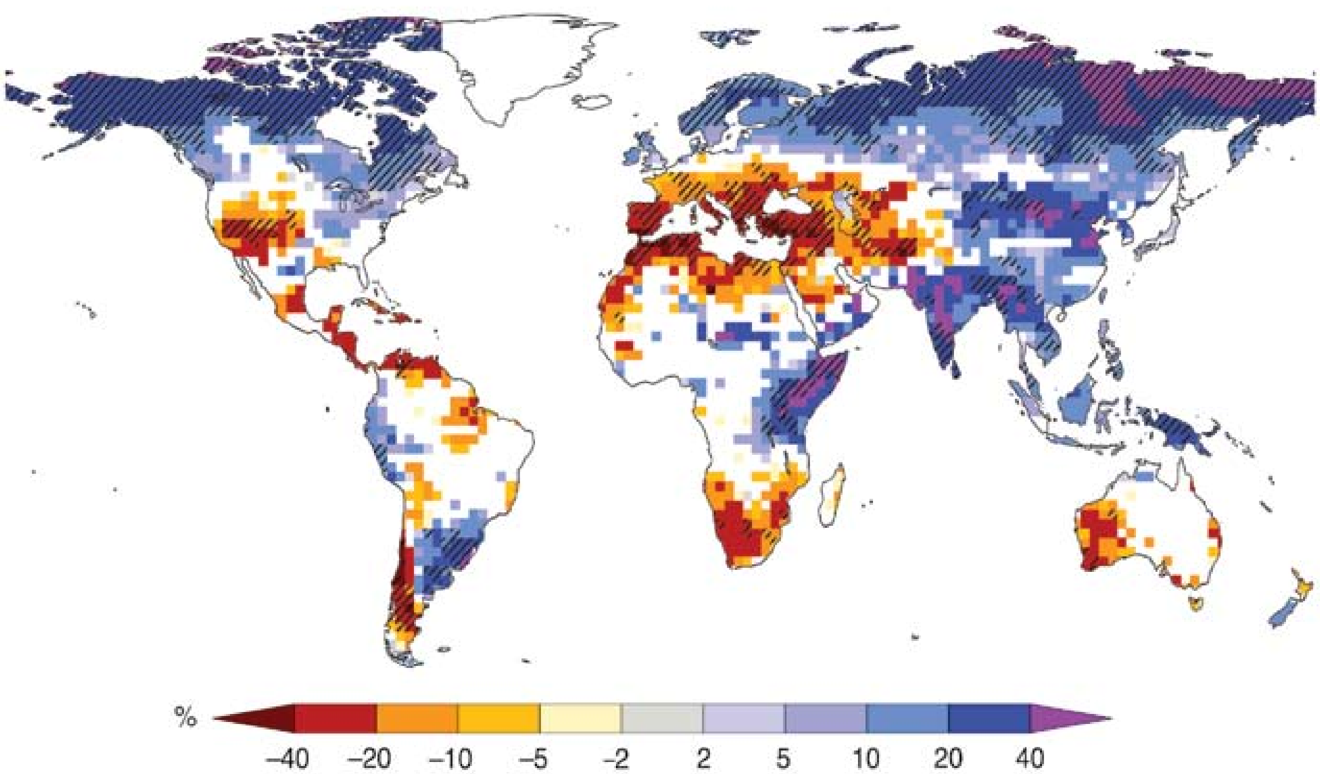


Figure 2.10: *Large-scale relative changes in annual runoff for the period 2090–2099, relative to 1980–1999. White areas are where less than 66% of the ensemble of 12 models agree on the sign of change, and hatched areas are where more than 90% of models agree on the sign of change (Milly et al., 2005). [Based on SYR Figure 3.5 and WGII Figure 3.4]*

2.3.7 Patterns of large-scale variability

Based on the global climate models assessed in AR4, sea-level pressure is projected to increase over the sub-tropics and mid-latitudes, and to decrease over high latitudes. These changes are associated with an expansion of the Hadley Circulation and positive trends in the Northern Annular Mode/North Atlantic Oscillation (NAM/NAO) and the Southern Annular Mode (SAM). As a result of these changes, storm tracks are projected to move polewards, with consequent changes in wind, precipitation and temperature patterns outside the tropics, continuing the broad pattern of observed trends over the last half-century. [WGI TS, 10.3.5.6, 10.3.6.4]

It is *likely* that future tropical cyclones will become more intense, with larger peak wind speeds and heavier precipitation, associated with ongoing increases of tropical SSTs. [WGI SPM, 10.3.6.3]

SSTs in the central and eastern equatorial Pacific are projected to warm more than those in the western equatorial Pacific, with a corresponding mean eastward shift in precipitation. All models show continued El Niño–Southern Oscillation (ENSO) interannual variability in the future, but large inter-model differences in projected changes in El Niño amplitude, and the inherent multi-decadal time-scale variability of El Niño in the models, preclude a definitive projection of trends in ENSO variability. [WGI TS, 10.3.5.3, 10.3.5.4]

Interannual variability in monthly mean surface air temperature is projected to decrease during the cold season in the extra-tropical Northern Hemisphere and to increase at low latitudes and warm-season northern mid-latitudes. The former is probably due to the decrease in sea ice and snow with increasing temperature. The summer decrease in soil moisture over the mid-latitude land surfaces contributes to the latter. Monthly mean precipitation variability is projected to increase in most areas, both in absolute value (standard deviation) and in relative value (coefficient of variation). However, the significance level of these projected variability changes is low. [WGI 10.3.5.1]

3

Linking climate change and water resources: impacts and responses

3.1 Observed climate change impacts

3.1.1 Observed effects due to changes in the cryosphere

Effects of changes in the cryosphere have been documented in relation to virtually all cryospheric components, with robust evidence that they are, in general, a response to the reduction of snow and ice masses due to enhanced warming.

3.1.1.1 Mountain glaciers and ice caps, ice sheets and ice shelves

Effects of changes in mountain glaciers and ice caps have been documented in runoff (Kaser et al., 2003; Box et al., 2006), changing hazard conditions (Haeberli and Burn, 2002) and ocean freshening (Bindoff et al., 2007). There is also emerging evidence of present crustal uplift in response to recent glacier melting in Alaska (Larsen et al., 2005). The enhanced melting, as well as the increased length of the melt season of glaciers, leads at first to increased river runoff and discharge peaks, while in the longer time-frame (decadal to century scale), glacier runoff is expected to decrease (Jansson et al., 2003). Evidence for increased runoff in recent decades due to enhanced glacier melt has already been detected in the tropical Andes and in the Alps. [WGI 4.6.2; WGII 1.3.1.1]

The formation of lakes is occurring as glaciers retreat from prominent Little Ice Age (LIA) moraines in several steep mountain ranges, including the Himalayas (see Box 5.4), the Andes and the Alps. Thawing of buried ice also threatens to destabilise the Little Ice Age moraines. These lakes thus have a high potential for glacial lake outburst floods (GLOFs). Governmental institutions in the respective countries have undertaken extensive safety work, and several of the lakes are now either solidly dammed or drained; but continued vigilance is needed, since many tens of potentially dangerous glacial lakes still exist in the Himalayas (Yamada, 1998) and the Andes (Ames, 1998), together with several more in other mountain ranges of the world. [WGII 1.3.1.1]

Glacier retreat causes striking changes in the landscape, which has affected living conditions and local tourism in many mountain regions around the world (Watson and Haeberli, 2004; Mölg et al., 2005). Figure 5.10 shows the effects of the retreat of the Chacaltaya Glacier on the local landscape and skiing industry. Warming produces an enhanced spring–summer melting of glaciers, particularly in areas of ablation, with a corresponding loss of seasonal snow cover that results in increased exposure of surface crevasses, which can in turn affect, for example, snow runway operations, as has been reported in the Antarctic Peninsula (Rivera et al., 2005). [WGII 1.3.1.1]

3.1.1.2 Snow cover and frozen ground

Due to less extended snow cover both in space and time, spring peak river flows have been occurring 1–2 weeks earlier during the last 65 years in North America and northern Eurasia. There is also evidence for an increase in winter base flow in northern Eurasia and North America, as well as a measured trend towards less snow at low altitudes, which is affecting skiing areas. [WGII 1.3.1.1]

Reductions in the extent of seasonally frozen ground and permafrost, and an increase in active-layer thickness, have resulted in:

- the disappearance of lakes due to draining within the permafrost, as detected in Alaska (Yoshikawa and Hinzman, 2003) and Siberia (see Figure 5.12) (Smith et al., 2005);
- a decrease in potential travel days of vehicles over frozen roads in Alaska;
- increased coastal erosion in the Arctic (e.g., Beaulieu and Allard, 2003).

[WGII 1.3.1.1, Chapter 15]

3.1.2 Hydrology and water resources

3.1.2.1 Changes in surface and groundwater systems

Since the TAR there have been many studies related to trends in river flows during the 20th century at scales ranging from catchment to global. Some of these studies have detected significant trends in some indicators of river flow, and some have demonstrated statistically significant links with trends in temperature or precipitation; but no globally homogeneous trend has been reported. Many studies, however, have found no trends, or have been unable to separate the effects of variations in temperature and precipitation from the effects of human interventions in the catchment, such as land-use change and reservoir construction. Variation in river flows from year to year is also very strongly influenced in some regions by large-scale atmospheric circulation patterns associated with ENSO, NAO and other variability systems that operate at within-decadal and multi-decadal time-scales. [WGII 1.3.2.1]

At the global scale, there is evidence of a broadly coherent pattern of change in annual runoff, with some regions experiencing an increase (Tao et al., 2003a, b, for China; Hyvarinen, 2003, for Finland; Walter et al., 2004, for the coterminous USA), particularly at higher latitudes, and others a decrease, for example in parts of West Africa, southern Europe and southern Latin America (Milly et al., 2005). Labat et al. (2004) claimed a 4% increase in global total runoff per 1°C rise in temperature during the 20th century, with regional variation around this trend, but this has been challenged due to the effects of non-climatic drivers on runoff and bias due to the small number of data points (Legates et al., 2005). Gedney et al. (2006) gave the first tentative evidence that CO_2 forcing leads to increases in runoff due to the effects of elevated CO_2 concentrations on plant physiology, although other evidence for such a relationship is difficult to find. The methodology used to search for trends can also influence results, since omitting the effects of cross-correlation between river catchments can lead to an overestimation of the number of catchments showing significant trends (Douglas et al., 2000). [WGII 1.3.2.1]

Groundwater flow in shallow aquifers is part of the hydrological cycle and is affected by climate variability and change through recharge processes (Chen et al., 2002), as well as by human interventions in many locations (Petheram et al., 2001). [WGII 1.3.2.1] Groundwater levels of many aquifers around the world show a decreasing trend over the last few decades [WGII 3.2, 10.4.2], but this is generally due to groundwater pumping surpassing groundwater recharge rates, and not to a climate-related decrease in groundwater recharge. There may be regions, such as south-western Australia, where increased groundwater withdrawals have been caused not only by increased water demand but also because of a climate-related decrease in recharge from surface water supplies (Government of Western Australia, 2003). In the upper carbonate aquifer near Winnipeg, Canada, shallow well hydrographs show no obvious trends, but exhibit variations of 3–4 years correlated with changes in annual temperature and precipitation (Ferguson and George, 2003). Owing to a lack of data and the very slow reaction of groundwater systems to changing recharge conditions, climate-related changes in groundwater recharges have not been observed. [WGII 1.3.2, 3.2]

At present, no globally consistent trend in lake levels has been found. While some lake levels have risen in Mongolia and China (Xinjiang) in response to increased snow- and ice melt, other lake levels in China (Qinghai), Australia, Africa (Zimbabwe, Zambia and Malawi), North America (North Dakota) and Europe (central Italy) have declined due to the combined effects of drought, warming and human activities. Within permafrost areas in the Arctic, recent warming has resulted in the temporary formation of lakes due to the onset of melting, which then drain rapidly due to permafrost degradation (e.g., Smith et al., 2005). A similar effect has been reported for a lake formed over an Arctic ice shelf (i.e., an epishelf lake[12]), which disappeared when the ice shelf collapsed (Mueller et al., 2003). Permafrost and epishelf lakes are treated in detail by Le Treut et al. (2007). [WGII 1.3.2.1]

3.1.2.2 Water quality

A climate-related warming of lakes and rivers has been observed over recent decades. [WGII 1.3.2] As a result, freshwater ecosystems have shown changes in species composition, organism abundance, productivity and phenological shifts (including earlier fish migration). [WGII 1.3.4] Also due to warming, many lakes have exhibited prolonged stratification with decreases in surface layer nutrient concentration [WGII 1.3.2], and prolonged depletion of oxygen in deeper layers. [WGII Box 4.1] Due to strong anthropogenic impacts not related to climate change, there is no evidence for consistent climate-related trends in other water quality parameters (e.g., salinity, pathogens or nutrients) in lakes, rivers and groundwater. [WGII 3.2]

Thermal structure of lakes

Higher water temperatures have been reported in lakes in response to warmer conditions (Table 3.1). Shorter periods of ice cover and decreases in river- and lake-ice thickness are treated in Section 2.1.2 and Le Treut et al. (2007). Phytoplankton dynamics and primary productivity have also been altered in conjunction with changes in lake physics. [WGII 1.3.4.4, Figure 1.2, Table 1.6] Since the 1960s, surface water temperatures have warmed by between 0.2 and 2.0°C in lakes and rivers in Europe, North America and Asia. Along with warming surface waters, deep-water temperatures (which reflect long-term trends) of the large East African lakes (Edward, Albert, Kivu, Victoria, Tanganyika and Malawi) have warmed by between 0.2 and 0.7°C since the early 1900s. Increased water temperature and longer ice-free seasons influence the thermal stratification and internal hydrodynamics of lakes. In warmer years, surface water temperatures are higher, evaporative water loss increases, summer stratification occurs earlier in the season, and thermoclines become shallower. In several lakes in Europe and North America, the stratified period has advanced by up to 20 days and lengthened by 2–3 weeks, with increased thermal stability. [WGII 1.3.2.3]

Chemistry

Increased stratification reduces water movement across the thermocline, inhibiting the upwelling and mixing that provide essential nutrients to the food web. There have been decreases in nutrients in the surface water and corresponding increases in deep-water concentrations of European and East African lakes because of reduced upwelling due to greater thermal stability. Many lakes and rivers have increased concentrations of sulphates, base cations and silica, and greater alkalinity and conductivity related to increased weathering of silicates, calcium and magnesium sulphates, or carbonates, in their catchment. In contrast, when warmer temperatures enhanced vegetative growth and soil development in some high-alpine ecosystems, alkalinity decreased because of increased organic acid inputs (Karst-Riddoch et al., 2005). Glacial melting increased the input of organochlorines (which had been atmospherically transported to and stored in the glacier) to a sub-alpine lake in Canada (Blais et al., 2001). [WGII 1.3.2.3]

Increased temperature also affects in-lake chemical processes (Table 3.1; see also WGII Table SM1.3 for additional observed changes in chemical water properties). There have been decreases in dissolved inorganic nitrogen from greater phytoplankton productivity (Sommaruga-Wograth et al., 1997; Rogora et al., 2003) and greater in-lake alkalinity generation and increases in pH in soft-water lakes (Psenner and Schmidt, 1992). Decreased solubility from higher temperatures significantly contributed to 11–13% of the decrease in aluminium concentration (Vesely et al., 2003), whereas lakes that had warmer water temperatures had increased mercury methylation and higher mercury levels in fish (Bodaly et al., 1993). A decrease in silicon content related to regional warming has been documented in Lake Baikal, Russia. River water-quality data from 27 rivers in Japan also suggest a deterioration in both chemical and biological features due to increases in air temperature. [WGII 1.3.2.3]

[12] A body of water, mostly fresh, trapped behind an ice shelf.

Erosion and sedimentation
Water erosion has increased in many areas of the world, largely as a consequence of anthropogenic land-use change. Due to lack of data, there is no evidence for or against past climate-related changes in erosion and sediment transport. [WGII 3.2]

3.1.2.3 Floods
A variety of climatic and non-climatic processes influence flood processes, resulting in river floods, flash floods, urban floods, sewer floods, glacial lake outburst floods (GLOFs, see Box 5.4) and coastal floods. These flood-producing processes include intense and/or long-lasting precipitation, snowmelt, dam break, reduced conveyance due to ice jams or landslides, or by storm. Floods depend on precipitation intensity, volume, timing, phase (rain or snow), antecedent conditions of rivers and their drainage basins (e.g., presence of snow and ice, soil character and status (frozen or not, saturated or unsaturated), wetness, rate and timing of snow/ice melt, urbanisation, existence of dykes, dams and reservoirs). Human encroachment into flood plains and lack of flood response plans increase the damage potential. [WGII 3.4.3] The observed increase in precipitation intensity and other observed climate changes, e.g., an increase in westerly weather patterns during winter over Europe, leading to very rainy low-pressure systems that often trigger floods (Kron and Berz, 2007), indicate that climate change might already have had an impact on the intensity and frequency of floods. [WGII 3.2] The Working Group I AR4 Summary for Policymakers concluded that it is *likely* that the frequency of heavy precipitation events has increased over most areas during the late 20th century, and that it is *more likely than not* that there has been a human contribution to this trend. [WGI Table SPM-2]

Globally, the number of great inland flood catastrophes during the last 10 years (1996–2005) is twice as large, per decade, as between 1950 and 1980, while related economic losses have increased by a factor of five (Kron and Berz, 2007). Dominant drivers of the upward trend of flood damage are socio-economic factors such as economic growth, increases in population and in the wealth concentrated in vulnerable areas, and land-use change. Floods have been the most reported natural disaster events in many regions, affecting 140 million people per year on average (WDR, 2003, 2004). In Bangladesh, during the 1998 flood, about 70% of the country's area was inundated (compared to an average value of 20–25%) (Mirza, 2003; Clarke and King, 2004). [WGII 3.2]

Since flood damages have grown more rapidly than population or economic growth, other factors must be considered, including climate change (Mills, 2005). The weight of observational evidence indicates an ongoing acceleration of the water cycle (Huntington, 2006). [WGII 3.4.3] The frequency of heavy precipitation events has increased, consistent with both warming and observed increases in atmospheric water vapour. [WGI SPM, 3.8, 3.9] However, no ubiquitous increase is visible in documented trends in high river flows. Although Milly et al.

Table 3.1: *Observed changes in runoff/streamflow, lake levels and floods/droughts. [WGII Table 1.3]*

Environmental factor	Observed changes	Time period	Location
Runoff/streamflow	Annual increase of 5%, winter increase of 25–90%, increase in winter base flow due to increased melt and thawing permafrost	1935–1999	Arctic Drainage Basin: Ob, Lena, Yenisey, Mackenzie
	1–2 week earlier peak streamflow due to earlier warming-driven snowmelt	1936–2000	Western North America, New England, Canada, northern Eurasia
Floods	Increasing catastrophic floods of frequency (0.5–1%) due to earlier break-up of river ice and heavy rain	Recent years	Russian Arctic rivers
Droughts	29% decrease in annual maximum daily streamflow due to temperature rise and increased evaporation with no change in precipitation	1847–1996	Southern Canada
	Due to dry and unusually warm summers related to warming of western tropical Pacific and Indian Oceans in recent years	1998–2004	Western USA
Water temperature	0.1–1.5°C increase in lakes	40 years	Europe, North America, Asia (100 stations)
	0.2–0.7°C increase (deep water) in lakes	100 years	East Africa (6 stations)
Water chemistry	Decreased nutrients from increased stratification or longer growing period in lakes and rivers	100 years	North America, Europe, Eastern Europe, East Africa (8 stations)
	Increased catchment weathering or internal processing in lakes and rivers	10–20 years	North America, Europe (88 stations)

(2002) identified an apparent increase in the frequency of 'large' floods (return period >100 years) across much of the globe from the analysis of data from large river basins, subsequent studies have provided less widespread evidence. Kundzewicz et al. (2005) found increases (in 27 locations) and decreases (in 31 locations) and no trend in the remaining 137 of the 195 catchments examined worldwide. [WGII 1.3.2.2]

3.1.2.4 Droughts

The term drought may refer to a meteorological drought (precipitation well below average), hydrological drought (low river flows and low water levels in rivers, lakes and groundwater), agricultural drought (low soil moisture), and environmental drought (a combination of the above). The socio-economic impacts of droughts may arise from the interaction between natural conditions and human factors such as changes in land use, land cover, and the demand for and use of water. Excessive water withdrawals can exacerbate the impact of drought. [WGII 3.4.3]

Droughts have become more common, especially in the tropics and sub-tropics, since the 1970s. The Working Group I AR4 Summary for Policymakers concluded that it is *likely* that the area affected by drought has increased since the 1970s, and it is *more likely than not* that there is a human contribution to this trend. [WGI Table SPM-2] Decreased land precipitation and increased temperatures, which enhance evapotranspiration and reduce soil moisture, are important factors that have contributed to more regions experiencing droughts, as measured by the Palmer Drought Severity Index (PDSI) (Dai et al., 2004b). [WGII 3.3.4]

The regions where droughts have occurred seem to be determined largely by changes in sea surface temperatures, especially in the tropics, through associated changes in the atmospheric circulation and precipitation. In the western USA, diminishing snow pack and subsequent reductions in soil moisture also appear to be factors. In Australia and Europe, direct links to global warming have been inferred through the extreme nature of high temperatures and heatwaves accompanying recent droughts. [WGI 3.ES, 3.3.4]

Using the PDSI, Dai et al. (2004b) found a large drying trend over Northern Hemisphere land since the mid-1950s, with widespread drying over much of Eurasia, northern Africa, Canada and Alaska (Figure 3.1). In the Southern Hemisphere, land surfaces were wet in the 1970s and relatively dry in the 1960s and 1990s, and there was a drying trend from 1974 to 1998, although trends over the entire 1948 to 2002 period were small. Decreases in land precipitation in recent decades are the main cause for the drying trends, although large surface warming during the last 2–3 decades is *likely* to have contributed to the drying. Globally, very dry areas (defined as land areas with a PDSI of less than –3.0) more than doubled (from ~12% to 30%) since the 1970s, with a large jump in the early 1980s due to an ENSO-related precipitation decrease over land, and subsequent increases primarily due to surface warming (Dai et al., 2004b). [WGI 3.3.4]

Droughts affect rain-fed agricultural production as well as water supply for domestic, industrial and agricultural purposes. Some semi-arid and sub-humid regions, e.g., Australia. [WGII 11.2.1], western USA and southern Canada [WGII 14.2.1], and the Sahel (Nicholson, 2005), have suffered from more intense and multi-annual droughts. [WGII 3.2]

The 2003 heatwave in Europe, attributable to global warming (Schär et al., 2004), was accompanied by annual precipitation deficits up to 300 mm. This drought contributed to the estimated 30% reduction in gross primary production of terrestrial ecosystems over Europe (Ciais et al., 2005). Many major rivers (e.g., the Po, Rhine, Loire and Danube) were at record low levels, resulting in disruption of inland navigation, irrigation and power plant cooling (Beniston and Diaz, 2004; Zebisch et al., 2005). The extreme glacier melt in the Alps prevented even lower flows of the Danube and Rhine Rivers (Fink et al., 2004). [WGII 12.6.1]

3.2 Future changes in water availability and demand due to climate change

3.2.1 Climate-related drivers of freshwater systems in the future

The most dominant climate drivers for water availability are precipitation, temperature and evaporative demand (determined by net radiation at the ground, atmospheric humidity and wind speed, and temperature). Temperature is particularly important in snow-dominated basins and in coastal areas, the latter due to the impact of temperature on sea level (steric sea-level rise due to thermal expansion of water). [WGII 3.3.1]

Projected changes in these components of the water balance are described in Section 2.3. In short, the total annual river runoff over the whole land surface is projected to increase, even though there are regions with significant increase and significant decrease in runoff. However, increased runoff cannot be fully utilised unless there is adequate infrastructure to capture and store the extra water. Over the oceans, a net increase in the term 'evaporation minus precipitation' is projected.

3.2.1.1 Groundwater

Climate change affects groundwater recharge rates (i.e., the renewable groundwater resources) and depths of groundwater tables. However, knowledge of current recharge and levels in both developed and developing countries is poor; and there has been very little research on the future impact of climate change on groundwater, or groundwater–surface water interactions. At high latitudes, thawing of permafrost causes changes in both the level and quality of groundwater, due to increased coupling with surface waters. [WGII 15.4.1] As many groundwaters both change into and are recharged from surface water, impacts of surface water flow regimes are expected to affect groundwater. Increased precipitation variability may decrease groundwater recharge in humid areas because more frequent

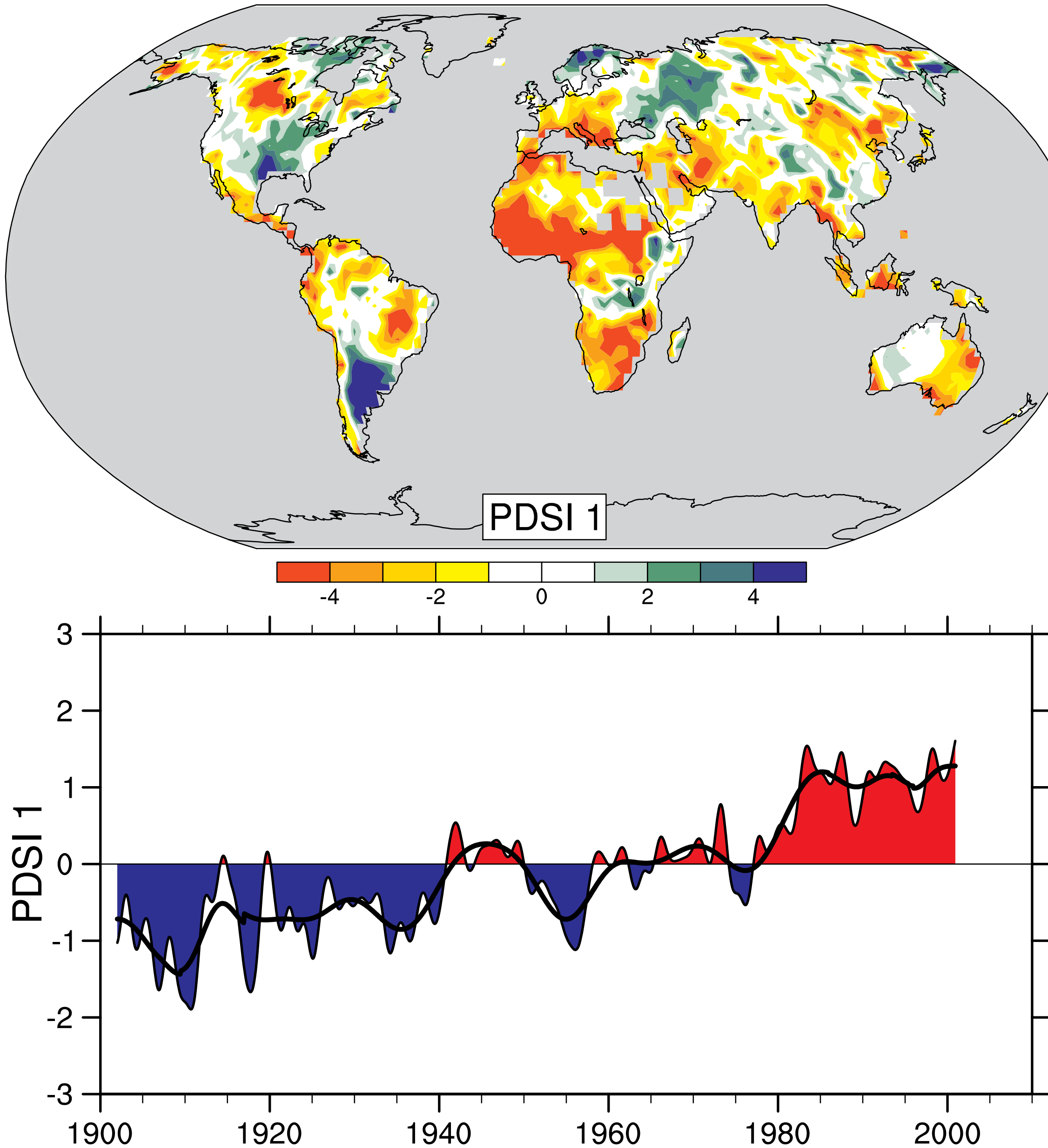


Figure 3.1: *The most important spatial pattern (the first component of a principal components analysis; top) of the monthly Palmer Drought Severity Index (PDSI) for 1900 to 2002. The PDSI is a prominent index of drought and measures the cumulative deficit (relative to local mean conditions) in surface land moisture by incorporating previous precipitation and estimates of moisture drawn into the atmosphere (based on atmospheric temperatures) into a hydrological accounting system.*[13] *The lower panel shows how the sign and strength of this pattern has changed since 1900. When the values shown in the lower plot are positive (or negative), the red and orange areas in the upper map are drier (or wetter) and the blue and green areas are wetter (or drier) than average. The smooth black curve shows decadal variations. The time-series approximately corresponds to a trend, and this pattern and its variations account for 67% of the linear trend of PDSI from 1900 to 2002 over the global land area. It therefore features widespread increasing African drought, especially in the Sahel, for instance. Note also the wetter areas, especially in eastern North and South America and northern Eurasia (after Dai et al., 2004b). [WGI FAQ 3.2]*

[13] Note that the PDSI does not realistically model drought in regions where precipitation is held in the snowpack, for example, in polar regions.

heavy precipitation events may result in the infiltration capacity of the soil being exceeded more often. In semi-arid and arid areas, however, increased precipitation variability may increase groundwater recharge, because only high-intensity rainfalls are able to infiltrate fast enough before evaporating, and alluvial aquifers are recharged mainly by inundations due to floods. [WGII 3.4.2]

According to the results of a global hydrological model (see Figure 3.2), groundwater recharge, when averaged globally, increases less than total runoff (by 2% as compared with 9% until the 2050s for the ECHAM4 climate change response to the SRES A2 scenario: Döll and Flörke, 2005). For all four climate change scenarios investigated (the ECHAM4 and HadCM3 GCMs with the SRES A2 and B2 emissions scenarios[14]), groundwater recharge was computed to decrease by the 2050s by more than 70% in north-eastern Brazil, south-western Africa and the southern rim of the Mediterranean Sea. However, as this study did not take account of an expected increase in the variability of daily precipitation, the decrease might be somewhat overestimated. Where the depth of the water table increases and groundwater recharge declines, wetlands dependent on aquifers are jeopardised and the base flow runoff in rivers during dry seasons is reduced. Regions in which groundwater recharge is

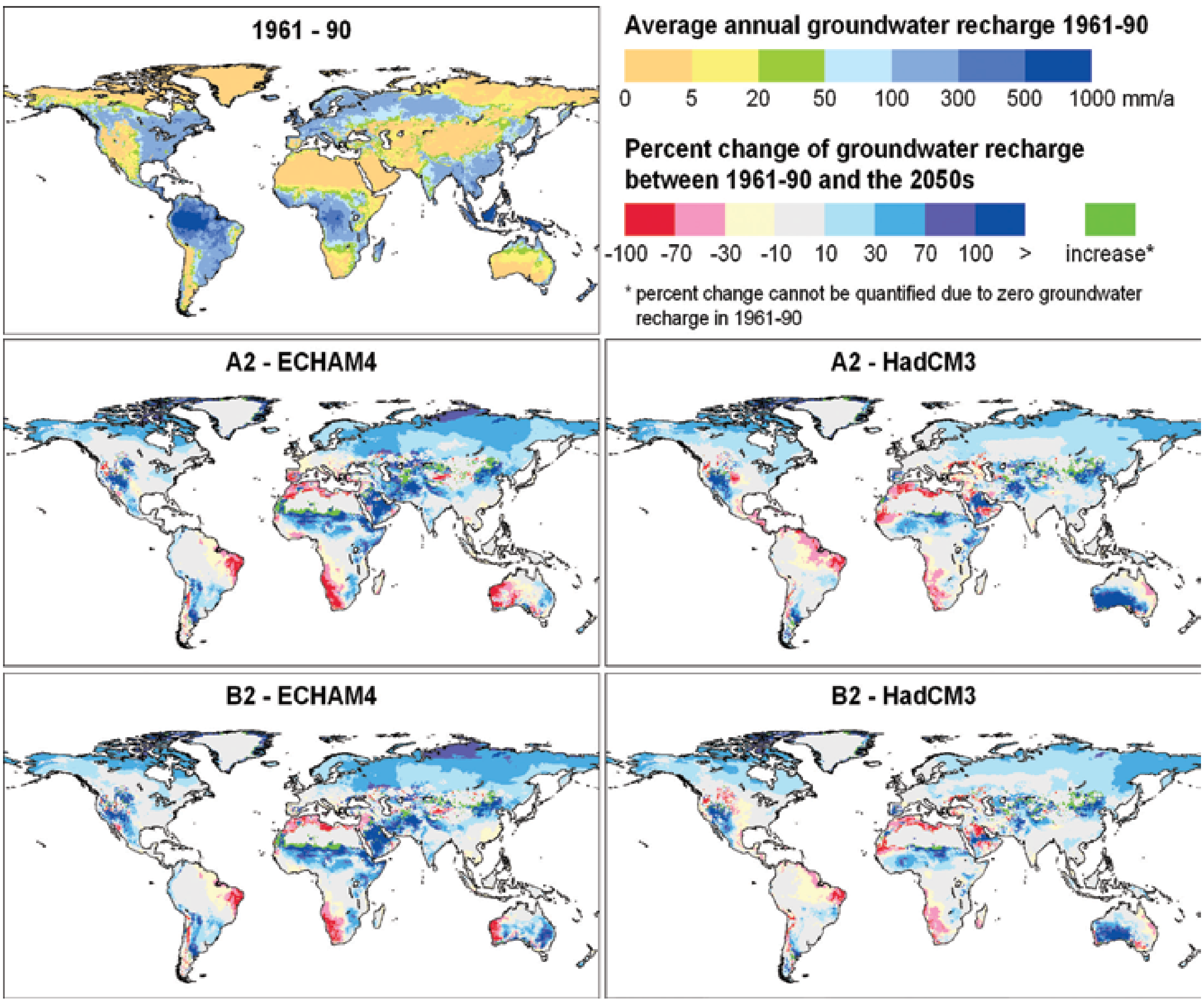


Figure 3.2: *Simulated impact of climate change on long-term average annual diffuse groundwater recharge. Percentage changes in 30-year average groundwater recharge between the present day (1961–1990) and the 2050s (2041–2070), as computed by the global hydrological model WGHM, applying four different climate change scenarios (based on the ECHAM4 and HadCM3 climate models and the SRES A2 and B2 emissions scenarios) (Döll and Flörke, 2005). [WGII Figure 3.5]*

[14] See Appendix I for model descriptions.

computed to increase by more than 30% by the 2050s include the Sahel, the Near East, northern China, Siberia and the western USA. In areas where water tables are already high, increased recharge might cause problems in towns and agricultural areas through soil salinisation and waterlogged soils. [WGII 3.4.2]

The few studies of climate change impacts on groundwater for individual aquifers show very site-specific and climate-model-specific results (e.g., Eckhardt and Ulbrich, 2003, for a low mountain range catchment in Central Europe; Brouyere et al., 2004, for a chalk aquifer in Belgium). For example, in the Ogallala Aquifer region, projected natural groundwater recharge decreases more than 20% in all simulations with warming of 2.5°C or greater (Rosenberg et al., 1999). [WGII 14.4] As a result of climate change, in many aquifers of the world the spring recharge shifts towards winter and summer recharge declines. [WGII 3.4.2]

3.2.1.2 Floods

As discussed in Section 2.3.1, heavy precipitation events are projected to become more frequent over most regions throughout the 21st century. This would affect the risk of flash flooding and urban flooding. [WGI 10.3.5, 10.3.6; WGII 3.4.3] Some potential impacts are shown in Table 3.2.

In a multi-model analysis, Palmer and Räisänen (2002) projected a considerable increase in the risk of a very wet winter over much of central and northern Europe, this being due to an increase in intense precipitation associated with mid-latitude storms. The probability of total boreal winter precipitation exceeding two standard deviations above normal was projected to increase considerably (five- to seven-fold) for a CO_2-doubling over large areas of Europe, with *likely* consequences for winter flood hazard. An increase in the risk of a very wet monsoon season in Asia was also projected (Palmer and Räisänen, 2002). According to Milly et al. (2002), for 15 out of 16 large basins worldwide, the control 100-year peak volumes of monthly river flow are projected to be exceeded more frequently for a CO_2-quadrupling. In some areas, what is given as a 100-year flood now (in the control run), is projected to occur much more frequently, even every 2–5 years, albeit with a large uncertainty in these projections. In many temperate regions, the contribution of snowmelt to spring floods is *likely* to decline (Zhang et al., 2005). [WGII 3.4.3]

Based on climate models, the area flooded in Bangladesh is projected to increase by at least 23–29% with a global temperature rise of 2°C (Mirza, 2003). [WGII 3.4.3]

Table 3.2: *Examples of possible impacts of climate change due to changes in extreme precipitation-related weather and climate events, based on projections to the mid- to late 21st century. These do not take into account any changes or developments in adaptive capacity. The likelihood estimates in column 2 relate to the phenomena listed in column 1. The direction of trend and likelihood of phenomena are for IPCC SRES projections of climate change. [WGI Table SPM-2; WGII Table SPM-2]*

Phenomenon[a] and direction of trend	Likelihood of future trends based on projections for 21st century using SRES scenarios	Examples of major projected impacts by sector			
		Agriculture, forestry and ecosystems [4.4, 5.4]	Water resources [3.4]	Human health [8.2]	Industry, settlements and society [7.4]
Heavy precipitation events: frequency increases over most areas	Very likely	Damage to crops; soil erosion; inability to cultivate land due to waterlogging of soils	Adverse effects on quality of surface and groundwater; contamination of water supply; water scarcity may be relieved	Increased risk of deaths, injuries and infectious, respiratory and skin diseases	Disruption of settlements, commerce, transport and societies due to flooding; pressures on urban and rural infrastructures; loss of property
Area affected by drought increases	Likely	Land degradation, lower yields/crop damage and failure; increased livestock deaths; increased risk of wildfire	More widespread water stress	Increased risk of food and water shortage; increased risk of malnutrition; increased risk of water- and food-borne diseases	Water shortages for settlements, industry and societies; reduced hydropower generation potentials; potential for population migration
Intense tropical cyclone activity increases	Likely	Damage to crops; windthrow (uprooting) of trees; damage to coral reefs	Power outages causing disruption of public water supply	Increased risk of deaths, injuries, water- and food-borne diseases; post-traumatic stress disorders	Disruption by flood and high winds; withdrawal of risk coverage in vulnerable areas by private insurers; potential for population migrations; loss of property

[a] See Working Group I Fourth Assessment Table 3.7 for further details regarding definitions.

Warming-induced reduction of firn[15] cover on glaciers causes enhanced and immediate runoff of melt water and can lead to flooding of glacial-fed rivers. [WGII 3.4.3]

There is a degree of uncertainty in estimates of future changes in flood frequency across the UK. Depending on which climate model is used, and on the importance of snowmelt contribution and catchment characteristics and location, the impact of climate change on the flood regime (magnitude and frequency) can be positive or negative, highlighting the uncertainty still remaining in climate change impacts (Reynard et al., 2004). [WGII 3.4.3]

3.2.1.3 Droughts

It is *likely* that the area affected by drought will increase. [WGI SPM] There is a tendency for drying of mid-continental areas during summer, indicating a greater risk of droughts in these regions. [WGI 10.ES] In a single-model study of global drought frequency, the proportion of the land surface experiencing extreme drought at any one time, the frequency of extreme drought events, and the mean drought duration, were projected to increase by 10- to 30-fold, two-fold, and six-fold, respectively, by the 2090s, for the SRES A2 scenario (Burke et al., 2006). [WGI 10.3.6; WGII 3.4.3] A decrease in summer precipitation in southern and central Europe, accompanied by rising temperatures (which enhance evaporative demand), would inevitably lead to both reduced summer soil moisture (cf. Douville et al., 2002; Christensen et al., 2007) and more frequent and intense droughts. [WGII 3.4.3] As shown in Figure 3.3, by the 2070s, a 100-year drought[16] of today's magnitude is projected to return, on average, more frequently than every 10 years in parts of Spain and Portugal, western France, Poland's Vistula Basin and western Turkey (Lehner et al., 2005). [WGII 3.4.3]

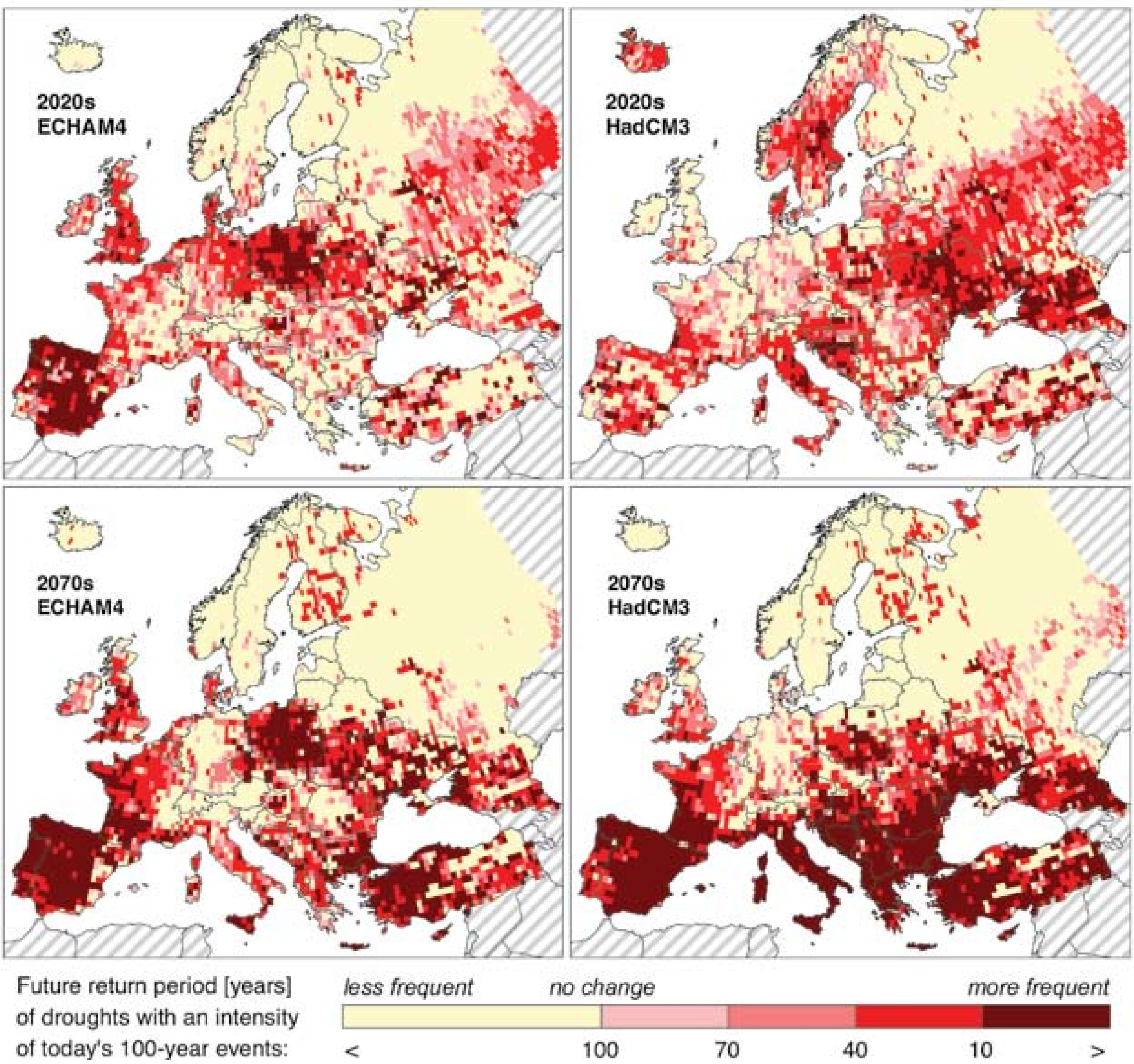


***Figure 3.3:** Change in the future recurrence of 100-year droughts, based on comparisons between climate and water use in 1961–1990 (Lehner et al., 2005). [WGII Figure 3.6]*

[15] Firn: aged snow (still permeable) that is at an intermediate stage towards becoming glacial ice (impermeable).

[16] Every year, the chance of exceedence of the 100-year flood is 1%, while the chance of exceedence of the 10-year flood is 10%.

Some impacts of increased drought area are shown in Table 3.2. Snowmelt is projected to become earlier and less abundant in the melt period, and this may increase the risk of droughts in snowmelt-fed basins in the low-flow season – summer and autumn. An increase in drought risk is projected for regions which depend heavily on glacial melt water for their main dry-season water supply (Barnett et al., 2005). In the Andes, glacial melt water supports river flow and water supply for tens of millions of people during the long dry season. Many small glaciers, e.g., in Bolivia, Ecuador and Peru (cf. Ramírez et al., 2001; Box 5.5), are expected to disappear within the next few decades. Water supply in areas fed by glacial and snow melt water from the Hindu Kush and Himalayas, on which hundreds of millions of people in China, Pakistan and India depend, will be adversely affected (Barnett et al., 2005). [WGII 3.4.3]

3.2.1.4 Water quality

Higher water temperatures, increased precipitation intensity, and longer periods of low flows are projected to exacerbate many forms of water pollution, including sediments, nutrients, dissolved organic carbon, pathogens, pesticides, salt and thermal pollution. This will promote algal blooms (Hall et al., 2002; Kumagai et al., 2003), and increase the bacterial and fungal content (Environment Canada, 2001). This will, in turn, impact ecosystems, human health, and the reliability and operating costs of water systems. [WGII 3.ES]

Rising temperatures are *likely* to lower water quality in lakes through increased thermal stability and altered mixing patterns, resulting in reduced oxygen concentrations and an increased release of phosphorus from the sediments. For example, already high phosphorus concentrations during summer in a bay of Lake Ontario could double with a 3–4°C increase in water temperature (Nicholls, 1999). However, rising temperatures can also improve water quality during winter/spring due to earlier ice break-up and consequent higher oxygen levels and reduced winter fish-kill. [WGII 4.4.8, 14.4.1]

More intense rainfall will lead to an increase in suspended solids (turbidity) in lakes and reservoirs due to soil fluvial erosion (Leemans and Kleidon, 2002), and pollutants will be introduced (Mimikou et al., 2000; Neff et al., 2000; Bouraoui et al., 2004). The projected increase in precipitation intensity is expected to lead to a deterioration of water quality, as it results in the enhanced transport of pathogens and other dissolved pollutants (e.g., pesticides) to surface waters and groundwater; and in increased erosion, which in turn leads to the mobilisation of adsorbed pollutants such as phosphorus and heavy metals. In addition, more frequent heavy rainfall events will overload the capacity of sewer systems and water and wastewater treatment plants more often. [WGII 3.4.4] An increased occurrence of low flows will lead to decreased contaminant dilution capacity, and thus higher pollutant concentrations, including pathogens. [WGII 3.4.4, 14.4.1] In areas with overall decreased runoff (e.g., in many semi-arid areas), water quality deterioration will be even worse.

In semi-arid and arid areas, climate change is *likely* to increase salinisation of shallow groundwater due to increased evapotranspiration. [WGII 3.4.2] As streamflow is projected to decrease in many semi-arid areas, the salinity of rivers and estuaries will increase. [WGII 3.4.4] For example, salinity levels in the headwaters of the Murray-Darling Basin in Australia are expected to increase by 13–19% by 2050 (Pittock, 2003). In general, decreased groundwater recharge, which reduces mobilisation of underground salt, may balance the effect of decreased dilution of salts in rivers and estuaries. [WGII 11.4]

In coastal areas, rising sea levels may have negative effects on storm-water drainage and sewage disposal [WGII 3.4.4] and increase the potential for the intrusion of saline water into fresh groundwater in coastal aquifers, thus adversely affecting groundwater resources. [WGII 3.4.2] For two small and flat coral islands off the coast of India, the thickness of freshwater lenses was computed to decrease from 25 m to 10 m and from 36 m to 28 m, respectively, for a sea-level rise of only 0.1 m (Bobba et al., 2000). Any decrease in groundwater recharge will exacerbate the effect of sea-level rise. In inland aquifers, a decrease in groundwater recharge can lead to saltwater intrusion from neighbouring saline aquifers (Chen et al., 2004). [WGII 3.4.2]

3.2.1.5 Water erosion and sedimentation

All studies on soil erosion show that the expected increase in rainfall intensity would lead to greater rates of erosion. [WGII 3.4.5] In addition, the shift of winter precipitation from less erosive snow to more erosive rainfall due to increasing winter temperatures enhances erosion, with this leading, for example, to negative water quality impacts in agricultural areas. [WGII 3.4.5, 14.4.1]

The melting of permafrost induces an erodible state in soil which was previously non-erodible. [WGII 3.4.5] Further indirect impacts of climate change on erosion are related to soil and vegetation changes caused by climate change and associated adaptation actions. [WGII 3.4.5] The very few studies on the impact of climate change on sediment transport suggest transport enhancement due to increased erosion, particularly in areas with increased runoff. [WGII 3.4.5]

3.2.2 Non-climatic drivers of freshwater systems in the future

Many non-climatic drivers affect freshwater resources at the global scale (UN, 2003). Both the quantity and quality of water resources are influenced by land-use change, construction and management of reservoirs, pollutant emissions and water and wastewater treatment. Water use is driven by changes in population, food consumption, economy (including water pricing), technology, lifestyle and societal views regarding the value of freshwater ecosystems. The vulnerability of freshwater systems to climate change also depends on national and international water management. It can be expected that the paradigm of 'integrated water resources management' (IWRM)[17] will be followed increasingly around the world (UN, 2002; World Bank, 2004a; World Water Council, 2006), and that such a movement has the potential to position water issues, both as a resource and an ecosystem, at the centre of the policy-making arena. This is *likely* to decrease the vulnerability of freshwater systems to climate change. Consideration of environmental flow requirements may lead to the modification of reservoir operations so that human use of these water resources might be restricted. [WGII 3.3.2]

3.2.3 Impacts of climate change on freshwater availability in the future

With respect to water supply, it is *very likely* that the costs of climate change will outweigh the benefits globally. One reason is that precipitation variability is *very likely* to increase, and more frequent floods and droughts are anticipated, as discussed in Sections 2.1.6 and 2.3.1. The risk of droughts in snowmelt-fed basins in the low-flow season will increase, as discussed in Section 3.2.1. The impacts of floods and droughts could be tempered by appropriate infrastructure investments and by changes in water and land-use management, but the implementation of such measures will entail costs (US Global Change Research Program, 2000). Water infrastructure, usage patterns and institutions have developed in the context of current conditions. Any substantial change in the frequency of floods and droughts, or in the quantity and quality or seasonal timing of water availability, will require adjustments that may be costly, not only in monetary terms but also in terms of societal and ecological impacts, including the need to manage potential conflicts between different interest groups (Miller et al., 1997). [WGII 3.5]

Hydrological changes may have impacts that are positive in some aspects and negative in others. For example, increased annual runoff may produce benefits for a variety of both instream and out-of-stream water users by increasing renewable water resources, but may simultaneously generate harm by increasing flood risk. In recent decades, a trend to wetter conditions in parts of southern South America has increased the area inundated by floods, but has also improved crop yields in the Pampas region of Argentina, and has provided new commercial fishing opportunities (Magrin et al., 2005). [WGII 13.2.4] Increased runoff could also damage areas with a shallow water table. In such areas, a water-table rise disturbs agricultural use and damages buildings in urban areas. In Russia, for example, the current annual damage caused by shallow water tables is estimated to be US$5–6 billion (Kharkina, 2004) and is *likely* to increase in the future. In addition, an increase in annual runoff may not lead to a beneficial increase in readily available water resources, if that additional runoff is concentrated during the high-flow season. [WGII 3.5]

Increased precipitation intensity may result in periods of increased turbidity and nutrient and pathogen loadings to surface water sources. The water utility serving New York City has identified heavy precipitation events as one of its major climate-change-related concerns because such events can raise turbidity levels in some of the city's main reservoirs up to 100 times the legal limit for source quality at the utility's intake, requiring substantial additional treatment and monitoring costs (Miller and Yates, 2006). [WGII 3.5.1]

3.2.4 Impacts of climate change on freshwater demand in the future

Higher temperatures and increased variability of precipitation would, in general, lead to increased irrigation water demand, even if the total precipitation during the growing season remains the same. The impact of climate change on optimal growing periods, and on yield-maximising irrigation water use, has been modelled assuming no change in either irrigated area and/or climate variability (Döll, 2002; Döll et al., 2003). Applying the IPCC SRES A2 and B2 scenarios as interpreted by two climate models, it was projected that the net irrigation requirements of China and India, the countries with the largest irrigated areas worldwide, would change by +2% to +15% in the case of China, and by −6% to +5% in the case of India, by 2020, depending on emissions scenarios and climate model (Döll, 2002; Döll et al., 2003). Different climate models project different worldwide changes in net irrigation requirements, with estimated increases ranging from 1–3% by the 2020s and 2–7% by the 2070s. The largest global-scale increases in net irrigation requirements result from a climate scenario based on the B2 emissions scenario. [WGII 3.5.1]

In a study of maize irrigation in Illinois under profit-maximising conditions, it was found that a 25% decrease in annual precipitation had the same effect on irrigation profitability as a 15% decrease combined with a doubling of the standard deviation of daily precipitation (Eheart and Tornil, 1999). This study also showed that profit-maximising irrigation water use responds more strongly to changes in precipitation than does yield-maximising water use, and that a doubling of atmospheric CO_2 has only a small effect. [WGII 3.5.1]

The increase in household water demand (for example through an increase in garden watering) and industrial water demand, due to climate change, is *likely* to be rather small, e.g., less than 5% by the 2050s at selected locations (Mote et al., 1999; Downing et al., 2003). An indirect, but small, secondary effect would be increased electricity demand for the cooling of buildings, which would tend to increase water withdrawals for the cooling of thermal power plants. A statistical analysis of water use in New

[17] The prevailing concept for water management which, however, has not been defined unambiguously. IWRM is based on four principles that were formulated by the *International Conference on Water and the Environment* in Dublin, 1992: (1) freshwater is a finite and vulnerable resource, essential to sustain life, development and the environment; (2) water development and management should be based on a participatory approach, involving users, planners and policymakers at all levels; (3) women play a central part in the provision, management and safeguarding of water; (4) water has an economic value in all its competing uses and should be recognised as an economic good.

York City showed that daily per capita water use on days above 25°C increases by 11 litres/°C (roughly 2% of current daily per capita use) (Protopapas et al., 2000). [WGII 3.5.1]

3.2.5 Impacts of climate change on water stress in the future

Global estimates of the number of people living in areas with water stress differ significantly between studies (Vörösmarty et al., 2000; Alcamo et al., 2003a, b, 2007; Oki et al., 2003; Arnell, 2004). Nevertheless, climate change is only one of many factors that influence future water stress; demographic, socio-economic and technological changes possibly play more important roles at most time horizons and in most regions. In the 2050s, differences in the population projections of the four IPCC SRES scenarios would have a greater impact on the number of people living in water-stressed river basins than the differences in the climate scenarios (Arnell, 2004). The number of people living in water-stressed river basins would increase significantly (Table 3.3). The change in the number of people expected to be under water stress after the 2050s greatly depends on the SRES scenario adopted. A substantial increase is projected under the A2 scenario, while the rate of increase is lower under the A1 and B1 scenarios because of the global increase in renewable freshwater resources and a slight decrease in population (Oki and Kanae, 2006). It should be noted that, using the per capita water availability indicator, climate change would appear to reduce overall water stress at the global level. This is because increases in runoff are concentrated heavily in the most populous parts of the world, mainly in eastern and south-eastern Asia. However, given that this increased runoff occurs mainly during high-flow seasons (Arnell, 2004), it may not alleviate dry-season problems if the extra water is not stored; and would not ease water stress in other regions of the world. Changes in seasonal patterns and an increasing probability of extreme events may offset the effects of increased annual available freshwater resources and demographic changes. [WGII 3.5.1]

If water stress is assessed not only as a function of population and climate change but also of changing water use, the importance of non-climatic drivers (income, water-use efficiency, water productivity, and industrial production) increases (Alcamo et al., 2007). Income growth sometimes has a larger impact than population growth on increasing water use and water stress (when expressed as the water withdrawal: water resources ratio). Water stress is modelled to decrease by the 2050s over 20–29% of the global land area and to increase over 62–76% of the global land area (considering two climate models and the SRES scenarios A2 and B2). The greater availability of water due to increased precipitation is the principal cause of decreasing water stress, while growing water withdrawals are the principal cause of increasing water stress. Growth of domestic water use, as stimulated by income growth, was found to be dominant (Alcamo et al., 2007). [WGII 3.5.1]

Table 3.3: *Impact of population growth and climate change on the number of people living in water-stressed river basins (defined as per capita renewable water resources of less than 1,000 m^3/yr) around 2050. [WGII Table 3.2]*

	Estimated population in water-stressed river basins in the year 2050 (billions)	
	Arnell (2004)	Alcamo et al. (2007)
1995: Baseline	1.4	1.6
2050: A2 emissions scenario	4.4–5.7	6.4–6.9
2050: B2 emissions scenario	2.8–4.0	4.9–5.2

Estimates are based on emissions scenarios for several climate model runs. The range is due to the various climate models and model runs that were used to translate emissions into climate scenarios

3.2.6 Impacts of climate change on costs and other socio-economic aspects of freshwater

The amount of water available for withdrawal is a function of runoff, groundwater recharge, aquifer conditions (e.g., degree of confinement, depth, thickness and boundaries), water quality and water supply infrastructure (e.g., reservoirs, pumping wells and distribution networks). Safe access to drinking water depends more on the level of water supply infrastructure than on the quantity of runoff. However, the goal of improved safe access to drinking water will be harder to achieve in regions where runoff and/or groundwater recharge decreases as a result of climate change. In addition, climate change leads to additional costs for the water supply sector, e.g., due to changing water levels affecting water supply infrastructure, which might hamper the extension of water supply services to more people. This leads, in turn, to higher socio-economic impacts and follow-up costs, especially in areas where the prevalence of water stress has also increased as a result of climate change. [WGII 3.5.1]

Climate change-induced changes in both the seasonal runoff regime and interannual runoff variability can be as important for water availability as changes in the long-term average annual runoff (US Global Change Research Program, 2000). People living in snowmelt-fed basins experiencing decreasing snow storage in winter may be negatively affected by decreased river flows in the summer and autumn (Barnett et al., 2005). The Rhine, for example, might suffer from a reduction of summer low flows of 5–12% by the 2050s, which will negatively affect water supply, particularly for thermal power plants (Middelkoop et al., 2001). Studies for the Elbe River Basin showed that actual evapotranspiration is projected to increase by 2050 (Krysanova and Wechsung, 2002), while river flow, groundwater recharge, crop yield and diffuse source pollution are *likely* to decrease (Krysanova et al., 2005). [WGII 3.5.1]

In western China, earlier spring snowmelt and declining glaciers are *likely* to reduce water availability for irrigated agriculture. Investment and operation costs for the additional wells and reservoirs which are required to guarantee a reliable water supply under climate change have been estimated for China. This cost is low in basins where the current water stress is low (e.g., Changjiang) and high where water stress is high (e.g., Huanghe River) (Kirshen et al., 2005a). Furthermore, the impact of climate change on water supply cost will increase in the future, not only because of stronger climate change, but also due to increasing demands. [WGII 3.5.1]

For an aquifer in Texas, the net income of farmers is projected to decrease by 16–30% by the 2030s and by 30–45% by the 2090s due to decreased irrigation water supply and increased irrigation water demand. Net benefit in total due to water use (dominated by municipal and industrial use) is projected to decrease by less than 2% over the same period (Chen et al., 2001). [WGII 3.5.1]

If freshwater supply has to be replaced by desalinated water due to climate change, then the cost of climate change includes the average cost of desalination, which is currently around US$1.00/m^3 for seawater and US$0.60/m^3 for brackish water (Zhou and Tol, 2005). The cost for freshwater chlorination is approximately US$0.02/m^3. In densely populated coastal areas of Egypt, China, Bangladesh, India and south-east Asia (FAO, 2003), desalination costs may be prohibitive. In these areas, particularly in Egypt, research in new desalination technology is required to reduce the costs, especially with the use of non-conventional energy sources that are associated with lower greenhouse-gas emissions. In addition, the desalination of brackish water can improve the economics of such projects (see Section 4.4.4). [WGII 3.5.1]

Future flood damages will depend greatly on settlement patterns, land-use decisions, the quality of flood forecasting, warning and response systems, and the value of structures and other property located in vulnerable areas (Mileti, 1999; Pielke and Downton, 2000; Changnon, 2005), as well as on climatic changes *per se*, such as changes in the frequency of tropical cyclones (Schiermeier, 2006). [WGII 3.5.2]

The impact of climate change on flood damages can be projected, based on modelled changes in the recurrence interval of current 20- or 100-year floods and in conjunction with flood damages from current events as determined from stage-discharge relations and detailed property data. With such a methodology, the average annual direct flood damage for three Australian drainage basins was projected to increase four- to ten-fold under doubled CO_2 conditions (Schreider et al., 2000). [WGII 3.5.2]

Choi and Fisher (2003) estimated the expected change in flood damages for selected US regions under two climate change scenarios in which mean annual precipitation increased by 13.5% and 21.5%, respectively, with the standard deviation of annual precipitation either remaining unchanged or increasing proportionally to the mean. Using a structural econometric (regression) model based on a time-series of flood damage and with population, a wealth indicator and annual precipitation as predictors, the mean and standard deviation of flood damage are projected to increase by more than 140% if the mean and standard deviation of annual precipitation increase by 13.5%. This estimate suggests that flood losses are related primarily to the exposure of people to natural hazards due to the lack of social infrastructure, since the explanatory power of the model including population and wealth is 82%, while adding precipitation increases this to 89%. [WGII 3.5.2]

Another study examined the potential flood damage impacts of changes in extreme precipitation events by using the Canadian Climate Center model and the IS92a scenario for the metro Boston area in the north-eastern USA (Kirshen et al., 2005b). This study found that, without adaptation investments, both the number of properties damaged by floods and the overall cost of flood damage would double by 2100, relative to what might be expected if there was no climate change. It also found that flood-related transportation delays would become an increasingly significant nuisance over the course of this century. The study concluded that the *likely* economic magnitude of these damages is sufficiently high to justify large expenditures on adaptation strategies such as universal flood-proofing in floodplains. [WGII 3.5.2]

These findings are also supported by a scenario study on the damages from river and coastal flooding in England and Wales in the 2080s, which combined four emissions scenarios with four scenarios of socio-economic change in an SRES-like framework (Hall et al., 2005). In all scenarios, flood damages are projected to increase unless current flood management policies, practices and infrastructure are changed. By the 2080s, annual damage is projected to be £5 billion in a B1-type world, as compared with £1 billion today, while with approximately the same climate change, damage is only £1.5 billion in a B2-type world. Both the B1 and B2 scenarios give approximately similar results if these numbers are normalised with respect to gross domestic product. In an A1-type world, the annual damage would amount to £15 billion by the 2050s and £21 billion by the 2080s (Evans et al., 2004; Hall et al., 2005). [WGII 3.5.2]

Increased flood periods in the future would disrupt navigation more often, and low flow conditions that restrict the loading of ships may increase. For example, restrictions on loading in the Rhine River may increase from 19 days under current climate conditions to 26–34 days in the 2050s (Middelkoop et al., 2001). [WGII 3.5.1]

Climate-change is *likely* to alter river discharge, resulting in important impacts on water availability for instream usage, particularly hydropower generation. Hydropower impacts for Europe have been estimated using a macro-scale hydrological model. The results indicate that by the 2070s the electricity production potential of hydropower plants existing at the end of the 20th century will increase (assuming IS92a emissions) by 15–30% in Scandinavia and northern Russia, where currently between 19% (Finland) and almost 100% (Norway) of electricity is produced by hydropower (Lehner et al., 2005). Decreases of 20–50% and more are found for Portugal, Spain, Ukraine and Bulgaria, where currently between 10% (Ukraine, Bulgaria) and 39% of the electricity is produced by hydropower (Lehner et al., 2005). For the whole of Europe (with a 20% hydropower fraction), hydropower potential is projected to decrease by 7–12% by the 2070s. [WGII 3.5.1]

In North America, potential reductions in the outflow of the Great Lakes could result in significant economic losses as a result of reduced hydropower generation both at Niagara and on the St. Lawrence River (Lofgren et al., 2002). For a CGCM1 model projection with 2°C global warming, Ontario's Niagara and St. Lawrence hydropower generation would decline by 25–35%, resulting in annual losses of Canadian $240–350 million at 2002 prices (Buttle et al., 2004). With the HadCM2[18] climate model, however, a small gain in hydropower potential (+3%) was found, worth approximately Canadian $25 million per year. Another study that examined a range of climate model scenarios found that a 2°C global warming could reduce hydropower generating capacity on the St. Lawrence River by 1–17% (LOSLR, 2006). [WGII 3.5.1]

3.2.7 Freshwater areas and sectors highly vulnerable to climate change

In many regions of the globe, climate change impacts on freshwater resources may affect sustainable development and put at risk, for example, the reduction of poverty and child mortality. Even with optimal water management, it is *very likely* that negative impacts on sustainable development cannot be avoided. Figure 3.4 shows some key cases around the world, where freshwater-related climate change impacts are a threat to the sustainable development of the affected regions. 'Sustainable' water resources management is generally sought to be achieved by integrated water resources management (IWRM: see Footnote 17 for a definition). However, the precise interpretation of this term varies considerably. All definitions broadly include the concept of maintaining and enhancing the environment, and particularly the water environment, taking into account competing users, instream ecosystems and wetlands. They also consider the wider environmental implications of water management policies such as the implications of water management policies on land management and, conversely, the implications of land management policies on the water environment. Water governance is an important component of managing water to achieve sustainable water resources for a range of political, socio-economic and administrative systems (GWP, 2002; Eakin and Lemos, 2006). [WGII 3.7]

3.2.8 Uncertainties in the projected impacts of climate change on freshwater systems

Uncertainties in climate change impacts on water resources are mainly due to the uncertainty in precipitation inputs and less due to the uncertainties in greenhouse gas emissions (Döll et al.,

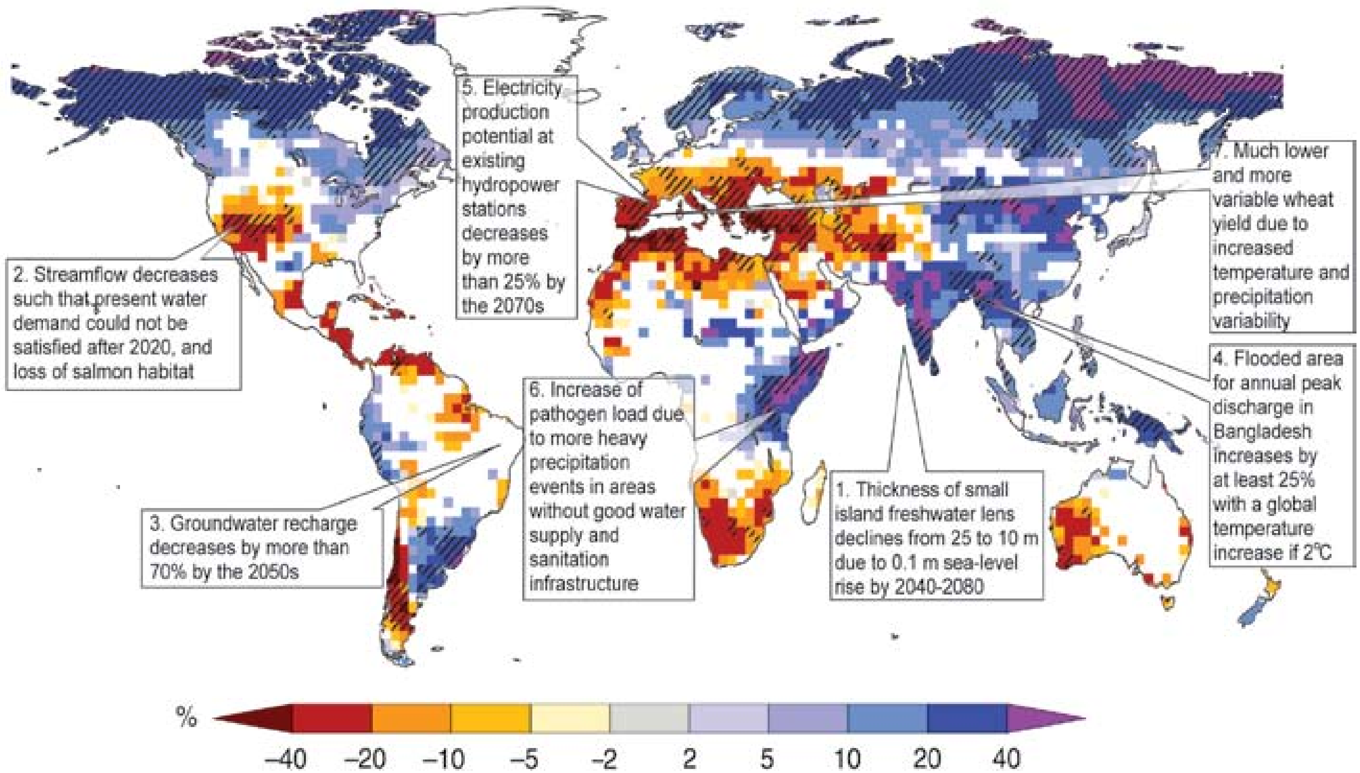


***Figure 3.4:** Illustrative map of future climate change impacts related to freshwater which threaten the sustainable development of the affected regions. 1: Bobba et al. (2000), 2: Barnett et al. (2004), 3: Döll and Flörke (2005), 4: Mirza et al. (2003), 5: Lehner et al. (2005), 6: Kistemann et al. (2002), 7: Porter and Semenov (2005). Background map, see Figure 2.10: Ensemble mean change in annual runoff (%) between present (1980–1999) and 2090–2099 for the SRES A1B emissions scenario (based on Milly et al., 2005). Areas with blue (red) colours indicate the increase (decrease) of annual runoff. [Based on WGII Figure 3.8 and SYR Figure 3.5]*

[18] See Appendix I for model descriptions.

2003; Arnell, 2004), in climate sensitivities (Prudhomme et al., 2003), or in hydrological models themselves (Kaspar, 2003). A further source of uncertainty regarding the projected impacts of climate change on freshwater systems is the nature, extent, and relative success of those initiatives and measures already planned as interventions. The impacts illustrated in Figure 3.4 would be realised differently depending on any adaptation measures taken. The feedbacks from adaptation measures to climate change are not fully considered in current future predictions, such as the longer growing season of crops and more regulations on river flow, with increased reservoir storage. The comparison of different sources of uncertainty in flood statistics in two UK catchments (Kay et al., 2006a) led to the conclusion that the largest source of uncertainty was the GCM structure, followed by the emissions scenarios and hydrological modelling. Similar conclusions were made by Prudhomme and Davies (2006) in regard to mean monthly flows and low-flow statistics in Great Britain. [WGII 3.3.1]

Multi-model probabilistic approaches are preferable to using the output of only one climate model, when assessing uncertainty in the impact of climate change on water resources. Since the TAR, several hydrological impact studies have used multi-model climate inputs (e.g., Arnell (2004) at the global scale and Jasper et al. (2004) at a river-basin scale), but studies incorporating probabilistic assessments are rare. [WGII 3.3.1]

In many impacts studies, time-series of observed climate values are adjusted by using the computed change in climate variables to obtain scenarios that are consistent with present-day conditions. These adjustments aim to minimise the impacts of the error in climate modelling of the GCMs under the assumption that the biases in climate modelling are of similar magnitude for current and future time horizons. This is particularly important for precipitation projections, where differences between the observed values and those computed by climate models are substantial. [WGII 3.3.1]

Changes in interannual or daily variability of climate variables are often not taken into account in hydrological impact studies. This leads to an underestimation of future floods and droughts as well as water availability and irrigation water requirements. [WGII 3.3.1] Selections of indicators and threshold values to quantify the impact of climate change on freshwater resources are also sources of uncertainty.

So as to overcome the mismatch of spatial grid scales between GCM and hydrological processes, techniques have been developed that downscale GCM outputs to a finer spatial (and temporal) resolution. [WGI TAR Chapter 10] The main assumption of these techniques is that the statistical relationships identified for current climate will remain valid under changes in future conditions. Downscaling techniques may allow modellers to incorporate daily variability in future changes (e.g., Diaz-Nieto and Wilby, 2005) and to apply a probabilistic framework to produce information on future river flows for water resource planning (Wilby and Harris, 2006). These approaches help to compare different sources of uncertainty affecting water resource projections. [WGII 3.3.1]

Efforts to quantify the economic impacts of climate-related changes in water resources are hampered by a lack of data and by the fact that the estimates are highly sensitive to both the estimation methods and the different assumptions used regarding allocation of changes in water availability across various types of water uses, e.g., between agricultural, urban or instream uses (Changnon, 2005; Schlenker et al., 2005; Young, 2005). [WGII 3.5]

3.3 Water-related adaptation to climate change: an overview

Water managers have long dealt with changing demands for water resources. To date, water managers have typically assumed that the natural resource base is reasonably constant over the medium term and, therefore, that past hydrological experience provides a good guide to future conditions. Climate change challenges these conventional assumptions and may alter the reliability of water management systems. [WGII 3.6.1] Management responses to climate change include the development of new approaches to system assessment and design, and non-structural methods through such mechanisms as the European Union Water Framework Directive. [WGII 12.2.2]

Table 3.4 summarises some supply-side and demand-side adaptation options, designed to ensure supplies during average and drought conditions. Supply-side options generally involve increases in storage capacity or abstraction from water courses and therefore may have adverse environmental consequences. Demand-side options may lack practical effectiveness because they rely on the cumulative actions of individuals. Some options may be inconsistent with mitigation measures because they involve high energy consumption, e.g., desalination, pumping.

A distinction is frequently made between autonomous and planned adaptations. *Autonomous adaptations* are those that do not constitute a conscious response to climate stimuli, but result from changes to meet altered demands, objectives and expectations which, whilst not deliberately designed to cope with climate change, may lessen the consequences of that change. Such adaptations are widespread in the water sector, although with varying degrees of effectiveness in coping with climate change (see Table 3.5). [WGII 3.6.1] In Latin America, some autonomous adaptation practices have been put in place, including the use of managing trans-basin diversions and the optimisation of water use. [WGII 13.5.1.3] In Africa, local communities and farmers have developed adaptation schemes to forecast rainfall using accumulated experience. Farmers in the Sahel also use traditional water harvesting systems to supplement irrigation practices. [WGII 9.6.2.1, 9.5.1, Table 9.2]

Planned adaptations are the result of deliberate policy decisions and specifically take climate change and variability into account,

Table 3.4: Some adaptation options for water supply and demand (the list is not exhaustive). [WGII Table 3.5]

Supply-side	Demand-side
Prospecting and extraction of groundwater	Improvement of water-use efficiency by recycling water
Increasing storage capacity by building reservoirs and dams	Reduction in water demand for irrigation by changing the cropping calendar, crop mix, irrigation method, and area planted
Desalination of sea water	Reduction in water demand for irrigation by importing agricultural products, i.e., virtual water
Expansion of rain-water storage	Promotion of indigenous practices for sustainable water use
Removal of invasive non-native vegetation from riparian areas	Expanded use of water markets to reallocate water to highly valued uses
Water transfer	Expanded use of economic incentives including metering and pricing to encourage water conservation

and have so far been implemented infrequently. Water managers in a few countries, including the Netherlands, Australia, the UK, Germany, the USA and Bangladesh, have begun to address directly the implications of climate change as part of their standard flood and water supply management practices. [WGII 3.2, 3.6.5, 17.2.2] These adaptations have generally taken the form of alterations to methods and procedures, such as design standards and the calculation of climate change allowances. For example, such adaptations have been implemented for flood preparedness in the UK and the Netherlands (Klijn et al., 2001; Richardson, 2002), for water supply in the UK (Arnell and Delaney, 2006), and for water planning in general in Bangladesh. [WGII 3.6.5, 17.2.2] Examples of 'concrete' actions in the water sector to adapt specifically and solely to a changing climate are very rare. This is partly because climate change may be only one of many drivers affecting strategies and investment plans (and it may not be the most important one over the short-term planning horizon), and partly due to uncertainty in projections of future hydrological changes.

Adaptation to changes in water availability and quality will have to be made, not only by water management agencies but also by individual users of the water environment. These will include industry, farmers (especially irrigators) and individual consumers. Although there is much experience with adaptation to changing demand and legislation, little is known about how such organisations and individuals will be able to adapt to a changing climate.

Table 3.5 outlines some of the adaptation measures, both planned and autonomous, currently in use across the world, as presented in the regional chapters in the WGII AR4. The table is not exhaustive, and many individual measures can be used in many locations.

There is *high confidence* that adaptation can reduce vulnerability, especially in the short term. [WGII 17.2, 18.1, 18.5, 20.3, 20.8] However, adaptive capacity is intimately connected to social and economic development, but it is not evenly distributed across and within societies. The poor, elderly, female, sick, and indigenous populations typically have less capacity. [WGII 7.1, 7.2, 7.4, 17.3]

It is possible to define five different types of limits on adaptation to the effects of climate change. [WGII 17.4.2]

(a) *Physical or ecological:* it may not be possible to prevent adverse effects of climate change through either technical means or institutional changes. For example, it may be impossible to adapt where rivers dry up completely. [WGII 3.6.4]

(b) *Technical, political or social:* for example, it may be difficult to find acceptable sites for new reservoirs, or for water users to consume less. [WGII 3.6.4]

(c) *Economic:* an adaptation strategy may simply be too costly in relation to the benefits achieved by its implementation.

(d) *Cultural and institutional:* these may include the institutional context within which water management operates, the low priority given to water management, lack of co-ordination between agencies, tensions between different scales, ineffective governance, and uncertainty over future climate change (Ivey et al., 2004; Naess et al., 2005; Crabbe and Robin, 2006); all act as institutional constraints on adaptation. [WGII 3.6.4]

(e) *Cognitive and informational:* for example, water managers may not recognise the challenge of climate change, or may give it low priority compared with other challenges. A key informational barrier is the lack of access to methodologies to cope consistently and rigorously with climate change. [WGII 17.4.2.4]

Climate change poses a conceptual challenge to water managers by introducing uncertainty in future hydrological conditions. It may also be very difficult to detect an underlying trend (Wilby, 2006), meaning that adaptation decisions may have to be made before it is clear how hydrological regimes may actually be changing. Water management in the face of climate change therefore needs to adopt a scenario-based approach (Beuhler, 2003; Simonovic and Li, 2003). This is being used in practice in countries such as the UK (Arnell and Delaney, 2006) and Australia (Dessai et al., 2005). However, there are two problems. First, there are often large differences in impact between scenarios, requiring that analyses be based on several scenarios. Second, water managers in some countries demand information on the likelihood of defined outcomes occurring in order to make risk-based decisions (e.g., Jones and Page,

Table 3.5: Some examples of adaptation in practice.

Region	Adaptation measure	Source
Africa	• Seasonal forecasts, their production, dissemination, uptake and integration in model-based decision-making support systems • Enhancing resilience to future periods of drought stress by improvements in present rain-fed farming systems through improvements in the physical infrastructure including: water harvesting systems; dam building; water conservation and agricultural practices; drip irrigation; development of drought-resistant and early-maturing crop varieties and alternative crop and hybrid varieties	WGII 9.5, Table 9.2
Asia	Improvement to agricultural infrastructure including: • pasture water supply • irrigation systems and their efficiency • use/storage of rain and snow water • information exchange system on new technologies at national as well as regional and international levels • access by herders, fishers and farmers to timely weather forecasts (rainfall and temperature)	WGII 10.5, Table 10.8
	• Recycling and reuse of municipal wastewater e.g., Singapore • Reduction of water wastage and leakage and use of market-oriented approaches to reduce wasteful water use	WGII 10.5.2
Australia and New Zealand	• National Water Initiative • Treatment plant to supply recycled water • Reduce channel seepage and conservation measures • Pipelines to replace open irrigation channels • Improve water-use efficiency and quality • Drought preparedness, new water pricing • Installation of rainwater tanks • Seawater desalination	WGII 11.2, Table 11.2, Box 11.2; see Table 5.2 in this volume
Europe	• Demand-side strategies such as household, industrial and agricultural water conservation, repairing leaky municipal and irrigation water reservoirs in highland areas and dykes in lowland areas • Expanded floodplain areas, emergency flood reservoirs, preserved areas for flood water and flood warning systems, especially in flash floods • Supply-side measures such as impounding rivers to form instream reservoirs, wastewater reuse and desalination systems and water pricing • Incorporation of regional and watershed-level strategies to adapt to climate change into plans for integrated water management	WGII 12.5.1
Latin America	• Rainwater catchments and storage systems • 'Self organisation' programmes for improving water supply systems in very poor communities • Water conservation practices, reuse of water, water recycling by modification of industrial processes and optimisation of water use	WGII 13.2.5.3, Box 13.2, 13.5.1
North America	• Improved water conservation and conservation tillage	WGII 14.2.4
	• Investments in water conservation systems and new water supply and distribution facilities • Changing the policy of the US National Flood Insurance to reduce the risk of multiple flood claims • Households with two flood-related claims now required to be elevated 2.5 cm above the 100-year flood level, or to relocate • Flushing the drainage systems and replacing the trunk sewer systems to meet more extreme 5-year flood criteria • Directing roof runoff to lawns to encourage infiltration, and increasing depression and street detention storage	WGII 14.5.1
Polar regions	• A successful adaptation strategy that has already been used to counteract the effects of drying of delta ponds involves managing water release from reservoirs to increase the probability of ice-jam formation and related flooding	WGII 15.6.2
	• Flow regulation for hydro-electric production, harvesting strategies and methods of drinking-water access • Strategies to deal with increased/decreased freshwater hazards (e.g., protective structures to reduce flood risks or increase floods for aquatic systems	WGII 15.2.2.2
Small Islands	• Desalination plants • Large storage reservoirs and improved water harvesting	WGII 16.4.1
	• Protection of groundwater, increasing rainwater harvesting and storage capacity, use of solar distillation, management of storm water and allocation of groundwater recharge areas in the islands	Box 16.5

2001). Techniques are therefore being developed to construct probability distributions of specified outcomes, requiring that assumptions be made about the probability distributions of the key drivers of impact uncertainty (e.g., Wilby and Harris, 2006). [WGII 3.6.4]

A second approach to coping with uncertainty, referred to as 'adaptive management' (Stakhiv, 1998), involves the increased use of water management measures that are relatively robust to uncertainty. Such tools include measures to reduce the demand for water and have been advocated as a means of minimising the exposure of a system to climate change (e.g., in California: Beuhler, 2003). Similarly, some resilient strategies for flood management, e.g., allowing rivers to flood temporarily, and reducing exposure to flood damage, are more robust to uncertainty than traditional flood protection measures (Klijn et al., 2004; Olsen, 2006). [WGII 3.6.4]

3.3.1 Integrated water resources management

Integrated water resources management (IWRM: see Footnote 17) should be an instrument to explore adaptation measures to climate change, but so far it is in its infancy. Successful integrated water management strategies include, among others: capturing society's views, reshaping planning processes, co-ordinating land and water resources management, recognising water quantity and quality linkages, conjunctive use of surface water and groundwater, protecting and restoring natural systems, and including consideration of climate change. In addition, integrated strategies explicitly address impediments to the flow of information. A fully integrated approach is not always needed but, rather, the appropriate scale for integration will depend on the extent to which it facilitates effective action in response to specific needs (Moench et al., 2003). In particular, an integrated approach to water management could help to resolve conflicts between competing water users. In several places in the western USA, water managers and various interest groups have been experimenting with methods to promote consensus-based decision making. These efforts include local watershed initiatives and state-led or federally-sponsored efforts to incorporate stakeholder involvement in planning processes (e.g., US Department of the Interior, 2005). Such initiatives can facilitate negotiations between competing interest groups to achieve mutually satisfactory problem solving that considers a wide range of factors. In the case of large watersheds, such as the Colorado River Basin, these factors cross several time- and space-scales (Table 3.6). [WGII 3.6.1, Box 14.2]

Table 3.6: *Cross-scale issues in the integrated water management of the Colorado River Basin (Pulwarty and Melis, 2001). [WGII Table 3.4]*

Temporal scale	Issue
Indeterminate	Flow necessary to protect endangered species
Long-term	Inter-basin allocation and allocation among basin states
Decadal	Upper basin delivery obligation
Year	Lake Powell fill obligations to achieve equalisation with Lake Mead storage
Seasonal	Peak heating and cooling months
Daily to monthly	Flood control operations
Hourly	Western Area Power Administration's power generation
Spatial scale	
Global	Climate influences, Grand Canyon National Park
Regional	Prior appropriation (e.g., Upper Colorado River Commission)
State	Different agreements on water marketing for within and out-of-state water districts
Municipal and communities	Watering schedules, treatment, domestic use

4

Climate change and water resources in systems and sectors

4.1 Ecosystems and biodiversity

4.1.1 Context

Temperature and moisture regimes are among the key variables that determine the distribution, growth and productivity, and reproduction of plants and animals. Changes in hydrology can influence species in a variety of ways, but the most completely understood processes are those that link moisture availability with intrinsic thresholds that govern metabolic and reproductive processes (Burkett et al., 2005). The changes in climate that are anticipated in the coming decades will have diverse effects on moisture availability, ranging from alterations in the timing and volume of streamflow to the lowering of water levels in many wetlands, the expansion of thermokarst lakes in the Arctic, and a decline in mist water availability in tropical mountain forests.

Observed global trends in precipitation, humidity, drought and runoff over the last century are summarised in WGI AR4 Chapter 3. Although changes in precipitation during the last century indicate considerable regional variation [WGI Figure 3.14], they also reveal some important and highly significant trends. Precipitation increased generally in the Northern Hemisphere from 1900 to 2005, but the tendency towards more widespread drought increased concomitantly for many large regions of the tropics and the Southern Hemisphere, notably the African Sahel and southern Africa, Central America, south Asia and eastern Australia. [WGI 3.3.5]

4.1.2 Projected changes in hydrology and implications for global biodiversity

The IPCC Fourth Assessment Report estimates of global warming vary in range from 0.5°C in the Southern Hemisphere to 2°C in the northern polar region by 2030 for SRES scenarios B1, A1 and A2, with B1 showing the highest warming. While the models simulate global mean precipitation increases, there is substantial spatial and temporal variation. General circulation models (GCMs) project an increase in precipitation at high latitudes, although the amount of that increase varies between models, and decreases in precipitation over many sub-tropical and mid-latitude areas in both hemispheres. [WGI Figures 10.8 and 10.12] Precipitation during the coming decades is projected to be more concentrated into more intense events, with longer periods of little precipitation in between. [WGI 10.3.6.1] The increase in the number of consecutive dry days is projected to be most significant in North and Central America, the Caribbean, north-eastern and south-western South America, southern Europe and the Mediterranean, southern Africa and western Australia. [WGI Figure 10.18] Impacts of warming and changes in precipitation patterns in tropical and sub-tropical regions have important implications for global biodiversity, because species diversity generally decreases with distance away from the Equator.

The changes in hydrology that are projected by WGI AR4 for the 21st century (see Section 2) will be *very likely* to impact biodiversity on every continent. Impacts on species have already been detected in most regions of the world. [WGII 1.3, 4.2] A review of 143 published studies by Root et al. (2003) indicates that animals and plants are already showing discernible changes consistent with the climatic trends of the 20th century. Approximately 80% of the changes were consistent with observed temperature change, but it should be recognised that temperature can also exert its influence on species through changes in moisture availability. [WGII 1.4.1]

Ecosystem responses to changes in hydrology often involve complex interactions of biotic and abiotic processes. The assemblages of species in ecological communities reflect the fact that these interactions and responses are often non-linear, which increases the difficulty of projecting specific ecological outcomes. Since the timing of responses is not always synchronous in species from different taxonomic groups, there may be a decoupling of species from their food sources, a disruption of symbiotic or facilitative relationships between species, and changes in competition between species. Owing to a combination of differential responses between species and interactions that could theoretically occur at any point in a food web, some of the ecological communities existing today could easily be disaggregated in the future (Root and Schneider, 2002; Burkett et al., 2005). [WGII 1.3.5.5, 4.2.2, 4.4]

Due to the combined effects of temperature and water stress, the extinction of some amphibians and other aquatic species is projected in Costa Rica, Spain and Australia (Pounds et al., 2006). [WGII Table 4.1] Drying of wetlands in the Sahel will affect the migration success of birds that use the Sahelian wetlands as stopovers in their migration to Northern Hemisphere breeding sites. In southern Africa, unprecedented levels of extinctions in both plant and animal species are envisaged. [WGII Table 9.1] In montane forests, many species depend on mist as their source of water: global warming will raise the cloud base and affect those species dependent on this resource. [WGII 13.4.1] Of all ecosystems, however, freshwater aquatic ecosystems appear to have the highest proportion of species threatened with extinction by climate change (Millennium Ecosystem Assessment, 2005b). [WGII 3.5.1]

4.1.3 Impacts of changes in hydrology on major ecosystem types

4.1.3.1 Lakes and streams

Impacts of global warming on lakes include an extended growing period at high latitudes, intensified stratification and nutrient loss from surface waters, decreased hypolimnetic oxygen (below the thermocline) in deep, stratified lakes, and expansion in range for many invasive aquatic weeds. Water levels are expected to increase in lakes at high latitudes, where climate models indicate increased precipitation, while water levels at mid- and low latitudes are projected to decline. Endorheic (terminal or closed) lakes are most vulnerable to a change in climate because of their sensitivity to changes in the balance of inflows and evaporation. Changes in inflows to such lakes can have very substantial effects and, under some climatic conditions, they may disappear entirely. The Aral Sea, for example, has been significantly reduced by increased abstractions of irrigation water upstream; and Qinghai Lake in China has shrunk following a fall in catchment precipitation. [WGII TAR 4.3.7]

The duration of ice cover in lakes and rivers at mid- to high latitudes has decreased by approximately two weeks during the past century in the Northern Hemisphere. [WGI TAR SPM] Increases in summer water temperature can increase anoxia in stratified lakes, increase the rate of phosphorus releases from lake-bottom sediments, and cause algal blooms that restructure the aquatic food web. [WGII 4.4.8] A unit increase in temperature in tropical lakes causes a proportionately higher density differential as compared with colder temperate lakes. Thus, projected tropical temperatures [WGI Chapters 10 and 11] will lead to strong thermal stratification, causing anoxia in deep layers of lakes and nutrient depletion in shallow lake waters. Reduced oxygen concentrations will generally reduce aquatic species diversity, especially in cases where water quality is impaired by eutrophication. [CCB 4.4]

Reduced oxygen concentrations tend to alter biotic assemblages, biogeochemistry and the overall productivity of lakes and streams. The thermal optima for many mid- to high-latitude cold-water taxa are lower than 20°C. Species extinctions are expected when warm summer temperatures and anoxia eliminate deep cold-water refugia. In the southern Great Plains of the USA, water temperatures are already approaching lethal limits for many native stream fish. Organic matter decomposition rates increase with temperature, thereby shortening the period over which detritus is available to aquatic invertebrates. [CCB 6.2] Invasive alien species represent a major threat to native biodiversity in aquatic ecosystems. [WGII 4.2.2] The rise in global temperature will tend to extend polewards the ranges of many invasive aquatic plants, such as *Eichhornia* and *Salvinia*. [RICC 2.3.6]

Effects of warming on riverine systems may be strongest in humid regions, where flows are less variable and biological interactions control the abundance of organisms. Drying of stream-beds and lakes for extended periods could reduce ecosystem productivity because of the restriction on aquatic habitat, combined with lowered water quality via increased oxygen deficits and pollutant concentrations. In semi-arid parts of the world, reductions in seasonal streamflow and complete drying up of lakes (such as in the Sahel of Africa) can have profound effects on ecosystem services, including the maintenance of biodiversity. [CCB 6.7]

Currently, species richness is highest in freshwater systems in central Europe and decreases to the north and south due to periodic droughts and salinisation (Declerck et al. 2005). Ensemble GCM runs for the IPCC AR4 indicate a south–north contrast in precipitation, with increases in the north and decreases in the south. [WGI 11.3.3.2] An increase in projected runoff and lower risk of drought could benefit the fauna of aquatic systems in northern Europe, while decreased water availability in the south could have the opposite effect (Álvarez Cobelas et al., 2005). [WGII 12.4.6]

4.1.3.2 Freshwater wetlands

The high degree of variability in the structure of wetland systems is due mainly to their individual hydrology, varying from peatland bogs in high-latitude boreal forests, through tropical monsoonal wetlands (e.g., the Kakadu wetlands, Australia), to high-altitude wetlands in the Tibetan and Andean mountains. Climate change will have its most pronounced effects on inland freshwater wetlands through altered precipitation and more frequent or intense disturbance events (droughts, storms, floods). Relatively small increases in precipitation variability can significantly affect wetland plants and animals at different stages of their life cycle (Keddy, 2000). [WGII 4.4.8] Generally, climatic warming is expected to start a drying trend in wetland ecosystems. This largely indirect influence of climate change, leading to alterations in the water level, would be the main agent in wetland ecosystem change and would overshadow the impacts of rising temperature and longer growing seasons in boreal and sub-Arctic peatlands (Gorham, 1991). Monsoonal areas are more likely to be affected by more intense rain events over shorter rainy seasons, exacerbating flooding and erosion in catchments and the wetlands themselves. [WGII TAR 5.8.3]

Most wetland processes are dependent on catchment-level hydrology, which can be altered by changes in land use as well as surface water resource management practices. [WGII TAR 5.ES] Recharge of local and regional groundwater systems, the position of the wetland relative to the local topography, and the gradient of larger regional groundwater systems are also critical factors in determining the variability and stability of moisture storage in wetlands in climatic zones where precipitation does not greatly exceed evaporation (Winter and Woo, 1990). Changes in recharge external to the wetland may be as important to the fate of the wetland under changing climatic conditions, as are the changes in direct precipitation and evaporation on the wetland itself (Woo et al., 1993). [WGII TAR 5.8.2.1] Thus, it may be very difficult, if not impossible, to adapt to the consequences of projected changes in water availability. [WGII TAR 5.8.4] Due, in part, to their limited capacity for adaptation, wetlands are considered to be among the ecosystems most vulnerable to climate change. [WGII 4.4.8]

Wetlands are often biodiversity hotspots. Many have world conservation status (Ramsar sites, World Heritage sites). Their loss could lead to significant extinctions, especially among amphibians and aquatic reptiles. [WGII 4.4.8] The TAR identified Arctic and sub-Arctic ombrotrophic ('cloud-fed') bogs and depressional wetlands with small catchments as the most vulnerable aquatic systems to climate change. [WGII TAR 5.8.5] The more recent AR4, however, suggests a very high degree of vulnerability for many additional wetland types, such as monsoonal wetlands in India and Australia, boreal peatlands, North America's prairie pothole wetlands and African Great Lake wetlands. [WGII 4.4.8, 4.4.10] The seasonal migration patterns and routes of many wetland species will have to change;

otherwise some species will be threatened with extinction. [WGII 4.4.8] For key habitats, small-scale restoration may be possible, if sufficient water is available. [WGII TAR 5.8.4]

Due to changes in hydrology associated with atmospheric warming, the area of wetland habitat has increased in some regions. In the Arctic region, thawing of permafrost is giving rise to new wetlands. [WGII 1.3] Thermokarst features, which result from the melting of ground ice in a region underlain by permafrost, can displace Arctic biota through either over-saturation or drying (Hinzman et al., 2005; Walsh et al., 2005). Extensive thermokarst development has been discovered in North America near Council, Alaska (Yoshikawa and Hinzman, 2003) and in central Yakutia (Gavriliev and Efremov, 2003). [WGI 4.7.2.3] Initially, permafrost thaw forms depressions for new wetlands and ponds that are interconnected by new drainage features. As the permafrost thaws further, surface waters drain into groundwater systems, leading to losses in freshwater habitat. [WGII 15.4.1.3] Warming may have already caused the loss of wetland area as lakes on the Yukon Delta expanded during the past century (Coleman and Huh, 2004). [WGII 15.6.2]

Small increases in the variability in precipitation regimes can significantly affect wetland plants and animals (Keddy, 2000; Burkett and Kusler, 2000). Biodiversity in seasonal wetlands, such as vernal pools, can be strongly impacted by changes in precipitation and soil moisture (Bauder, 2005). In monsoonal regions, prolonged dry periods promote terrestrialisation of wetlands, as witnessed in Keoladeo National Park (Chauhan and Gopal, 2001). [WGII 4.4.8]

4.1.3.3 Coasts and estuaries

Changes in the timing and volume of freshwater runoff will affect salinity, sediment and nutrient availability, and moisture regimes in coastal ecosystems. Climate change can affect each of these variables by altering precipitation and locally driven runoff or, more importantly, runoff from watersheds that drain into the coastal zone. [WGII 6.4.1.3] Hydrology has a strong influence on the distribution of coastal wetland plant communities, which typically grade inland from salt, to brackish, to freshwater species. [WGII 6.4.1.4]

The effects of sea-level rise on coastal landforms vary among coastal regions because the rate of sea-level rise is not spatially uniform [WGI 5.5.2] and because some coastal regions experience uplift or subsidence due to processes that are independent of climate change. Such processes include groundwater withdrawals, oil and gas extraction, and isostacy (adjustment of the Earth's surface on geological timescales to changes in surface mass; e.g., due to changes in ice sheet mass following the last deglaciation). In addition to changes in elevation along the coast, factors arising inland can influence the net effect of sea-level rise on coastal ecosystems. The natural ecosystems within watersheds have been fragmented and the downstream flow of water, sediment and nutrients to the coast has been disrupted (Nilsson et al., 2005). Land-use change and hydrological modifications have had downstream impacts, in addition to localised influences, including human development on the coast. Erosion has increased the sediment load reaching the coast; for example, suspended loads in the Huanghe (Yellow) River have increased 2–10 times over the past 2,000 years (Jiongxin, 2003). In contrast, damming and channelisation have greatly reduced the supply of sediments to the coast on other rivers through the retention of sediment in dams (Syvistki et al., 2005), and this effect will probably dominate during the 21st century. [WGII 6.4]

Climate model ensemble runs by Milly et al. (2005) indicate that climate change during the next 50–100 years will increase discharges to coastal waters in the Arctic, in northern Argentina and southern Brazil, parts of the Indian sub-continent and China, while reduced discharges to coastal waters are suggested in southern Argentina and Chile, western Australia, western and southern Africa, and in the Mediterranean Basin. [WGII 6.3.2; see Figure 2.10 in this volume] If river discharge decreases, the salinity of coastal estuaries and wetlands is expected to increase and the amount of sediments and nutrients delivered to the coast to decrease. In coastal areas where streamflow decreases, salinity will tend to advance upstream, thereby altering the zonation of plant and animal species as well as the availability of freshwater for human use. The increased salinity of coastal waters since 1950 has contributed to the decline of cabbage palm forests in Florida (Williams et al., 1999) and bald cypress forests in Louisiana (Krauss et al., 2000). Increasing salinity has also played a role in the expansion of mangroves into adjacent marshes in the Florida Everglades (Ross et al., 2000) and throughout south-eastern Australia during the past 50 years (Saintilan and Williams, 1999). [WGII 6.4.1.4] Saltwater intrusion as a result of a combination of sea-level rise, decreases in river flows and increased drought frequency are expected to alter estuarine-dependent coastal fisheries during this century in parts of Africa, Australia and Asia. [WGII 6.4.1.3, 9.4.4, 10.4.1, 11.4.2]

Deltaic coasts are particularly vulnerable to changes in runoff and sediment transport, which affect the ability of a delta to cope with the physical impacts of climatic change. In Asia, where human activities have led to increased sediment loads of major rivers in the past, the construction of upstream dams is now depleting the supply of sediments to many deltas, with increased coastal erosion becoming a widespread consequence (Li et al., 2004; Syvitski et al., 2005; Ericson et al., 2006). [WGII 6.2.3, 6.4.1] In the subsiding Mississippi River deltaic plain of south-east Louisiana, sediment starvation due to human intervention in deltaic processes and concurrent increases in the salinity and water levels of coastal marshes occurred so rapidly that 1,565 km^2 of intertidal coastal marshes and adjacent coastal lowlands were converted to open water between 1978 and 2000 (Barras et al., 2003). [WGII 6.4.1]

Some of the greatest potential impacts of climate change on estuaries may result from changes in physical mixing characteristics caused by changes in freshwater runoff (Scavia et al., 2002). Freshwater inflows into estuaries influence water residence time, nutrient delivery, vertical stratification, salinity, and control of phytoplankton growth rates (Moore et al., 1997). Changes in river discharges into shallow near-shore marine environments will lead to changes in turbidity, salinity, stratification and nutrient availability (Justic et al., 2005). [WGII 6.4.1.3]

4.1.3.4 Mountain ecosystems

The zonation of ecosystems along mountain gradients is mediated by temperature and soil moisture. Recent studies (Williams et al., 2003; Pounds and Puschendorf, 2004; Andreone et al., 2005; Pounds et al., 2006) have shown the disproportionate risk of extinctions in mountain ecosystems and, in particular, among endemic species. [WGII 4.4.7] Many species of amphibians, small mammals, fish, birds and plants are highly vulnerable to the ongoing and projected changes in climate that alter their highly specialised mountain niche. [WGII 1.3.5.2, 4.4.7, 9.4.5]

In many snowmelt-dominated watersheds, temperature increase has shifted the magnitude and timing of hydrological events. A trend towards earlier peak spring streamflow and increased winter base flows has been observed in North America and Eurasia. [WGII 1.3.2] A greater fraction of annual precipitation is falling as rain rather than snow at 74% of the weather stations studied in the western mountains of the USA between 1949 and 2004 (Knowles et al., 2006). Since the 1970s, winter snow depth and spring snow cover have decreased in Canada, particularly in the west, where air temperatures have consistently increased (Brown and Braaten, 1998). Spring and summer snow cover is decreasing in the western USA (Groisman et al., 2004). The April 1st snow water equivalent (SWE) has decreased by 15–30% since 1950 in the western mountains of North America, particularly at lower elevations in spring, primarily due to warming rather than to changes in precipitation (Mote et al., 2005). Streamflow peaks in the snowmelt-dominated western mountains of the USA occurred 1–4 weeks earlier in 2002 than in 1948 (Stewart et al., 2005). [WGII 14.2.1]

The duration and depth of snow cover, often correlated with mean temperature and precipitation (Keller et al., 2005; Monson et al., 2006), is a key factor in many alpine ecosystems (Körner, 1999). Missing snow cover exposes plants and animals to frost, and influences water supply in spring (Keller et al., 2005). If animal movements are disrupted by changing snow patterns, as has been found in Colorado (Inouye et al., 2000), increased wildlife mortality may result through a mismatch between wildlife and environment. [WGII 4.4.7] For each 1°C of temperature increase, the duration of snow cover is expected to decline by several weeks at mid-elevations in the European Alps. It is *virtually certain* that European mountain flora will undergo major changes in response to climate change, with changes in snow-cover duration being a more important driver than the direct effects of temperature on animal metabolism. [WGII 12.4.3]

Changing runoff from glacier melt has significant effects on ecosystem services. Biota of small-watershed streams sustained by glacial melt are highly vulnerable to extirpation. [WGII 1.3.1, 3.2, 3.4.3]

4.1.3.5 Forests, savannas and grasslands

The availability of water is a key factor in the restructuring of forest and grassland systems as the climate warms. Climate change is known to alter the likelihood of increased wildfire size and frequency, while also inducing stress in trees, which indirectly exacerbates the effects of these disturbances. Many forest ecosystems in the tropics, high latitudes and high altitudes are becoming increasingly susceptible to drought and associated changes in fire, pests and diseases. [WGII Chapter 4, 5.1.2, 13.4] It has been estimated that up to 40% of the Amazonian forests could be affected by even slight decreases in precipitation (Rowell and Moore, 2000). Multi-model GCM simulations of precipitation changes over South America during the next 100 years show a substantial (20% or more) decrease in June, July and August precipitation in the Amazon Basin, but a slight increase (approximately 5%) in December, January and February. [WGI 11.6.3.2] These projected changes in precipitation, coupled with increased temperature, portend a replacement of some Amazonian forests by ecosystems that have more resistance to the multiple stresses caused by temperature increase, droughts and fires. [WGII 13.4.2]

Increases in drought conditions in several regions (Europe, parts of Latin America) during the growing season are projected to accompany increasing summer temperatures and precipitation declines, with widespread effects on forest net ecosystem productivity. Effects of drought on forests include mortality due to disease, drought stress and pests; a reduction in resilience; and biotic feedbacks that vary from site to site. [WGII 4.4.5] In some regions, forests are projected to replace other vegetation types, such as tundra and grasslands, and the availability of water can be just as important as temperature and CO_2-enrichment effects on photosynthesis. [WGII 4.4.3, 4.4.5]

Numerous studies have evaluated the direct CO_2 fertilisation impact and warming effects on dominant forest and grassland types. Studies involving a wide range of woody and herbaceous species suggest that enhancements in photosynthesis due to projected CO_2 enrichment will be dependent upon water availability. [WGII 4.4.3] Higher-order effects of CO_2 enrichment in forests and savannas can have important feedbacks on water resources. For example, atmospheric CO_2 enrichment can have adverse effects on the nutritional value of litter in streams (Tuchman et al., 2003), and soil water balance can be strongly influenced by elevated CO_2 in most grassland types. [WGII 4.4.10] Grassland and savanna productivity is highly sensitive to precipitation variability. In assessments of tall-grass prairie productivity, for example, increased rainfall variability was more significant than rainfall amount, with a 50% increase in dry-spell duration causing a 10% reduction in net primary productivity (Fay et al., 2003a). [WGII 4.4.3]

4.2 Agriculture and food security, land use and forestry

4.2.1 Context

The productivity of agricultural, forestry and fisheries systems depends critically on the temporal and spatial distribution of precipitation and evaporation, as well as, especially for crops, on the availability of freshwater resources for irrigation. [WGII 5.2.1] Production systems in marginal areas with respect to water face increased climatic vulnerability and risk under climate change, due to factors that include, for instance, degradation of land resources through soil erosion, over-extraction of groundwater and associated salinisation, and over-grazing of dryland (FAO, 2003). [WGII 5.2.2] Smallholder agriculture in such marginal areas is especially vulnerable to climate change and variability, and socio-economic stressors often compound already difficult environmental conditions. [WGII 5.2.2, Table 5.2, Box 5.3] In forests, fires and insect outbreaks linked to the frequency of extreme events have been shown to increase climate vulnerability. In fisheries, water pollution and changes in water resources also increase vulnerability and risk. [WGII 5.2.2]

4.2.1.1 Agriculture and food security

Water plays a crucial role in food production regionally and worldwide. On the one hand, more than 80% of global agricultural land is rain-fed; in these regions, crop productivity depends solely on sufficient precipitation to meet evaporative demand and associated soil moisture distribution (FAO, 2003). [WGII 5.4.1.2] Where these variables are limited by climate, such as in arid and semi-arid regions in the tropics and sub-tropics, as well as in Mediterranean-type regions in Europe, Australia and South America, agricultural production is very vulnerable to climate change (FAO, 2003). On the other hand, global food production depends on water not only in the form of precipitation but also, and critically so, in the form of available water resources for irrigation. Indeed, irrigated land, representing a mere 18% of global agricultural land, produces 1 billion tonnes of grain annually, or about half the world's total supply; this is because irrigated crops yield on average 2–3 times more than their rain-fed counterparts[19] (FAO, 2003).

While too little water leads to vulnerability of production, too much water can also have deleterious effects on crop productivity, either directly, e.g., by affecting soil properties and by damaging plant growth, or indirectly, e.g., by harming or delaying necessary farm operations. Heavy precipitation events, excessive soil moisture and flooding disrupt food production and rural livelihoods worldwide (Rosenzweig et al., 2002). [WGII 5.4.2.1]

By critically affecting crop productivity and food production, in addition to being a necessity in food preparation processes, water plays a critical role in food security. Currently, 850 million people in the world are still undernourished (FAO, 2003). [WGII 5.3.2.1, 5.6.5] Socio-economic pressures over the next several decades will lead to increased competition between irrigation needs and demand from non-agricultural sectors, potentially reducing the availability and quality of water resources for food. [WGII 3.3.2] Recent studies indicate that it is *unlikely* that the Millennium Development Goal (MDG) for hunger will be met by 2015. [WGII 5.6.5] At the same time, during this century, climate change may further reduce water availability for global food production, as a result of projected mean changes in temperature and precipitation regimes, as well as due to projected increases in the frequency of extreme events, such as droughts and flooding (Rosenzweig et al., 2002). [WGII 5.6.5]

Climate impacts assessments of food production are, in general, critically dependent upon the specifics of the GCM precipitation projections used. [WGII 5.4.1.2] A wide range of precipitation scenarios is currently available. In general, assessments using scenarios of reduced regional precipitation typically result in negative crop production signals, and *vice versa*. Projections of increased aridity in several Mediterranean-type environments (Europe, Australia and South America), as well as in marginal arid and semi-arid tropical regions, especially sub-Saharan Africa, appear to be robust across models (see Figure 2.10). These regions face increased vulnerability under climate change, as shown in Figure 4.1. [WGII 5.3.1]

4.2.1.2 Land use and forest ecosystems

Forest ecosystems occupy roughly 4 billion ha of land, an area comparable to that used by crops and pastures combined. Of this land, only about 200 million ha are used for commercial forestry production globally (FAO, 2003). [WGII 4.4.5, 5.1.1, 5.4.5]

Forests are key determinants of water supply, quality and quantity, in both developing and developed countries. The importance of forests as watersheds may increase substantially in the next few decades, as freshwater resources become increasingly scarce, particularly in developing countries (Mountain Agenda, 1997; Liniger and Weingartner, 1998). [LULUCF 2.5.1.1.4; WGII 4.1.1]

Forests contribute to the regional water cycle, with large potential effects of land-use changes on local and regional climates (Harding, 1992; Lean et al., 1996). On the other hand, forest protection can have drought and flood mitigation benefits, especially in the tropics (Kramer et al., 1997; Pattanayak and Kramer, 2000). [LULUCF 2.5.1.1.6]

Afforestation and reforestation may increase humidity, lower temperature and increase rainfall in the regions affected (Harding, 1992; Blythe et al., 1994); deforestation can instead lead to decreased local rainfall and increased temperature. In Amazonia and Asia, deforestation may lead to new climate conditions unsuitable for successful regeneration of rainforest species (Chan, 1986; Gash and Shuttleworth, 1991; Meher-Homji, 1992). [LULUCF 2.5.1.1.6]

[19] See Section 1.3 for a discussion of the interrelationships between irrigation, climate change and groundwater recharge. This is also mentioned in Sections 5.1.3 (on Africa) and 5.2.3 (on Asia).

Forest ecosystems are differentially sensitive to climatic change (e.g., Kirschbaum and Fischlin, 1996; Sala et al., 2000; Gitay et al., 2001), with temperature-limited biomes being sensitive to impacts of warming, and water-limited biomes being sensitive to increasing levels of drought. Some, such as fire-dependent ecosystems, may change rapidly in response to climate and other environmental changes (Scheffer et al., 2001; Sankaran et al., 2005). [WGII 4.1, 4.4.5]

Forest ecosystems, and the biodiversity associated with them, may be particularly at risk in Africa, due to a combination of socio-economic pressures, and land-use and climate-change factors. [WGII 4.2] By 2100, negative impacts across about 25% of Africa (especially southern and western Africa) may cause a decline in both water quality and ecosystem goods and services. [WGII 4.ES, 4.4.8] Indeed, changes in a variety of ecosystems are already being detected and documented, particularly in southern Africa. [WGII 9.2.1.4]

4.2.2 Observations

4.2.2.1 Climate impacts and water

Although agriculture and forestry are known to be highly dependent on climate, evidence of observed changes related to regional climate changes, and specifically to water, is difficult to find. Agriculture and forestry are also strongly influenced by non-climate factors, especially management practices and technological changes (Easterling, 2003) on local and regional scales, as well as market prices and policies related to subsidies. [WGII 1.3.6]

Although responses to recent climate change are difficult to identify in human systems, due to multiple non-climate driving forces and the existence of adaptation, effects have been detected in forestry and a few agricultural systems. Changes in several aspects of the human health system have been related to recent warming. Adaptation to recent warming is beginning to be systematically documented. In comparison with other factors, recent warming has been of limited consequence in agriculture and forestry. A significant advance in phenology, however, has been observed for agriculture and forestry in large parts of the Northern Hemisphere, with limited responses in crop management. The lengthening of the growing season has contributed to an observed increase in forest productivity in many regions, while warmer and drier conditions are partly responsible for reduced forest productivity and increased forest fires in North America and the Mediterranean Basin. Both agriculture and forestry have shown vulnerability to recent trends in heatwaves, droughts and floods. [WGII 1.3.6, 1.3.9, 5.2]

4.2.2.2 Atmospheric CO_2 and water dynamics

The effects of elevated atmospheric CO_2 on plant function may have important implications for water resources, since leaf-level water-use efficiency increases due to increased stomatal resistance as compared to current concentrations. For C_3 plant species (including most food crops), the CO_2 effect may be relatively greater for crops that are under moisture stress, compared to well-irrigated crops. [WGII TAR 5.3.3.1] However, the large-scale implications of CO_2–water interactions (i.e., at canopy, field and regional level) are highly uncertain. In general, it is recognised that the positive effects of elevated CO_2 on plant water relations are expected to be offset by increased evaporative demand under warmer temperatures. [WGII TAR 5.3.3.1]

Many recent studies confirm and extend TAR findings that temperature and precipitation changes in future decades will modify, and often limit, direct CO_2 effects on plants. For instance, high temperatures during flowering may lower CO_2 effects by reducing grain number, size and quality (Thomas et al., 2003; Baker et al., 2004; Caldwell et al., 2005). Likewise, increased water demand under warming may reduce the expected positive CO_2 effects. Rain-fed wheat grown at 450 ppm CO_2 shows grain yield increases up to 0.8°C warming, but yields then decline beyond 1.5°C warming; additional irrigation is needed to counterbalance these negative effects. [WGII 5.4.1.2]

Finally, plant physiologists and crop modellers alike recognise that the effects of elevated CO_2, measured in experimental settings and implemented in models, may overestimate actual field and farm-level responses. This is due to many limiting factors that typically operate at the field level, such as pests, weeds, competition for resources, soil water and air quality. These critical factors are poorly investigated in large-scale experimental settings, and are thus not well integrated into the leading plant growth models. Understanding the key dynamics characterising the interactions of elevated CO_2 with climate, soil and water quality, pests, weeds and diseases, climate variability and ecosystem vulnerability remains a priority for understanding the future impacts of climate change on managed systems. [WGII 5.4.1, 5.8.2]

4.2.3 Projections

Changes in water demand and availability under climate change will significantly affect agricultural activities and food security, forestry and fisheries in the 21st century. On the one hand, changes in evaporation:precipitation ratios will modify plant water demand with respect to a baseline with no climate change. On the other hand, modified patterns of precipitation and storage cycles at the watershed scale will change the seasonal, annual and interannual availability of water for terrestrial and aquatic agro-ecosystems (FAO, 2003). Climate changes increase irrigation demand in the majority of world regions due to a combination of decreased rainfall and increased evaporation arising from increased temperatures. [WGII 5.8.1]

It is expected that projected changes in the frequency and severity of extreme climate events, such as increased frequency of heat stress, droughts and flooding, will have significant consequences on food, forestry (and the risk of forest fires) and other agro-ecosystem production, over and above the impacts of changes in mean variables alone. [WGII 5.ES] In particular, more than 90% of simulations predict increased droughts in the sub-tropics by the end of the 21st century [WGI SPM], while increased extremes in precipitation are projected in the major agricultural production areas of southern and eastern Asia, eastern Australia and northern Europe. [WGI 11.3, 11.4, 11.7] It should be noted that climate change impact models for food, forest products and fibre do not yet include these recent findings on the projected patterns of precipitation change; negative impacts are projected to be worse than currently computed, once the effects of extremes on productivity are included. [WGII 5.4.1, 5.4.2]

Percentage changes in annual mean runoff are indicative of the mean water availability for vegetation cover. Projected changes between now and 2100 [WGII Chapter 3] show some consistent patterns: increases in high latitudes and the wet tropics, and decreases in mid-latitudes and some parts of the dry tropics (Figure 4.1b). Declines in water availability are indicative of increased water stress, indicating, in particular, a worsening in regions where water for production is already a scarce commodity (e.g., in the Mediterranean Basin, Central America and sub-tropical regions of Africa and Australia, see Figure 4.1b). [WGII 5.3.1]

Finally, it may be important to recognise that production systems and water resources will be critically shaped in the coming decades by the concurrent interactions of socio-economic and climate drivers. For instance, increased demand for irrigation water in agriculture will depend both on changed climatic conditions and on increased demand for food by a growing population; in addition, water availability for forest productivity will depend on both climatic drivers and critical anthropogenic impacts, particularly deforestation in tropical zones. In the Amazon Basin, for instance, a combination of deforestation and increased fragmentation may trigger severe droughts over and above the climate signal, leading to increased fire danger. [WGII 5.3.2.2]

4.2.3.1 Crops

In general, while moderate warming in high-latitude regions would benefit crop and pasture yields, even slight warming in low-latitude areas, or areas that are seasonally dry, would have a detrimental effect on yields. Modelling results for a range of sites show that, in high-latitude regions, moderate to medium increases in local temperature (1–3°C), along with associated CO_2 increases and rainfall changes, can have small, beneficial impacts on crop yields. However, in low-latitude regions, even moderate temperature increases (1–2°C) are *likely* to have negative yield impacts for major cereals. Further warming has increasingly negative impacts in all regions. [WGII 5.ES]

Regions where agriculture is currently a marginal enterprise, largely due to a combination of poor soils, water scarcity and rural poverty, may suffer increasingly as a result of climate change impacts on water. As a result, even small changes in climate will increase the number of people at risk of hunger, with the impact being particularly great in sub-Saharan Africa. [WGII 5.ES]

Increases in the frequency of climate extremes may lower crop yields beyond the impacts of mean climate change. Simulation studies since the TAR have considered specific aspects of increased climate variability within climate change scenarios. Rosenzweig et al. (2002) computed that, under scenarios of increased heavy precipitation, production losses due to excessive soil moisture (already significant today) would double in the USA to US$3 billion/yr in 2030. In Bangladesh, the risk of crop losses is projected to increase due to higher flood frequency under climate change. Finally, climate change impact studies that incorporate higher rainfall intensity indicate an increased risk of soil erosion; in arid and semi-arid regions, high rainfall intensity may be associated with a higher possibility of

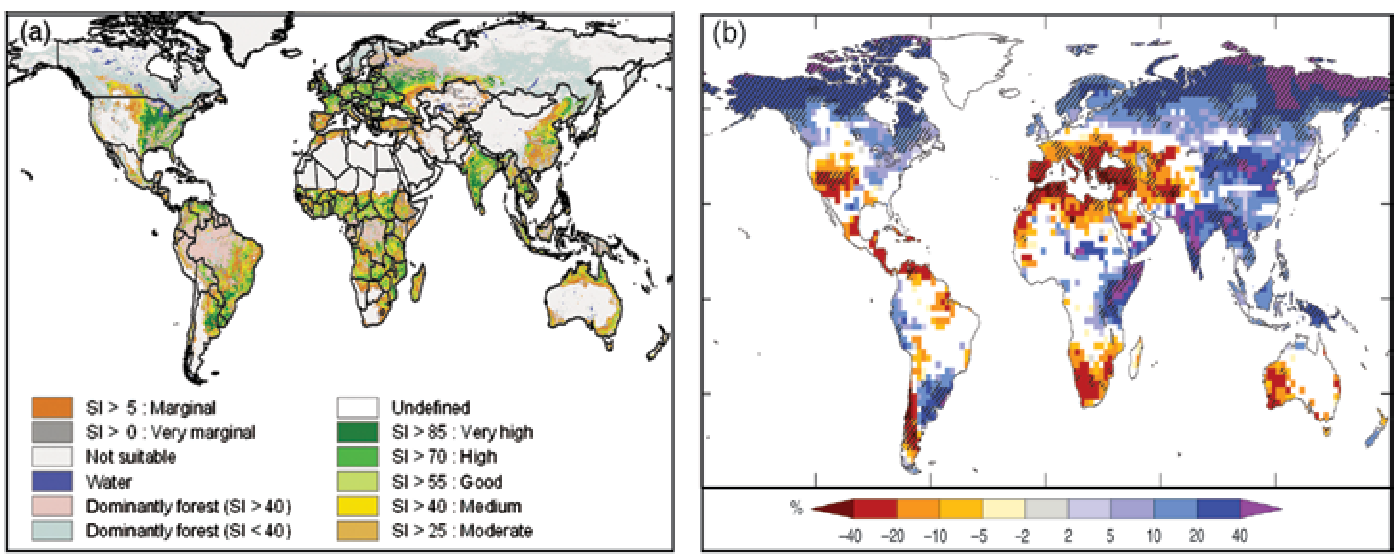


Figure 4.1: *(a) Current suitability for rain-fed crops (excluding forest ecosystems) (after Fischer et al., 2002b). SI = suitability index [WGII Figure 5.1a]; (b) ensemble mean percentage projected change in annual mean runoff between the present (1980–1999) and 2090–2099. [Based on SYR Figure 3.5]*

salinisation, due to increased loss of water past the crop root zone. [WGII 5.4.2.1]

Impacts of climate change on irrigation water requirements may be large. A few new studies have further quantified the impacts of climate change on regional and global irrigation requirements, irrespective of the positive effects of elevated CO_2 on crop water-use efficiency. Döll (2002), in considering the direct impacts of climate change on crop evaporative demand, but without any CO_2 effects, estimated an increase in *net* crop irrigation requirements (i.e., net of transpiration losses) of between 5% and 8% globally by 2070, with larger regional signals (e.g., +15%) in south-east Asia. [WGII 5.4.2.1]

Fischer et al. (2006), in a study that included positive CO_2 effects on crop water-use efficiency, computed increases in global net irrigation requirements of 20% by 2080, with larger impacts in developed *versus* developing regions, due to both increased evaporative demands and longer growing seasons under climate change. Fischer et al. (2006) and Arnell et al. (2004) also projected increases in water stress (measured as the ratio of irrigation withdrawals to renewable water resources) in the Middle East and south-east Asia. Recent regional studies have likewise underlined critical climate change/water dynamics in key irrigated areas, such as northern Africa (increased irrigation requirements; Abou-Hadid et al., 2003) and China (decreased requirements; Tao et al., 2003a). [WGII 5.4.2.1]

At the national scale, some integrative studies exist. In the USA, two modelling studies on adaptation of the agricultural sector to climate change (i.e., shifts between irrigated and rain-fed production) foresee a decrease in both irrigated areas and withdrawals beyond 2030 under various climate scenarios (Reilly et al., 2003; Thomson et al., 2005a). This is related to a declining yield gap between irrigated and rain-fed agriculture caused either by yield reductions of irrigated crops due to higher temperatures, or by yield increases of rain-fed crops due to higher precipitation. These studies did not take into account the increasing variability of daily precipitation and, as such, rain-fed yields are probably overestimated. [WGII 3.5.1]

For developing countries, a 14% increase in irrigation water withdrawal by 2030 was foreseen in an FAO study that did not consider the impacts of climate change (Bruinsma, 2003). However, the four Millennium Ecosystem Assessment scenarios project much smaller increases in irrigation withdrawal at the global scale, as they assume that the area under irrigation will only increase by between 0% and 6% by 2030; and between 0% and 10% by 2050. [WGII 3.5.1]

The overwhelming water use increases are *likely* to occur in the domestic and industrial sectors, with withdrawals increasing by between 14% and 83% by 2050 (Millennium Ecosystem Assessment, 2005a, b). This is based on the idea that the value of water will be much higher for domestic and industrial uses, which is particularly true under conditions of water stress. [WGII 3.5.1]

Locally, irrigated agriculture may face new problems linked to the spatial and temporal distribution of streamflow. For instance, at low latitudes, especially in south-east Asia, early snowmelt may cause spring flooding and lead to a summer irrigation water shortage. [WGII 5.8.2]

4.2.3.2 Pastures and livestock

Many of the world's rangelands are in semi-arid areas and susceptible to water deficits; any further decline in water resources will greatly impact carrying capacity. As a result, increased climate variability and droughts may lead to livestock loss. Specifically, the impact on animal productivity due to increased variability in weather patterns is *likely* to be far greater than effects associated with changes in average climatic conditions. The most frequent catastrophic losses arising from a lack of prior conditioning to weather events occur in confined cattle feedlots, with economic losses from reduced cattle performance exceeding those associated with cattle death losses by several-fold. [WGII 5.4.3.1]

Many of the world's rangelands are affected by El Niño–Southern Oscillation (ENSO) events. Under ENSO-related drought events, in dry regions there are risks of positive feedback between the degradation of both soils and vegetation and reductions in rainfall, with consequences in terms of loss of both pastoral and farming lands. [WGII 5.4.3.1] However, while WGI TAR indicated an increased likelihood of ENSO frequency under climate change, the WGI AR4 did not find correlations between ENSO and climate change. [WGI TAR SPM; WGI 10.3.5.4]

A survey of experimental data worldwide suggested that mild warming generally increases grassland productivity, with the strongest positive responses at high latitudes, and that the productivity and composition of plant species in rangelands are highly correlated with precipitation. In addition, recent findings (see Figure 4.1) projected declines in rainfall in some major grassland and rangeland areas (e.g., South America, southern and northern Africa, western Asia, Australia and southern Europe). [WGII 5.4.3.2]

Elevated atmospheric CO_2 can reduce soil water depletion in different native and semi-native temperate and Mediterranean grassland. However, in conjunction with climate change, increased variability in rainfall and warmer temperatures may create more severe soil moisture limitations, and hence reduced productivity, offsetting the beneficial effects of CO_2. Other impacts on livestock occur directly through the increase in thermal heat load. [WGII 5.4.3.2]

4.2.3.3 Fisheries

Negative impacts of climate change on aquaculture and freshwater fisheries include: stress due to increased temperature and oxygen demand and decreased pH; uncertain future water quality and volume; extreme weather events; increased frequency of disease and toxic events; sea-level rise and conflicts of interest with coastal defence needs; and uncertain

Box 4.1: Climate change and the fisheries of the lower Mekong – an example of multiple stresses due to human activity on a megadelta fisheries system. [WGII Box 5.3]

Fisheries are central to the lives of the people, particularly the rural poor, who live in the lower Mekong countries. Two-thirds of the basin's 60 million people are in some way active in fisheries, which represent about 10% of the GDP of Cambodia and the Lao People's Democratic Republic (PDR). There are approximately 1,000 species of fish commonly found in the river, with many more marine vagrants, making it one of the most prolific and diverse faunas in the world (MRC, 2003). Recent estimates of the annual catch from capture fisheries alone exceed 2.5 million tonnes (Hortle and Bush, 2003), with the delta contributing over 30% of this.

Direct effects of climate change will occur due to changing patterns of precipitation, snowmelt and rising sea level, which will affect hydrology and water quality. Indirect effects will result from changing vegetation patterns that may alter the food chain and increase soil erosion. It is *likely* that human impacts on the fisheries (caused by population growth, flood mitigation, increased water abstractions, changes in land use, and over-fishing) will be greater than the effects of climate, but the pressures are strongly interrelated.

An analysis of the impact of climate change scenarios on the flow of the Mekong (Hoanh et al., 2004) estimated increased maximum monthly flows of 35–41% in the basin and 16–19% in the delta (the lower value is for years 2010–2038 and the higher value for years 2070–2099, compared with 1961–1990 levels). Minimum monthly flows were estimated to decrease by 17–24% in the basin and 26–29% in the delta. Increased flooding would positively affect fisheries yields, but a reduction in dry season habitat may reduce the recruitment of some species. However, planned water-management interventions, primarily dams, are expected to have the opposite effects on hydrology, namely marginally decreasing wet-season flows and considerably increasing dry-season flows (World Bank, 2004b).

Models indicate that even a modest sea-level rise of 20 cm would cause contour lines of water levels in the Mekong delta to shift 25 km inland during the flood season and saltwater to move further upstream (although confined within canals) during the dry season (Wassmann et al., 2004). Inland movement of saltwater would significantly alter the species composition of fisheries, but may not be detrimental for overall fisheries yields.

future supplies of fishmeal and oils from capture fisheries. A case study of the multiple stresses that may affect fisheries in developing countries is included in Box 4.1. [WGII 5.4.6.1]

Positive impacts include increased growth rates and food conversion efficiencies; increased length of growing season; range expansion; and the use of new areas due to decreased ice cover. [WGII 5.4.6.1]

4.2.4 Adaptation, vulnerability and sustainable development

Water management is a critical component that needs to adapt in the face of both climate and socio-economic pressures in the coming decades. Changes in water use will be driven by the combined effects of: changes in water availability, changes in water demand from land, as well as from other competing sectors including urban, and changes in water management.

Practices that increase the productivity of irrigation water use – defined as crop output per unit water use – may provide significant adaptation potential for all land production systems under future climate change. At the same time, improvements in irrigation efficiency are critical to ensure the availability of water both for food production and for competing human and environmental needs. [WGII 3.5.1]

Several simulation studies suggest the possibility of relative benefits of adaptation in the land sector with low to moderate warming, although several response strategies may place extra stress on water and other environmental resources as warming increases. *Autonomous adaptation* actions are defined as responses that will be implemented by individual farmers, rural communities and/or farmers' organisations, depending on perceived or real climate change in the coming decades, and without intervention and/or co-ordination by regional and national governments and international agreements. To this end, maladaptation, e.g., pressure to cultivate marginal land, or to adopt unsustainable cultivation practices as yields drop, may increase land degradation and endanger the biodiversity of both wild and domestic species, possibly jeopardising future ability to respond to increasing climate risk later in the century. *Planned adaptation*, therefore, including changes in policies, institutions and dedicated infrastructure, will be needed to facilitate and maximise long-term benefits of adaptation responses to climate change. [WGII 5.5]

4.2.4.1 Autonomous adaptation

Options for autonomous adaptation are largely extensions or intensifications of existing risk management and production enhancement activities, and are therefore already available to farmers and communities. These include, with respect to water:

- adoption of varieties/species with increased resistance to heat shock and drought;
- modification of irrigation techniques, including amount, timing or technology;
- adoption of water-efficient technologies to 'harvest' water, conserve soil moisture (e.g. crop residue retention), and reduce siltation and saltwater intrusion;
- improved water management to prevent waterlogging, erosion and leaching;
- modification of crop calendars, i.e., timing or location of cropping activities;
- implementation of seasonal climate forecasting.

Additional adaptation strategies may involve land-use changes that take advantage of modified agro-climatic conditions. [WGII 5.5.1]

A few simulation studies show the importance of irrigation water as an adaptation technique to reduce climate change impacts. In general, however, projections suggest that the greatest relative benefit from adaptation is to be gained under conditions of low to moderate warming, and that adaptation practices that involve increased irrigation water use may in fact place additional stress on water and environmental resources as warming and evaporative demand increase. [WGII 5.8.1]

Many adaptation strategies in key production sectors other than crop agriculture have also been explored, although, without a direct focus on water issues. Adaptation strategies that may nonetheless affect water use include, for livestock systems, altered rotation of pastures, modification of times of grazing, alteration of forage and animal species/breeds, altered integration within mixed livestock/crop systems, including the use of adapted forage crops, care to ensure adequate water supplies, and the use of supplementary feeds and concentrates. Pastoralist coping strategies in semi-arid and arid Kenya and southern Ethiopia are discussed in Box 4.2. [WGII 5.4.7]

Adaptation strategies for forestry may include changes in management intensity, species mix, rotation periods, adjusting to altered wood size and quality, and adjusting fire management systems. [WGII 5.5.1]

With respect to marine ecosystems, with the exception of aquaculture and some freshwater fisheries, the exploitation of natural fish populations precludes the kind of management adaptations to climate change suggested for the crop, livestock and forest sectors. Adaptation options thus centre on altering catch size and effort. The scope for autonomous adaptation is increasingly restricted as new regulations governing the exploitation of fisheries and marine ecosystems come into force. [WGII 5.5.1]

If widely adopted, adaptation strategies in production systems have substantial potential to offset negative climate change impacts and take advantage of positive ones. However, there has been little evaluation of how effective and widely adopted these adaptations may be, given the complex nature of decision making; the diversity of responses across regions; time lags

Box 4.2: Pastoralist coping strategies in northern Kenya and southern Ethiopia. [WGII Box 5.5]

African pastoralism has evolved in adaptation to harsh environments with very high spatial and temporal variability of rainfall (Ellis, 1995). Several recent studies (Ndikumana et al., 2000; Hendy and Morton, 2001; Oba, 2001; McPeak and Barrett, 2001; Morton, 2006) have focused on the coping strategies used by pastoralists during recent droughts in northern Kenya and southern Ethiopia, and the longer-term adaptations that underlie them.

- *Mobility* remains the most important pastoralist adaptation to spatial and temporal variations in rainfall, and in drought years many communities make use of fall-back grazing areas unused in 'normal' dry seasons because of distance, land tenure constraints, animal disease problems or conflict. However, encroachment on and individuation of communal grazing lands, and the desire to settle in order to access human services and food aid, have severely limited pastoral mobility.
- Pastoralists engage in *herd accumulation*, and most evidence now suggests that this is a rational form of insurance against drought.
- A small proportion of pastoralists now hold some of their wealth in bank accounts, and others use informal savings and credit mechanisms through shop-keepers.
- Pastoralists also use *supplementary feed* for livestock, purchased or lopped from trees, as a coping strategy; they intensify *animal disease management* through indigenous and scientific techniques; they pay for *access to water* from powered boreholes.
- *Livelihood diversification* away from pastoralism in this region predominantly takes the form of shifts into low-income or environmentally unsustainable occupations such as charcoal production, rather than an adaptive strategy to reduce *ex ante* vulnerability.
- A number of *intra-community mechanisms* distribute both livestock products and the use of live animals to the destitute, but these appear to be breaking down because of the high levels of covariate risk within communities.

in implementation; and possible economic, institutional and cultural barriers to change. For example, the realisable adaptive capacity of poor subsistence farming/herding communities is generally considered to be very low. Likewise, large areas of forests receive minimal direct human management, limiting adaptation opportunities. Even in more intensively managed forests, where adaptation activities may be more feasible, long time lags between planting and harvesting may complicate the adoption of effective adaptation strategies. [WGII 5.1.1]

4.2.4.2 Planned adaptation

Planned adaptation solutions should focus on developing new infrastructure, policies, and institutions that support, facilitate, co-ordinate and maximise the benefits of new management and land-use arrangements. This can be achieved in general through improved governance, including addressing climate change in development programmes; increasing investment in irrigation infrastructure and efficient water-use technologies; ensuring appropriate transport and storage infrastructure; revising land tenure arrangements (including attention to well-defined property rights); and establishing accessible, efficiently functioning markets for products and inputs (including water pricing schemes) and for financial services (including insurance). [WGII 5.5]

Planned adaptation and policy co-ordination across multiple institutions may be necessary to facilitate adaptation to climate change, in particular where falling yields create pressure to cultivate marginal land or adopt unsustainable cultivation practices, increasing both land degradation and the use of resources, including water. [WGII 5.4.7]

A number of global-, national- and basin-scale adaptation assessments show that, in general, semi-arid and arid basins are most vulnerable with respect to water stress. If precipitation decreases, then demand for irrigation water would make it impossible to satisfy all other demands. Projected streamflow changes in the Sacramento-Joaquin and Colorado River Basins indicate that present-day water demand cannot be fulfilled by 2020, even with adaptive management practices. Increased irrigation usage would reduce both runoff and downstream flow (Eheart and Tornil, 1999). [WGII 3.5.1]

Policies aimed at rewarding improvements in irrigation efficiency, either through market mechanisms or increased regulations and improved governance, are an important tool for enhancing adaptation capacity at a regional scale. Unintended consequences may be increased consumptive water use upstream, resulting in downstream users being deprived of water that would otherwise have re-entered the stream as return flow (Huffaker, 2005). [WGII 3.5.1]

In addition to techniques already available to farmers and land managers today, new technical options need to be made available through dedicated research and development efforts, to be planned and implemented now, in order to augment overall capacity to respond to climate change in future decades. Technological options for enhanced R&D include traditional breeding and biotechnology for improved resistance to climate stresses such as drought and flooding in crop, forage, livestock, forest and fisheries species (Box 4.3).

Box 4.3: Will biotechnology assist agricultural and forest adaptation? [WGII Box 5.6]

Biotechnology and conventional breeding may help develop new cultivars with enhanced traits better suited to adapt to climate change conditions. These include drought and temperature stress resistance; resistance to pests and disease, salinity and waterlogging. Additional opportunities for new cultivars include changes in phenology or enhanced responses to elevated CO_2. With respect to water, a number of studies have documented genetic modifications to major crop species (e.g., maize and soybeans) that increased their water-deficit tolerance (as reviewed by Drennen et al., 1993; Kishor et al., 1995; Pilon-Smits et al., 1995; Cheikh et al., 2000), although this may not extend to the wider range of crop plants. In general, too little is currently known about how the desired traits achieved by genetic modification perform in real farming and forestry applications (Sinclair and Purcell, 2005).

4.2.4.3 Food security and vulnerability

All four dimensions of food security: namely, food availability (production and trade), access to food, stability of food supplies, and food utilisation (the actual processes involved in the preparation and consumption of food), are *likely* to be affected by climate change. Importantly, food security will depend not only on climate and socio-economic impacts on food production, but also (and critically so) on changes to trade flows, stocks, and food aid policy. In particular, climate change will result in mixed and geographically varying impacts on food production and, thus, access to food. Tropical developing countries, many of which have poor land and water resources and already face serious food insecurity, may be particularly vulnerable to climate change. [WGII 5.6.5]

Changes in the frequency and intensity of droughts and flooding will affect the stability of, and access to, critical food supplies. Rainfall deficits can dramatically reduce both crop yields and livestock numbers in the semi-arid tropics. Food insecurity and loss of livelihood would be further exacerbated by the loss of both cultivated land and coastal fish nurseries as a result of inundation and coastal erosion in low-lying areas. [WGII 5.6.5]

Climate change may also affect food utilisation through impacts on environmental resources, with important additional health consequences. [WGII Chapter 8] For example, decreased water availability in already water-scarce regions, particularly in the sub-tropics, has direct negative implications for both food processing and consumption. Conversely, the increased risk of flooding of human settlements in coastal areas from both rising sea levels and increased heavy precipitation may increase food contamination and disease, reducing consumption patterns. [WGII 5.6.5]

4.2.4.4 Water quality issues

In developing countries, the microbiological quality of water is poor because of the lack of sanitation, lack of proper treatment methods, and poor health conditions (Lipp et al., 2001; Jiménez, 2003; Maya et al., 2003; WHO, 2004). Climate change may impose additional stresses on water quality, especially in developing countries (Magadza, 2000; Kashyap, 2004; Pachauri, 2004). As yet there are no studies focusing on micro-organism life cycles relevant to developing countries under climate change, including a much-needed focus on the effects of poorly treated wastewater use for irrigation and its links to endemic outbreaks of *helminthiasis* (WHO/UNICEF, 2000). [WGII 3.4.4]

About 10% of the world's population consumes crops irrigated with untreated or poorly treated wastewater, mostly in developing countries in Africa, Asia and Latin America. This number is projected to grow with population and food demand. [WGII 8.2.5] Increased use of properly treated wastewater for irrigation is therefore a strategy to combat both water scarcity and some related health problems. [WGII 3.4.4]

4.2.4.5 Rural communities, sustainable development and water conflicts

Transboundary water co-operation is recognised as an effective policy and management tool to improve water management across large regions sharing common resources. Climate change and increased water demand in future decades will represent an added challenge to such framework agreements, increasing the potential for conflict at the local level. For instance, unilateral measures for adapting to climate-change-related water shortages can lead to increased competition for water resources. Furthermore, shifts in land productivity may lead to a range of new or modified agricultural systems, necessary to maintain production, including intensification practices. The latter, in turn, can lead to additional environmental pressures, resulting in loss of habitat and reduced biodiversity, siltation, soil erosion and soil degradation. [WGII 5.7]

Impacts on trade, economic, and environmental development and land use may also be expected from measures implemented to substitute fossil fuels through biofuels, such as by the European Biomass Action Plan. Large-scale biofuel production raises questions on several issues including fertiliser and pesticide requirements, nutrient cycling, energy balance, biodiversity impacts, hydrology and erosion, conflicts with food production, and the level of financial subsidies required. In fact, the emerging challenges of future decades include finding balance in the competition for land and raw materials for the food, forestry and energy sectors, e.g., devising solutions that ensure food and local rural development rights while maximising energy and climate mitigation needs. [LULUCF 4.5.1]

In North America, drought may increase in continental interiors and production areas may shift northwards (Mills, 1994), especially for maize and soybean production (Brklacich et al., 1997). [WGII TAR 15.2.3.1] In Mexico, production losses may be dominated by droughts, as agro-ecological zones suitable for maize cultivation decrease (Conde et al., 1997). [WGII TAR 14.2.2.1] Drought is an important issue throughout Australia for social, political, geographical and environmental reasons. A change in climate towards drier conditions as a result of lower rainfall and higher evaporative demand would trigger more frequent or longer drought declarations under current Australian drought policy schemes. [WGII TAR 12.5.6]

Water resources are a key vulnerability in Africa for household, agricultural and industrial uses. In shared river basins, regional co-operation protocols are needed to minimise both adverse impacts and the potential for conflicts. For instance, the surface area of Lake Chad varies from 20,000 km^2 during the dry season to 50,000 km^2 during the wet season. While precise boundaries have been established between Chad, Nigeria, Cameroon and Niger, sectors of these boundaries that are located in the rivers that drain into Lake Chad have never been determined, and additional complications arise as a result of both flooding and water recession. Similar problems on the Kovango River between Botswana and Namibia led to military confrontation. [WGII TAR 10.2.1.2]

Growing water scarcity, increasing population, degradation of shared freshwater ecosystems and competing demands for shrinking natural resources distributed over such a huge area involving so many countries have the potential for creating bilateral and multilateral conflicts. In semi-arid Africa, pastoralism is the main economic activity, with pastoral communities including transnational migrants in search of new seasonal grazing. In drought situations, such pastoralists may come into conflict with settled agrarian systems. [WGII TAR 10.2.1.2]

Asia dominates world aquaculture, with China alone producing about 70% of all farmed fish, shrimp and shellfish (FAO, 2006). Fish, an important source of food protein, is critical to food security in many countries of Asia, particularly among poor communities in coastal areas. Fish farming requires land and water, two resources that are already in short supply in many countries in Asia. Water diversion for shrimp ponds has lowered groundwater levels noticeably in coastal areas of Thailand. [WGII TAR 11.2.4.4]

At least 14 major international river watersheds exist in Asia. Watershed management is challenging in countries with high population density, which are often responsible for the use of even the most fragile and unsuitable areas in the watersheds for cultivation, residential, and other intensive activities. As a result, in many countries, in particular Bangladesh, Nepal, the Philippines, Indonesia and Vietnam, many watersheds suffer badly from deforestation, indiscriminate land conversion, excessive soil erosion and declining land productivity. In the absence of appropriate adaptation strategies, these watersheds are highly vulnerable to climate change. [WGII TAR 11.2.3.2]

4.2.4.6 Mitigation

Adaptation responses and mitigation actions may occur simultaneously in the agricultural and forestry sector; their efficacy will depend on the patterns of realised climate change in the coming decades. The associated interactions between these factors (climate change, adaptation and mitigation) will frequently involve water resources. [WGIII 8.5, Table 8.9]

Adaptation and mitigation strategies may either exhibit synergies, where both actions reinforce each other, or be mutually counter-productive. With respect to water, examples of adaptation strategies that reduce mitigation options largely involve irrigation, in relation to the energy costs of delivering water and the additional greenhouse gas emissions that may be associated with modified cultivation practices. Using renewables for water extraction and delivery could, however, eliminate such conflict. Likewise, some mitigation strategies may have negative adaptation consequences, such as increasing dependence on energy crops, which may compete for water resources, reduce biodiversity, and thus increase vulnerability to climatic extremes. [WGIII 12.1.4, 12.1.4]

On the other hand, many carbon-sequestration practices involving reduced tillage, increased crop cover and use of improved rotation systems, in essence constitute – and were in fact originally developed as – 'good-practice' agro-forestry, leading to production systems that are more resilient to climate variability, thus providing good adaptation in the face of increased pressure on water and soil resources (Rosenzweig and Tubiello, 2007). [WGII 5.4.2; WGIII 8.5]

4.3 Human health

4.3.1 Context

Human health, incorporating physical, social and psychological well-being, depends on an adequate supply of potable water and a safe environment. Human beings are exposed to climate change directly through weather patterns (more intense and frequent extreme events), and indirectly through changes in water, air, food quality and quantity, ecosystems, agriculture, livelihoods and infrastructure. [WGII 8.1.1] Due to the very large number of people that may be affected, malnutrition and water scarcity may be the most important health consequences of climate change (see Sections 4.2 and 4.4). [WGII 8.4.2.3]

Population health has improved remarkably over the last 50 years, but substantial inequalities in health persist within and between countries. The Millennium Development Goal (MDG) of reducing the mortality rate in children aged under 5 years old by two-thirds by 2015 is *unlikely* to be reached in some developing countries. Poor health increases vulnerability and reduces the capacity of individuals and groups to adapt to climate change. Populations with high rates of disease and disability cope less successfully with stresses of all kinds, including those related to climate change. [WGII 8.1.1]

The World Health Organization (WHO) and UNICEF Joint Monitoring Programme currently estimates that 1.1 billion people (17% of the global population) lack access to water resources, where access is defined as the availability of at least 20 litres of water per person per day from an improved water source within a distance of 1 km. An improved water source is one that provides 'safe' water, such as a household connection or a bore hole. Nearly two-thirds of the people without access are in Asia. In sub-Saharan Africa, 42% of the population is without access to improved water. The WHO estimates that the total burden of disease due to inadequate water supply, and poor sanitation and hygiene, is 1.7 million deaths per year. Health outcomes related to water supply and sanitation are a focal point of concern for climate change in many countries. In vulnerable regions, the concentration of risks from both food and water insecurity can make the impact of any weather extreme (for example, flood and drought) particularly severe for the households affected. [WGII 9.2.2]

Changes in climate extremes have the potential to cause severe impacts on human health. Flooding is expected to become more severe with climate change, and this will have implications for human health. Vulnerability to flooding is reduced when the infrastructure is in place to remove solid waste, manage waste water, and supply potable water. [WGII 8.2.2]

Lack of water for hygiene is currently responsible for a significant burden of disease worldwide. A small and unquantified proportion of this burden can be attributed to climate variability or climate extremes. 'Water scarcity' is associated with multiple adverse health outcomes, including diseases associated with water contaminated with faecal and other hazardous substances (e.g., parasites).

Childhood mortality and morbidity due to diarrhoea in low-income countries, especially in sub-Saharan Africa, remains high despite improvements in care and the use of oral rehydration therapy. Climate change is expected to increase water scarcity, but it is difficult to assess what this means at the household level for the availability of water, and therefore for health and hygiene. There is a lack of information linking large-scale modelling of climate change to small-scale impacts at the population or household level. Furthermore, any assessments of future health impacts via changes in water availability need to take into account future improvements in access to 'safe' water. [WGII 8.2.5, 8.4.2.2]

4.3.1.1 Implications for drinking-water quality

The relationship between rainfall, river flow and contamination of the water supply is highly complex, as discussed below both for piped water supplies and for direct contact with surface waters. If river flows are reduced as a consequence of less rainfall, then their ability to dilute effluent is also reduced – leading to increased pathogen or chemical loading. This could represent an increase in human exposures or, in places with piped water supplies, an increased challenge to water treatment plants. During the dry summer of 2003, low flows in the Netherlands resulted in apparent changes in water quality (Senhorst and Zwolsman, 2005). The marked seasonality of cholera outbreaks in the Amazon was associated with low river flow in the dry season (Gerolomo and Penna, 1999), probably due to high pathogen concentrations in pools. [WGII 8.2.5]

Drainage and storm water management is important in low-income urban communities, as blocked drains can cause flooding and increased transmission of vector-borne diseases (Parkinson and Butler, 2005). Cities with combined sewer overflows can experience increased sewage contamination during flood events. [WGII 8.2.5]

In high-income countries, rainfall and runoff events may increase the total microbial load in watercourses and drinking-water reservoirs, although the linkage to cases of human disease is less certain because the concentration of contaminants is diluted. The seasonal contamination of surface water in early spring in North America and Europe may explain some of the seasonality in sporadic cases of water-borne diseases such as *cryptosporidiosis* and *campylobacteriosis*. A significant proportion of notified water-borne disease outbreaks are related to heavy precipitation events, often in conjunction with treatment failures. [WGII 14.2.5, 8.2.5]

Freshwater harmful algal blooms (HABs) produce toxins that can cause human diseases. The occurrence of such blooms in surface waters (rives and lakes) may increase due to higher temperatures. However, the threat to human health is very low, as direct contact with blooms is generally restricted. There is a low risk of contamination of water supplies with algal toxins but the implications for human health are uncertain. [WGII 8.2.4, 3.4.4]

In areas with poor water supply infrastructure, the transmission of enteric pathogens peaks during the rainy season. In addition, higher temperatures were found to be associated with increased episodes of diarrhoeal disease (Checkley et al., 2000; Singh et al., 2001; Vasilev, 2003; Lama et al., 2004). The underlying incidence of these diseases is associated with poor hygiene and lack of access to safe water. [WGII 8.2.5]

4.3.1.2 Disasters, including wind storms and floods

The previous sections have described how climate change will affect the risk of water-related disasters, including glacial lake outburst floods (GLOFs), increased storm surge intensity, and changes in flood risk (see Section 3.2) including flash flooding and urban flooding, with some reductions in risk of spring snowmelt floods. [WGII 3.4.3] Floods have a considerable impact on health both in terms of number of deaths and disease burden, and also in terms of damage to the health infrastructure. [WGII 8.2.2] While the risk of infectious disease following flooding is generally low in high-income countries, populations with poor infrastructure and high burdens of infectious disease often experience increased rates of diarrhoeal diseases after flood events. There is increasing evidence of the impact that climate-related disasters have on mental health, with people who have suffered the effects of floods experiencing long-term anxiety and depression. [WGII 8.2.2, 16.4.5]

Flooding and heavy rainfall may lead to contamination of water with chemicals, heavy metals or other hazardous substances, either from storage or from chemicals already in the environment (e.g., pesticides). Increases in both population density and industrial development in areas subject to natural disasters increase both the probability of future disasters and the potential for mass human exposure to hazardous materials during these events. [WGII 8.2.2]

4.3.1.3 Drought and infectious disease

For a few infectious diseases, there is an established rainfall association that is not related to the consumption of drinking-water (quality or quantity) or arthropod vectors. The spatial distribution, intensity and seasonality of meningococcal (epidemic) *meningitis* in the Sahelian region of Africa is related to climatic and environmental factors, particularly drought, although the causal mechanism is not well understood. The geographical distribution of *meningitis* has expanded in West Africa in recent years, which may be attributable to environmental change driven both by land-use changes and by regional climate change. [WGII 8.2.3.1]

4.3.1.4 Dust storms

Windblown dust originating in desert regions of Africa, the Arabian Peninsula, Mongolia, central Asia and China can affect air quality and population health in distant areas. When compared with non-dust weather conditions, dust can carry large concentrations of respirable particles; trace elements that can affect human health; fungal spores; and bacteria. [WGII 8.2.6.4]

4.3.1.5 Vector-borne diseases

Climate influences the spatial distribution, intensity of transmission, and seasonality of diseases transmitted by vectors (e.g., malaria) and diseases that have water snails as an intermediate host (e.g., *schistosomiasis*). [WGII 8.2.8] During droughts, mosquito activity is reduced but, if transmission drops significantly, the population of non-immune individuals may increase. In the long term, the incidence of mosquito-borne diseases such as malaria decreases because mosquito abundance is reduced, although epidemics may still occur when suitable climate conditions occur. [WGII 8.2.3.1]

The distribution of *schistosomiasis*, a water-related parasitic disease with aquatic snails as intermediate hosts, is influenced by climate factors in some locations, For example, the observed change in the distribution of *schistosomiasis* in China over the past decade may in part reflect the recent warming trend. Irrigation schemes have also been shown to increase the incidence of *schistosomiasis*, when appropriate control measures are not implemented. [WGII 8.2.8.3]

4.3.2 Observations

There is a wide range of driving forces that can affect and modify the impact of climate change on human health outcomes. Because of the complexity of the association between climate factors and disease, it is often not possible to attribute changes in specific disease patterns to observed climate changes. Furthermore, health data series of sufficient quality and length are rarely available for such studies. There are no published studies of water-related impacts on health that describe patterns of disease that are robustly attributed to observed climate change. However, there are several reports of adaptive responses in the water sector designed to reduce the impacts of climate change. [WGII Chapter 7]

Observed trends in water-related disasters (floods, wind storms) and the role of climate change are discussed elsewhere. [WGII 1.3]

4.3.3 Projections

Climate change is expected to have a range of adverse effects on populations where the water and sanitation infrastructure is inadequate to meet local needs. Access to safe water remains an extremely important global health issue. More than two billion people live in the dry regions of the world, and these people suffer more than others from malnutrition, infant mortality and diseases related to contaminated or insufficient water. Water scarcity constitutes a serious constraint to sustainable development (Rockstrom, 2003). [WGII 8.2.5, 8.4.2.2]

4.3.4 Adaptation, vulnerability and sustainable development

Weak public health systems and limited access to primary health care contribute both to high levels of vulnerability and to low adaptive capacity for hundreds of millions of people. [WGII 8.6] Fundamental constraints exist in low-income countries, where population health will depend upon improvements in the health, water, agriculture, transport, energy and housing sectors. Poverty and weak governance are the most serious obstacles to effective adaptation. Despite economic growth, low-income countries are *likely* to remain vulnerable over the medium term, with fewer options than high-income countries for adapting to climate change. Therefore, if adaptation strategies are to be effective, they should be designed in the context of the development, environment and health policies in place in the target area. Many options that can be used to reduce future vulnerability are of value in adapting to current climate, and can also be used to achieve other environmental and social objectives. [WGII 8.6.3]

The potential adverse health effects of any adaptation strategy should be evaluated before that strategy is implemented. For example, a micro-dam and irrigation programmes have been shown to increase local malaria mortality. [WGII 8.6.4] Measures to combat water scarcity, such as the reuse of untreated or partially treated wastewater for irrigation, also have implications for human health. Irrigation is currently an important determinant of the spread of infectious diseases such as malaria and *schistosomiasis* (Sutherst, 2004). Strict water-quality guidelines for wastewater irrigation are designed to prevent health risks from pathogenic organisms, and to guarantee crop quality (Steenvoorden and Endreny, 2004). Some diseases, such as *helminthiasis*, are transmitted by consuming crops irrigated with polluted water or wastewater and, in the rural and peri-urban areas of most low-income countries, the use of sewage and wastewater for irrigation, a common practice, is a source of faecal–oral disease transmission. At present, at least one-tenth of the world’s population consumes crops irrigated with wastewater. However, increasing water scarcity and food demand, coupled with poor sanitation, will facilitate the use of low-quality water. If such problems are to be controlled, then programmes of wastewater treatment and planned wastewater reuse need to be developed. [WGII 8.6.4, 3.4.4]

4.4 Water supply and sanitation

The observed effects of climate change on water resource quantity and quality have been discussed in detail in Sections 4.2 and 4.3. This section summarises the main points and describes their implications for water supply and sanitation services.

4.4.1 Context

Statistics on present-day access to safe water have already been provided in Section 4.3.1. Access to safe water is now regarded as a universal human right. However, the world is facing increasing problems in providing water services, particularly in developing countries. There are several reasons for this, which are not necessarily linked to climate change. A lack of available water, a higher and more uneven water demand resulting from population growth in concentrated areas, an increase in urbanisation, more intense use of water to improve general well-being, and the challenge to improve water governance, are variables that already pose a tremendous challenge to providing satisfactory water services. In this context, climate change simply represents an additional burden for water utilities, or any other organisation providing water services, in meeting customers’ needs. It is difficult to identify climate change effects at a local level, but the observed effects combined with projections provide a useful basis to prepare for the future.

4.4.2 Observations

Table 4.1 summarises possible linkages between climate change and water services.

Table 4.1: Observed effects of climate change and its observed/possible impacts on water services. [WGII Chapter 3]

Observed effect	Observed/possible impacts
Increase in atmospheric temperature	• Reduction in water availability in basins fed by glaciers that are shrinking, as observed in some cities along the Andes in South America (Ames, 1998; Kaser and Osmaston, 2002)
Increase in surface water temperature	• Reductions in dissolved oxygen content, mixing patterns, and self purification capacity • Increase in algal blooms
Sea-level rise	• Salinisation of coastal aquifers
Shifts in precipitation patterns	• Changes in water availability due to changes in precipitation and other related phenomena (e.g., groundwater recharge, evapotranspiration)
Increase in interannual precipitation variability	• Increases the difficulty of flood control and reservoir utilisation during the flooding season
Increased evapotranspiration	• Water availability reduction • Salinisation of water resources • Lower groundwater levels
More frequent and intense extreme events	• Floods affect water quality and water infrastructure integrity, and increase fluvial erosion, which introduces different kinds of pollutants to water resources • Droughts affect water availability and water quality

4.4.3 Projections

Reduced water availability may result from:
a. decreased flows in basins fed by shrinking glaciers and longer and more frequent dry seasons,
b. decreased summer precipitation leading to a reduction of stored water in reservoirs fed with seasonal rivers (du Plessis et al., 2003),
c. interannual precipitation variability and seasonal shifts in streamflow,
d. reductions in inland groundwater levels,
e. the increase in evapotranspiration as a result of higher air temperatures, lengthening of the growing season and increased irrigation water usage,
f. salinisation (Chen et al., 2004).

According to projections, the number of people at risk from increasing water stress will be between 0.4 billion and 1.7 billion by the 2020s, between 1.0 billion and 2.0 billion by the 2050s and between 1.1 billion and 3.2 billion by the 2080s (Arnell, 2004), the range being due to the different SRES scenarios considered. [WGII 3.2, 3.5.1]

In some areas, low water availability will lead to groundwater over-exploitation and, with it, increasing costs of supplying water for any use as a result of the need to pump water from deeper and further away. Additionally, groundwater over-exploitation may lead in some cases to water quality deterioration. For some regions of India, Bangladesh, China, north Africa, Mexico and Argentina, there are more than 100 million people suffering from arsenic poisoning and fluorosis (a disease of the teeth or bones caused by excessive consumption of fluoride in drinking water) (UN, 2003); this can result in an even worse situation if people are forced to use more water from groundwater as a result of the lack of reliable surface water sources. [WGII 3.4.4]

Increasing water scarcity combined with increased food demand and/or water use for irrigation as a result of higher temperatures are *likely* to lead to enhanced water reuse. Areas with low sanitation coverage might be found to be practising (as a new activity or to a greater degree) uncontrolled water reuse (reuse that is performed using polluted water or even wastewater). [WGII 3.3.2, 8.6.4]

Water quality deterioration as result of flow variation. Where a reduction in water resources is expected, a higher water pollutant concentration will result from a lower dilution capacity. [WGII 3.4.4, 14.4.1] At the same time, increased water flows will displace and transport diverse compounds from the soil to water resources through fluvial erosion. [WGII 3.4]

Similarly, an increase in morbidity and mortality rates from water-borne diseases for both more humid and drier scenarios is expected, owing to an insufficient supply of potable water (Kovats et al., 2005; Ebi et al., 2006), and the greater presence of pathogens conveyed by high water flows during extreme precipitation. Increased precipitation may also result in higher turbidity and nutrient loadings in water. The water utility of New York City has identified heavy precipitation events as one of its major climate-change-related concerns because they can raise turbidity levels in some of the city's main reservoirs by up to 100 times the legal limit for source quality at the utility's intakes, requiring substantial additional treatment and monitoring costs (Miller and Yates, 2006). [WGII 3.5.1]

Increased runoff. In some regions, more water will be available which, considering the present global water situation, will be generally beneficial. Nevertheless, provisions need to be made to use this to the world's advantage. For example, while increased runoff in eastern and southern Asia is expected as a result of climate change, water shortages in these areas may not be addressed, given a lack of resources for investing in the new storage capacity required to capture the additional water and to enable its use during the dry season. [WGII 3.5.1]

Higher precipitation in cities may affect the performance of sewer systems; uncontrolled surcharges may introduce microbial and chemical pollutants to water resources that are difficult to handle through the use of conventional drinking-water treatment processes. Several studies have shown that the transmission of enteric pathogens resistant to chlorination, such as *Cryptosporidium*, is high during the rainy season (Nchito et al., 1998; Kang et al., 2001). This is a situation that could be magnified in developing countries, where health levels are lower and the pathogen content in wastewater is higher (Jiménez, 2003). In addition, extreme precipitation leading to floods puts water infrastructure at risk. During floods, water and wastewater treatment facilities are often out of service, leaving the population with no sanitary protection. [WGII 3.2, 3.4.4, 8.2.5]

Water quality impairment as result of higher temperatures. Warmer temperatures, combined with higher phosphorus concentrations in lakes and reservoirs, promote algal blooms that impair water quality through undesirable colour, odour and taste, and possible toxicity to humans, livestock and wildlife. Dealing with such polluted water has a high cost with the available technology, even for water utilities from developed countries (Environment Canada, 2001). Higher water temperatures will also enhance the transfer of volatile and semi-volatile pollutants (ammonia, mercury, PCBs (polychlorinated biphenyls), dioxins, pesticides) from water and wastewater to the atmosphere. [WGII 3.4.4]

Increased salinisation. The salinisation of water supplies from coastal aquifers due to sea-level rise is an important issue, as around one-quarter of the world's population live in coastal regions that are generally water-scarce and undergoing rapid population growth (Small and Nicholls, 2003; Millennium Ecosystem Assessment, 2005b). Salinisation can also affect inland aquifers due to a reduction in groundwater recharge (Chen et al., 2004). [WGII 3.2, 3.4.2]

The populations that will be most affected by climate change with respect to water services are those located in the already water-stressed basins of Africa, the Mediterranean region, the Near East, southern Asia, northern China, Australia, the USA, central and northern Mexico, north-eastern Brazil and the west coast of South America. Those particularly at risk will be populations living in megacities, rural areas strongly dependent on groundwater, small islands, and in glacier- or snowmelt-fed basins (more than one-sixth of the world's population live in snowmelt basins). Problems will be more critical in economically depressed areas, where water stress will be enhanced by socio-economic factors (Alcamo and Henrichs, 2002; Ragab and Prudhomme, 2002). [WGII 3.3.2, 3.5.1]

4.4.4 Adaptation, vulnerability and sustainable development

Given the problems envisaged above, it is important for water utilities located in regions at risk to plan accordingly. Most water supply systems are well able to cope with the relatively small changes in mean temperature and precipitation that are projected to occur in the decades ahead, except at the margin where a change in the mean requires a change in the system design or the technology used; e.g., where reduced precipitation makes additional reservoirs necessary (Harman et al., 2005), or leads to saline intrusion into the lower reaches of a river, or requires new water treatment systems to remove salts. A recent example of adaptation is in southern Africa (Ruosteenoja et al. 2003), where the city of Beira in Mozambique is already extending its 50 km pumping main a further 5 km inland to be certain of fresh water. [WGII 7.4.2.3.1]

Water services are usually provided using engineered systems. These systems are designed using safety factors and have a life expectancy of 20–50 years (for storage reservoirs it can be even longer). Reviews of the resilience of water supplies and the performance of water infrastructure have typically been done by using observed conditions alone. The use of climate projections should also be considered, especially in cases involving systems that deal with floods and droughts.

Decrease in water availability. Except for a few industrialised countries, water use is increasing around the world due to population and economic growth, lifestyle changes and expanded water supply systems. [WGII 3.3] It is important to implement efficient water-use programmes in regions where water availability is *likely* to decrease, as large investments might be required to ensure adequate supplies, either by building new storage reservoirs or by using alternative water sources. Reductions in water use can delay, or even eliminate, the need for additional infrastructure. One of the quickest ways to increase water availability is through minimising water losses in urban networks and in irrigation systems. Other alternatives for reducing the need for new water supplies include rainwater harvesting as well as controlled reuse. [WGII 3.5, 3.6]

Lower water quality caused by flow variations. The protection of water resources is an important, cost-effective strategy for facing future problems concerning water quality. While this is a common practice for some countries, new and innovative approaches to water quality management are required around the world. One such approach is the implementation of water safety plans (WSP) to perform a comprehensive assessment and management of risks from the catchment to consumer, as proposed by the WHO (2005). Also, the design and operation of water and wastewater treatment plants should be reviewed periodically, particularly in vulnerable areas, to ensure or increase their reliability and their ability to cope with uncertain flow variations.

Desalinisation. Water treatment methods are an option for dealing with increasing salt content in places at risk, such as highly urbanised coastal areas relying on aquifers sensitive to saline intrusion. At present, available technologies are based mostly on membranes and are more costly than conventional methods for the treatment of freshwater supplies. The desalination cost for seawater is estimated at around US\$1/m^3, for brackish water it is US\$0.60/m^3 (Zhou and Tol, 2005), and freshwater chlorination costs US\$0.02/m^3. Fortunately the cost of desalinisation has been falling, although it still has a high energy demand. Desalinisation costs need to be compared with the costs of extending pipelines and eventually relocating water treatment works in order to have access to freshwater. As a rough working rule, the cost of construction of the abstraction and treatment works and the pumping main for an urban settlement's water supply is about half the cost of the entire system. [WGII 7.5] However, in the densely populated coastal areas of Egypt, China, Bangladesh, India and south-east Asia, desalination costs may still be prohibitive. [WGII 3.5.1] If the use of desalination increases in the future, environmental side-effects such as impingement on and entrainment of marine organisms by seawater desalination plants, and the safe disposal of highly concentrated brines that can also contain other chemicals, will need to be addressed. [WGII 3.3.2]

More and different approaches for coping with wastewater. For sewers and wastewater treatment plants, strategies for coping with higher and more variable flows will be needed. These should include new approaches such as the use of decentralised systems, the construction of separate sewers, the treatment of combined sewer overflows (i.e., the mixture of wastewater and runoff in cities), and injecting rainwater into the subsoil. Given the high cost involved in increasing the capacity of urban wastewater treatment plants, appropriately financed schemes should be put in place to consider local conditions. For rural areas, sanitation coverage is generally too low, and local action plans need to be formulated using low-cost technologies, depending on the locality and involving the community. [WGII 7.4.2.3]

Better administration of water resources. As well as considering the adaptation measures already discussed, integrated water management, including climate change as an additional variable, should be considered as an efficient tool. Reduced, increased or a greater variability in water availability will lead to conflicts between water users (agriculture, industries, ecosystems and settlements). The institutions governing water allocation will play a major role in determining the overall social impact of a change in water availability, as well as the distribution of gains and losses across different sectors of society. Institutional settings need to find better ways to allocate water, using principles – such as equity and efficiency – that may be politically difficult to implement in practice. These settings also need to consider the management of international basins and surface and groundwater basins. [WGII 3.5.1]

To confront the additional stress induced by climate change, public participation in water planning will be necessary, particularly in regard to changing views on the value of water, the importance and role that water reuse will play in the future, and the contribution that society is willing to make to the mitigation of water-related impacts.

To implement policy based on the principles of integrated water management, better co-ordination between different governmental entities should be sought, and institutional and legal frameworks should be reviewed to facilitate the implementation of adaptation measures. Climate change will be felt by all stakeholders involved in the water management process, including users. Therefore, all should be aware of its possible impacts on the system in order to take appropriate decisions and be prepared to pay the costs involved. In the case of wastewater disposal norms, for example, the overall strategy used will possibly need to be reviewed, as long as it is based on the self-purification capacity of surface water, which will be reduced by higher temperatures. [WGII 3.4.4]

Developed countries. In developed countries, drinking-water receives extensive treatment before it is supplied to the consumer and the wastewater treatment level is high. Such benefits, as well as proper water source protection, need to be maintained under future climatic change, even if additional cost is to be incurred, for instance by including additional water treatment requirements. For small communities or rural areas, measures to be considered may include water source protection as a better cost–benefit option.

Developing countries. Unfortunately, some countries may not have sufficient economic resources to face the challenges posed by climate change. Poor countries already need additional resources to overcome problems with inadequate infrastructure, and thus they will be more vulnerable to projected impacts on water quantity and quality, unless low-cost options and affordable finance options are available.

Because several of the already identified adaptation and mitigation options are simply not viable, it is expected that developing countries may have to adapt by using unsustainable practices such as increasing groundwater over-exploitation or reusing a greater amount of untreated wastewater. These 'solutions' are attractive because they can easily be implemented at an individual, personal, level. Therefore, low-cost and safe options which do not necessarily imply conventional solutions need to be developed, particularly to provide water services for poor communities that do not even have formal water utilities in many instances. Unfortunately, there are few studies available on this issue. [WGII 3.4.3, 8.6.4]

In summary, climate change can have positive and negative impacts on water services. It is important, therefore, to be aware of its consequences at a local level and to plan accordingly. At the present time, only some water utilities in a few countries, including the Netherlands, the UK, Canada and the USA, have begun to consider the implications of climate change in the context of flood control and water supply management. [WGII 3.6]

4.5 Settlements and infrastructure

Changes in water availability, water quality, precipitation characteristics, and the likelihood and magnitude of flooding events are expected to play a major role in driving the impacts of climate change on human settlements and infrastructure (Shepherd et al., 2002; Klein et al., 2003; London Climate Change Partnership, 2004; Sherbinin et al., 2006). These impacts will vary regionally. In addition, impacts will depend greatly on the geophysical setting, level of socio-economic development, water allocation institutions, nature of the local economic base, infrastructure characteristics and other stressors. These include pollution, ecosystem degradation, land subsidence (due either to loss of permafrost, natural isostatic processes, or human activities such as groundwater use) and population growth (UNWWAP, 2003, 2006; Faruqui et al., 2001; UNDP, 2006). Globally, locations most at risk of freshwater supply problems due to climate change are small islands, arid and semi-arid developing countries, regions whose freshwater is supplied by rivers fed by glacial melt or seasonal snowmelt, and countries with a high proportion of coastal lowlands and coastal megacities, particularly in the Asia–Pacific region (Alcamo and Henrichs, 2002; Ragab and Prudhomme, 2002). [WGII 6.4.2, 20.3]

Growing population density in high-risk locations, such as coastal and riverine areas, is *very likely* to increase vulnerability to the water-related impacts of climate change, including flood and storm damages and water quality degradation as a result of saline intrusion. [WGII 6.4.2, 7.4.2.4] Settlements whose economies are closely linked to a climate-sensitive water-dependent activity, such as irrigated agriculture, water-related tourism and snow skiing, are *likely* to be especially vulnerable to the water resource impacts of climate change (Elsasser and Burki, 2002; Hayhoe et al., 2004). [WGII 7.4.3, 12.4.9]

Infrastructure associated with settlements includes buildings, transportation networks, coastal facilities, water supply and wastewater infrastructure, and energy facilities. Infrastructure impacts include both direct damages, for example as a result of flood events or structural instabilities caused by rainfall erosion or changes in the water table, as well as impacts on the performance, cost and adequacy of facilities that were not designed for the climate conditions projected to prevail in the future. [WGII 3.4.3, 3.5, 7.4.2.3]

4.5.1 Settlements

Many human settlements currently lack access to adequate, safe water supplies. The World Health Organization estimates that 1.1 billion people worldwide do not have access to safe drinking water, and 2.4 billion are without access to adequate sanitation (WHO/UNICEF, 2000). Poor urban households frequently do not have networked water supply access, and thus are especially vulnerable to rising costs for drinking water (UN-HABITAT, 2003; UNCHS, 2003, 2006; UNDP, 2006). For example, in Jakarta, some households without regular water service reportedly spend up to 25% of their income on water and, during the hot summer of 1998 in Amman, Jordan, refugee-camp residents who were not connected to the municipal water system paid much higher rates for water than other households (Faruqui et al., 2001). The impacts of climate change on water availability and source water quality are *very likely* to make it increasingly difficult to address these problems, especially in areas where water stress is projected to increase due to declining runoff coupled with increasing population. [WGII 3.5.1] Rapidly growing settlements in semi-arid areas of developing countries, particularly poor communities that have limited adaptive capacity, are especially vulnerable to declines in water availability and associated increases in the costs of securing reliable supplies (Millennium Ecosystem Assessment, 2005b). [WGII 7.4]

In both developed and developing countries, the expected continuation of rapid population growth in coastal cities will increase human exposure to flooding and related storm damages from hurricanes and other coastal storms. [WGII 7.4.2.4] That very development is contributing to the loss of deltaic wetlands that could buffer the storm impacts. [WGII 6.4.1.2] In addition, much of the growth is occurring in relatively water-scarce coastal areas, thus exacerbating imbalances between water demand and availability (Small and Nicholls, 2003; Millennium Ecosystem Assessment, 2005b).

4.5.2 Infrastructure

4.5.2.1 Transportation networks

Flooding due to sea-level rise and increases in the intensity of extreme weather events (such as storms and hurricanes) pose threats to transportation networks in some areas. These include localised street-flooding, flooding of subway systems, and flood and landslide-related damages to bridges, roads and railways. For example, in London, which has the world's oldest subway system, more intense rainfall events are predicted to increase the risk of flooding in the Underground and highways. This would necessitate improvements in the drainage systems of these networks (Arkell and Darch, 2006). Similarly, recent research on the surface transportation system of the Boston Metropolitan Area has predicted that increased flooding will cause increased trip delays and cancellations, which will result in lost work-days, sales and production (Suarez et al., 2005). However, those costs would be small in comparison to flood-related damages to Boston's transportation infrastructure (Kirshen et al., 2006). [WGII 7.4.2.3.3] An example of present-day vulnerability that could be exacerbated by increased precipitation intensity is the fact that India's Konkan Railway annually suffers roughly US$1 million in damages due to landslides during the rainy season (Shukla et al., 2005). [WGII 7.4.2.3.3]

4.5.2.2 Built environment

Flooding, landslides and severe storms (such as hurricanes) pose the greatest risks for damages to buildings in both developed and developing countries, because housing and other assets are increasingly located in coastal areas, on slopes, in ravines and other risk-prone sites (Bigio, 2003; UN-HABITAT, 2003). Informal settlements within urban areas of developing-country cities are especially vulnerable, as they tend to be built on relatively hazardous sites that are susceptible to floods, landslides and other climate-related disasters (Cross, 2001; UN-HABITAT, 2003). [WGII 7.4.2.4]

Other impacts on buildings include the potential for accelerated weathering due to increased precipitation intensity and storm frequency (e.g., Graves and Phillipson, 2000), and increased structural damage due to water table decline and subsidence (e.g., Sanders and Phillipson, 2003), or due to the impacts of a rising water table (Kharkina, 2004). [WGII 3.5]

Another area of concern is the future performance of storm-water drainage systems. In regions affected by increasingly intense storms, the capacity of these systems will need to be increased to prevent local flooding and the resulting damages to buildings and other infrastructure (UK Water Industry Research, 2004). [WGII 7.6.4]

4.5.2.3 Coastal infrastructure

Infrastructure in low-lying coastal areas is vulnerable to damage from sea-level rise, flooding, hurricanes and other storms. The stock of coastal infrastructure at risk is increasing rapidly as a result of the continuing growth of coastal cities and expanding tourism in areas such as the Caribbean (e.g., Hareau et al., 1999; Lewsey et al., 2004; Kumar, 2006). In some areas, damage costs due to an increase in sea level have been estimated, and are often substantial. For example, in Poland, estimated damage costs due to a possible rise in sea level of 1 metre by 2100 are US$30 billion, due to impacts on urban areas, sewers, ports and other infrastructure (Zeidler, 1997). The same study estimated that a projected 1 metre rise in sea level in Vietnam would subject 17 million people to flooding and cause damages of up to US$17 billion, with substantial impacts penetrating inland beyond the coastal zone. [WGII 6.3, 6.4, 6.5]

4.5.2.4 Energy infrastructure

Hydrological changes will directly affect the potential output of hydro-electric facilities – both those currently existing and possible future projects. There are large regional differences in the extent of hydropower development. In Africa, where little of the continent's hydropower potential has been developed, climate change simulations for the Batoka Gorge hydro-electric scheme on the Zambezi River projected a significant reduction in river flows (e.g., a decline in mean monthly flow from 3.21×10^9 m^3 to 2.07×10^9 m^3) and declining power production (e.g., a decrease in mean monthly production from 780 GWh to 613 GWh) (Harrison and Whittington, 2002). A reduction in hydro-electric power is also anticipated elsewhere, where and when river flows are expected to decline (e.g., Whittington and Gundry, 1998; Magadza, 2000). In some other areas, hydro-electric generation is projected to increase. For example, estimates for the 2070s, under the IS92a emissions scenario, indicate that the electricity production potential of hydropower plants existing at the end of the 20th century would increase by 15–30% in Scandinavia and northern Russia, where between 19% (Finland) and almost 100% (Norway) of the electricity is produced by hydropower (Lehner et al., 2005). [WGII 3.5] Other energy infrastructure, such as power transmission lines, offshore drilling rigs and pipelines, may be vulnerable to damage from flooding and more intense storm events. [WGII 7.5] In addition, problems with cooling water availability (because of reduced quantity or higher water temperature) could disrupt energy supplies by adversely affecting energy production in thermal and nuclear power plants (EEA, 2005).

4.5.3 Adaptation

The impacts of changes in the frequency of floods and droughts or in the quantity, quality or seasonal timing of water availability could be tempered by appropriate infrastructure investments, and by changes in water and land-use management. Co-ordinated planning may be valuable because there are many points at which impacts on the different infrastructures interact. For instance, the failure of flood defences can interrupt power supplies, which in turn puts water and wastewater pumping stations out of action.

Improved incorporation of current climate variability into water-related management would make adaptation to future climate change easier (*very high confidence*). [WGII 3.6] For example, managing current flood risks by maintaining green areas and natural buffers around streams in urban settings would also help to reduce the adverse impacts of future heavier storm runoff. However, any of these responses will entail costs, not only in monetary terms but also in terms of societal impacts, including the need to manage potential conflicts between different interest groups. [WGII 3.5]

4.6 Economy: insurance, tourism, industry, transportation

4.6.1 Context

Climate and water resources impact on several secondary and tertiary sectors of the economy such as insurance, industry, tourism and transportation. Water-related effects of climate change in these sectors can be positive as well as negative, but extreme climate events and other abrupt changes tend to affect human systems more severely than gradual change, partly because they offer less time for adaptation. [WGII 7.1.3]

Global losses reveal rapidly rising costs due to extreme weather-related events since the 1970s. One study has found that, while the dominant signal remains that of the significant increases in the values of exposure at risk, once losses are normalised for exposure, there still remains an underlying rising trend. For specific regions and perils, including the most extreme floods on some of the largest rivers, there is evidence for an increase in occurrence. [WGII 1.3.8.5]

To demonstrate the large impact of climate variability on insurance losses, flooding is responsible for 10% of weather-related insurance losses globally. Drought also has an impact: data from the UK show a lagged relationship between the cost of insurance claims related to subsidence and (low) summer rainfall. However, in developing countries, losses due to extreme events are measured more in terms of human life than they are in terms of insurance. For example, the Sahelian drought, despite its high severity, had only a small impact on the formal financial sector, due to the low penetration of insurance. [WGII TAR 8.2.3]

4.6.2 Socio-economic costs, mitigation, adaptation, vulnerability, sustainable development

Of all the possible water-related impacts on transportation, the greatest cost is that of flooding. The cost of delays and lost trips is relatively small compared with damage to the infrastructure and to other property (Kirshen et al., 2006). In the last 10 years, there have been four cases when flooding of urban underground rail systems has caused damages of more than €10 million (US$13 million) and numerous cases of lesser damage (Compton et al., 2002). [WGII 7.4.2.3.3]

Industrial sectors are generally thought to be less vulnerable to the impacts of climate change than such sectors as agriculture. Among the major exceptions are industrial facilities located in climate-sensitive areas (such as floodplains) (Ruth et al., 2004) and those dependent on climate-sensitive commodities such as food-processing plants. [WGII 7.4.2.1]

The specific insurance risk coverage currently available within a country will have been shaped by the impact of past catastrophes. Because of the high concentration of losses due to catastrophic floods, private-sector flood insurance is generally restricted (or even unavailable) so that, in several countries, governments have developed alternative state-backed flood insurance schemes (Swiss Re, 1998). [WGII 7.4.2.2.4]

For the finance sector, climate-change-related risks are increasingly considered for specific 'susceptible' sectors such as hydro-electric projects, irrigation and agriculture, and tourism (UNEP/GRID-Arendal, 2002). [WGII 7.4.2.2]

Effects of climate change on tourism include changes in the availability of water, which could be positive or negative (Braun et al., 1999; Uyarra et al., 2005). Warmer climates open up the possibility of extending exotic environments (such as palm trees in western Europe), which could be considered by some tourists as positive but could lead to a spatial extension and amplification of water- and vector-borne diseases. Droughts and the extension of arid environments (and the effects of extreme weather events) might discourage tourists, although it is not entirely clear what they consider to be unacceptable. [WGII 7.4.2.2.3] Areas dependent on the availability of snow (e.g., for winter tourism) are among those most vulnerable to global warming. [WGII 11.4.9, 12.4.9, 14.4.7]

Transportation of bulk freight by inland waterways, such as the Rhine, can be disrupted during floods and droughts (Parry, 2000). [WGII 7.4.2.2.2]

Insurance spreads risk and assists with adaptation, while managing insurance funds has implications for mitigation. [WGII 18.5] Adaptation costs and benefits have been assessed in a more limited manner for transportation infrastructure (e.g., Dore and Burton, 2001). [WGII 17.2.3]

5

Analysing regional aspects of climate change and water resources

5.1 Africa

5.1.1 Context

Water is one of several current and future critical issues facing Africa. Water supplies from rivers, lakes and rainfall are characterised by their unequal natural geographical distribution and accessibility, and unsustainable water use. Climate change has the potential to impose additional pressures on water availability and accessibility. Arnell (2004) described the implications of the IPCC's SRES scenarios for a river-runoff projection for 2050 using the HadCM3[20] climate model. These experiments indicate a significant decrease in runoff in the north and south of Africa, while the runoff in eastern Africa and parts of semi-arid sub-Saharan Africa is projected to increase. However, multi-model results (Figures 2.8 and 2.9) show considerable variation among models, with the decrease in northern Africa and the increase in eastern Africa emerging as the most robust responses. There is a wide spread in projections of precipitation in sub-Saharan Africa, with some models projecting increases and others decreases. Projected impacts should be viewed in the context of this substantial uncertainty. [WGI 11.2, Table 11.1; WGII 9.4.1]

By 2025, water availability in nine countries[21], mainly in eastern and southern Africa, is projected to be less than 1,000 m^3/person/yr. Twelve countries[22] would be limited to 1,000–1,700 m^3/person/yr, and the population at risk of water stress could be up to 460 million people, mainly in western Africa (UNEP/GRID-Arendal, 2002).[23] These estimates are based on population growth rates only and do not take into account the variation in water resources due to climate change. In addition, one estimate shows the proportion of the African population at risk of water stress and scarcity increasing from 47% in 2000 to 65% in 2025 (Ashton, 2002). This could generate conflicts over water, particularly in arid and semi-arid regions. [WGII 9.2, 9.4]

A specific example is the south-western Cape, South Africa, where one study shows water supply capacity decreasing either as precipitation decreases or as potential evaporation increases. This projects a water supply reduction of 0.32%/yr by 2020, while climate change associated with global warming is projected to raise water demand by 0.6%/yr in the Cape Metropolitan Region (New, 2002).

With regard to the Nile Basin, Conway (2005) found that there is no clear indication of how Nile River flow would be affected by climate change, because of uncertainty in projected rainfall patterns in the basin and the influence of complex water management and water governance structures. [WGII 9.4.2]

Responses to rainfall shifts are already being observed in many terrestrial water sources that could be considered possible indicators of future water stress linked to climate variability. In the eastern parts of the continent, interannual lake level fluctuations have been observed, with low values in 1993–1997 and higher levels (e.g., of Lakes Tanganyika, Victoria and Turkana) in 1997–1998, the latter being linked to an excess in rainfall in late 1997 coupled with large-scale perturbations in the Indian Ocean (Mercier et al., 2002). Higher water temperatures have also been reported in lakes in response to warmer conditions (see Figure 5.1). [WGII 9.2.1.1, 1.3.2.3]

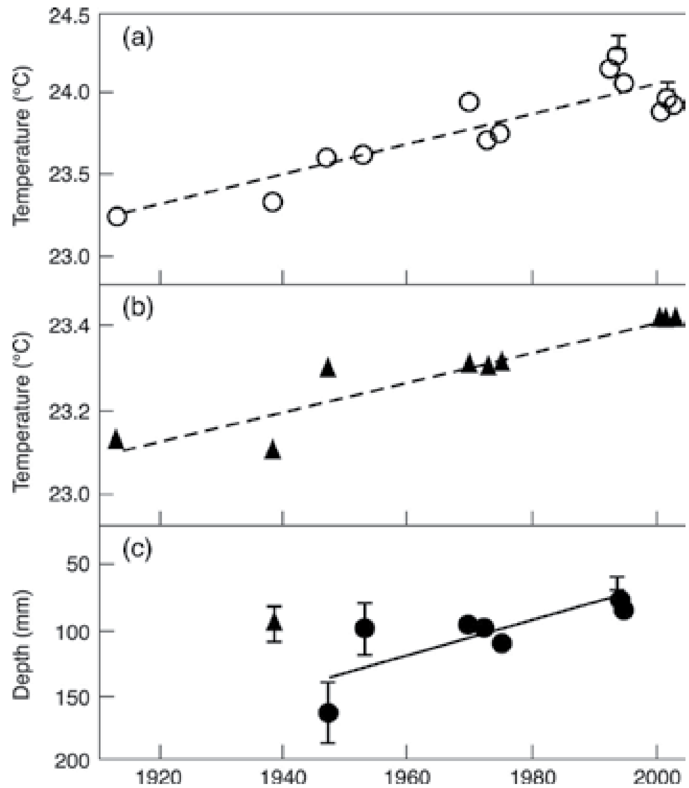


Figure 5.1: Historical and recent measurements from Lake Tanganyika, East Africa: (a) upper mixed layer (surface water) temperatures; (b) deep-water (600 m) temperatures; (c) depth of the upper mixed layer. Triangles represent data collected by a different method. Error bars represent standard deviations. Reprinted by permission from Macmillan Publishers Ltd. [Nature] (O'Reilly et al., 2003), copyright 2003. [WGII Figure 1.2]

5.1.2 Current observations

5.1.2.1 Climate variability

The Sahel region of West Africa experiences marked multi-decadal variability in rainfall (e.g., Dai et al., 2004a), associated with changes in atmospheric circulation and related changes in tropical sea surface temperature patterns in the Pacific, Indian and Atlantic Basins (e.g., ENSO and the AMO). Very

[20] See Appendix I for model descriptions.

[21] Djibouti, Cape Verde, Kenya, Burundi, Rwanda, Malawi, Somalia, Egypt and South Africa.

[22] Mauritius, Lesotho, Ethiopia, Zimbabwe, Tanzania, Burkina Faso, Mozambique, Ghana, Togo, Nigeria, Uganda and Madagascar.

[23] Only five countries in Africa currently (1990 data) have water access volume less than 1,000 m^3/person/yr. These are Rwanda, Burundi, Kenya, Cape Verde and Djibouti.

dry conditions were experienced from the 1970s to the 1990s, after a wetter period in the 1950s and 1960s. The rainfall deficit was mainly related to a reduction in the number of significant rainfall events occurring during the peak monsoon period (July to September) and during the first rainy season south of about 9°N. The decreasing rainfall and devastating droughts in the Sahel region during the last three decades of the 20th century (Figure 5.2) are among the largest climate changes anywhere. Sahel rainfall reached a minimum after the 1982/83 El Niño event. [WGI 3.7.4] Modelling studies suggest that Sahel rainfall has been influenced more by large-scale climate variations (possibly linked to changes in anthropogenic aerosols), than by local land-use change. [WGI 9.5.4]

5.1.2.2 Water resources

About 25% of the contemporary African population experiences water stress, while 69% live under conditions of relative water abundance (Vörösmarty et al., 2005). However, this relative abundance does not take into account other factors such as the extent to which that water is potable and accessible, and the availability of sanitation. Despite considerable improvements in access in the 1990s, only about 62% of Africans had access to improved water supplies in the year 2000 (WHO/UNICEF, 2000). [WGII 9.2.1]

One-third of the people in Africa live in drought-prone areas and are vulnerable to the impacts of droughts (World Water Forum, 2000), which have contributed to migration, cultural separation, population dislocation and the collapse of ancient cultures. Droughts have mainly affected the Sahel, the Horn of Africa and southern Africa, particularly since the end of the 1960s, with severe impacts on food security and, ultimately, the occurrence of famine. In West Africa, a decline in annual rainfall has been observed since the end of the 1960s, with a decrease of 20–40% in the period 1968–1990 as compared with the 30 years between 1931 and 1960 (Nicholson et al., 2000; Chappell and Agnew, 2004; Dai et al., 2004a). The influence of the ENSO decadal variations has also been recognised in south-west Africa, influenced in part by the North Atlantic Oscillation (NAO) (Nicholson and Selato, 2000). [WGII 9.2.1]

5.1.2.3 Energy

The electricity supply in the majority of African States is derived from hydro-electric power. There are few available studies that examine the impacts of climate change on energy use in Africa (Warren et al., 2006). [WGII 9.4.2] Nevertheless, the continent is characterised by a high dependency on fuelwood as a major source of energy in rural areas – representing about 70% of total energy consumption in the continent. Any impact of climate change on biomass production would, in turn, impact on the availability of wood-fuel energy. Access to energy is severely constrained in sub-Saharan Africa, with an estimated 51% of urban populations and only 8% of rural populations having access to electricity. This can be compared with the 99% of urban populations and 80% of rural populations that have access in northern Africa. Further challenges from urbanisation, rising energy demands and volatile oil prices further compound energy issues in Africa. [WGII 9.2.2.8]

5.1.2.4 Health

Malaria

The spatial distribution, intensity of transmission, and seasonality of malaria is influenced by climate in sub-Saharan Africa; socio-economic development has had only limited impact on curtailing disease distribution (Hay et al., 2002a; Craig et al., 2004). [WGII 8.2.8.2]

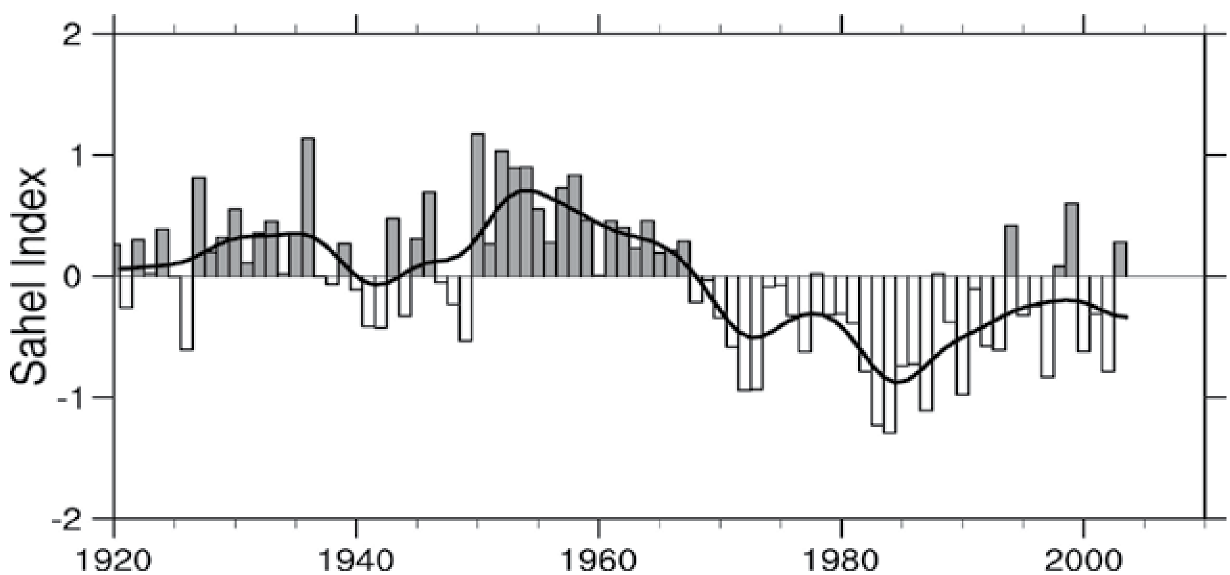


Figure 5.2: *Time-series of Sahel (10°N–20°N, 18°W–20°E) regional rainfall (April–October) from 1920 to 2003 derived from gridding normalised station anomalies and then averaging using area weighting (adapted from Dai et al., 2004a). Positive values (shaded bars) indicate conditions wetter than the long-term mean and negative values (unfilled bars) indicate conditions drier than the long-term mean. The smooth black curve shows decadal variations. [WGI Figure 3.37]*

Rainfall can be a limiting factor for mosquito populations and there is some evidence of reductions in transmission associated with decadal decreases in rainfall. Evidence of the predictability of unusually high or low malaria anomalies from both sea surface temperature (Thomson et al., 2005b) and multi-model ensemble seasonal climate forecasts in Botswana (Thomson et al., 2006) supports the practical and routine use of seasonal forecasts for malaria control in southern Africa (DaSilva et al., 2004). [WGII 8.2.8.2]

The effects of observed climate change on the geographical distribution of malaria and its transmission intensity in highland regions remains controversial. Analyses of time-series data in some sites in East Africa indicate that malaria incidence has increased in the apparent absence of climate trends (Hay et al., 2002a, b; Shanks et al., 2002). The suggested driving forces behind the resurgence of malaria include drug resistance of the malaria parasite and a decrease in vector control activities. However, the validity of this conclusion has been questioned because it may have resulted from inappropriate use of the climatic data (Patz, 2002). Analysis of updated temperature data for these regions has found a significant warming trend since the end of the 1970s, with the magnitude of the change affecting transmission potential (Pascual et al., 2006). In southern Africa, long-term trends for malaria were not significantly associated with climate, although seasonal changes in case numbers were significantly associated with a number of climatic variables (Craig et al., 2004). Drug resistance and HIV infection were associated with long-term malaria trends in the same area (Craig et al., 2004). [WGII 8.2.8.2]

A number of further studies have reported associations between interannual variability in temperature and malaria transmission in the African highlands. An analysis of de-trended time-series malaria data in Madagascar indicated that minimum temperature at the start of the transmission season, corresponding to the months when the human–vector contact is greatest, accounts for most of the variability between years (Bouma, 2003). In highland areas of Kenya, malaria admissions have been associated with rainfall and unusually high maximum temperatures 3–4 months previously (Githeko and Ndegwa, 2001). An analysis of malaria morbidity data for the period from the late 1980s until the early 1990s from 50 sites across Ethiopia found that epidemics were associated with high minimum temperatures in the preceding months (Abeku et al., 2003). An analysis of data from seven highland sites in East Africa reported that short-term climate variability played a more important role than long-term trends in initiating malaria epidemics (Zhou et al., 2004, 2005), although the method used to test this hypothesis has been challenged (Hay et al., 2005). [WGII 8.2.8.2]

Other water-related diseases

While infectious diseases such as cholera are being eradicated in other parts of the world, they are re-emerging in Africa. Child mortality due to diarrhoea in low-income countries, especially in sub-Saharan Africa, remains high despite improvements in care and the use of oral rehydration therapy (Kosek et al., 2003). Children may survive the acute illness but may later die due to persistent diarrhoea or malnutrition. Several studies have shown that transmission of enteric pathogens is higher during the rainy season (Nchito et al., 1998; Kang et al., 2001). [WGII 8.2.5, 9.2.2.6]

5.1.2.5 Agricultural sector

The agricultural sector is a critical mainstay of local livelihoods and national GDP in some countries in Africa. Agriculture contributions to GDP vary across countries, but assessments suggest an average contribution of 21% (ranging from 10% to 70%) (Mendelsohn et al., 2000b). Even where the contribution of agriculture to GDP is low, the sector may still support the livelihoods of very large sections of the population, so that any reduction in output will have impacts on poverty and food security. This sector is particularly sensitive to climate, including periods of climate variability. In many parts of Africa, farmers and pastoralists also have to contend with other extreme natural resource challenges and constraints such as poor soil fertility, pests, crop diseases and a lack of access to inputs and improved seeds. These challenges are usually aggravated by periods of prolonged droughts and floods (Mendelsohn et al., 2000a, b; Stige et al., 2006). [WGII 9.2.1.3]

5.1.2.6 Ecosystems and biodiversity

Ecosystems and their biodiversity contribute significantly to human well-being in Africa. [WGII Chapter 9] The rich biodiversity in Africa, which occurs principally outside formally conserved areas, is under threat from climate variability and change and other stresses (e.g., Box 5.1). Africa's social and economic development is constrained by climate change, habitat loss, over-harvesting of selected species, the spread of alien species, and activities such as hunting and deforestation, which threaten to undermine the integrity of the continent's rich but fragile ecosystems (UNEP/GRID-Arendal, 2002). Approximately half of the sub-humid and semi-arid parts of the southern African region, for example, are at moderate to high risk of desertification. In West Africa, the long-term decline in rainfall from the 1970s to the 1990s has caused a 25–35 km shift southward in the Sahel, Sudan and Guinean ecological zones in the second half of the 20th century (Gonzalez, 2001). This has resulted in the loss of grassland and acacia, loss of flora/fauna, and shifting sand dunes in the Sahel; effects that are already being observed (ECF and Potsdam Institute, 2004). [WGII 9.2.1.4]

5.1.3 Projected changes

5.1.3.1 Water resources

Increased populations in Africa are expected to experience water stress before 2025, i.e., in less than two decades from the publication of this report, mainly due to increased water demand. [WGII 9.4.1] Climate change is expected to exacerbate this condition. In some assessments, the population at risk of increased water stress in Africa, for the full range of SRES scenarios, is projected to be 75–250 million and 350–600 million people by the 2020s and 2050s, respectively (Arnell, 2004). However, the impact of climate change on water resources across the continent is not uniform. An analysis of six climate models (Arnell, 2004) shows a *likely* increase in the

Box 5.1: Environmental changes on Mt. Kilimanjaro. [Adapted from WGII Box 9.1]

There is evidence that climate change is modifying natural mountain ecosystems on Mt. Kilimanjaro. For example, as a result of dry climatic conditions, the increased frequency and intensity of fires on the slopes of Mt. Kilimanjaro led to a downward shift of the upper forest line by several hundreds of metres during the 20th century (Figure 5.3, Table 5.1). The resulting decrease in cloud-forest cover by 150 km^2 since 1976 has had a major impact on the capturing of fog as well as on the temporary storage of rain, and thus on the water balance of the mountain (Hemp, 2005).

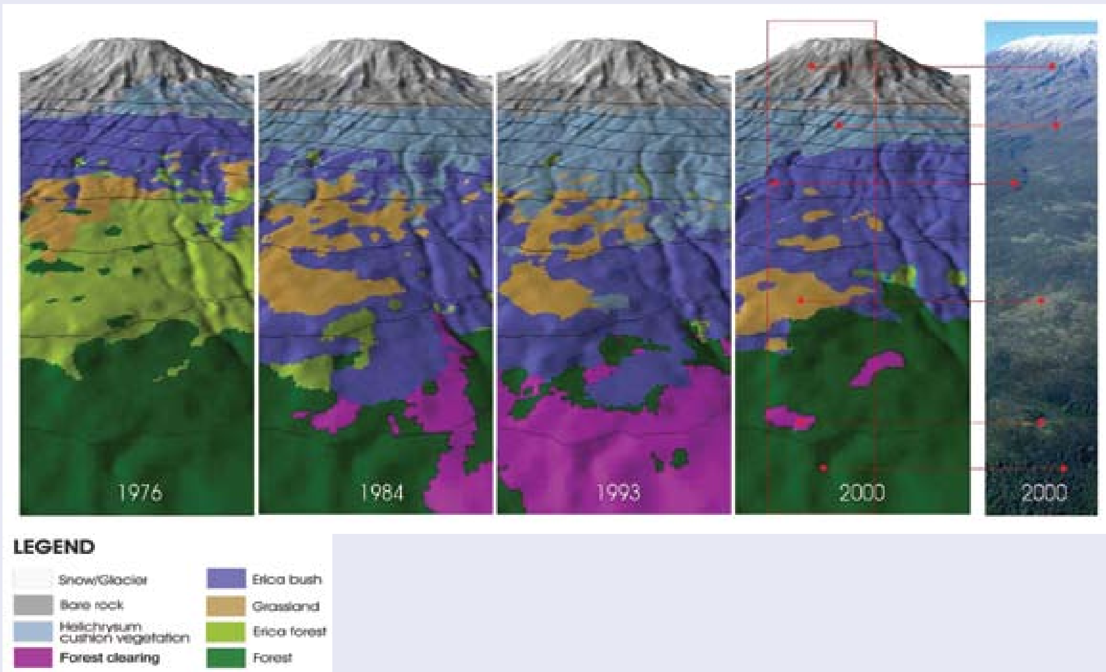


Figure 5.3: *Land cover changes induced by complex land use and climate interactions on Kilimanjaro (Hemp, 2005). Reprinted by permission from Blackwell Publishing Ltd.*

Table 5.1: *Land cover changes in the upper regions of Kilimanjaro (Hemp, 2005).*

Vegetation type	Area 1976 (km^2)	Area 2000 (km^2)	Change (%)
Montane forest	1066	974	-9
Subalpine Erica forest	187	32	-83
Erica bush	202	257	+27
Helichrysum cushion vegetation	69	218	+216
Grassland	90	44	-51

number of people who could experience water stress by 2055 in northern and southern Africa (Figure 5.4). In contrast, more people in eastern and western Africa will be *likely* to experience a reduction rather than an increase in water stress (Arnell, 2006a). [WGII 3.2, Figure 3.2, Figure 3.4, 9.4.1, Figure 9.3]

Groundwater is most commonly the primary source of drinking water in Africa, particularly in rural areas which rely on low-cost dug wells and boreholes. Its recharge is projected to decrease with decreased precipitation and runoff, resulting in increased water stress in those areas where groundwater supplements dry season water demands for agriculture and household use. [WGII 3.4.2, Figure 3.5]

A study of the impacts of a 1°C temperature increase in one watershed in the Maghreb region projects a runoff deficit of some 10% (Agoumi, 2003), assuming precipitation levels remain constant. [WGII 9.4.1, 3.2, 3.4.2]

5.1.3.2 Energy

Although not many energy studies have been undertaken for Africa, a study of hydro-electric power generation conducted in the Zambezi Basin, taken in conjunction with projections of future runoff, indicate that hydropower generation would be negatively affected by climate change, particularly in river basins that are situated in sub-humid regions (Riebsame et al., 1995; Salewicz, 1995). [WGII TAR 10.2.11, Table 10.1]

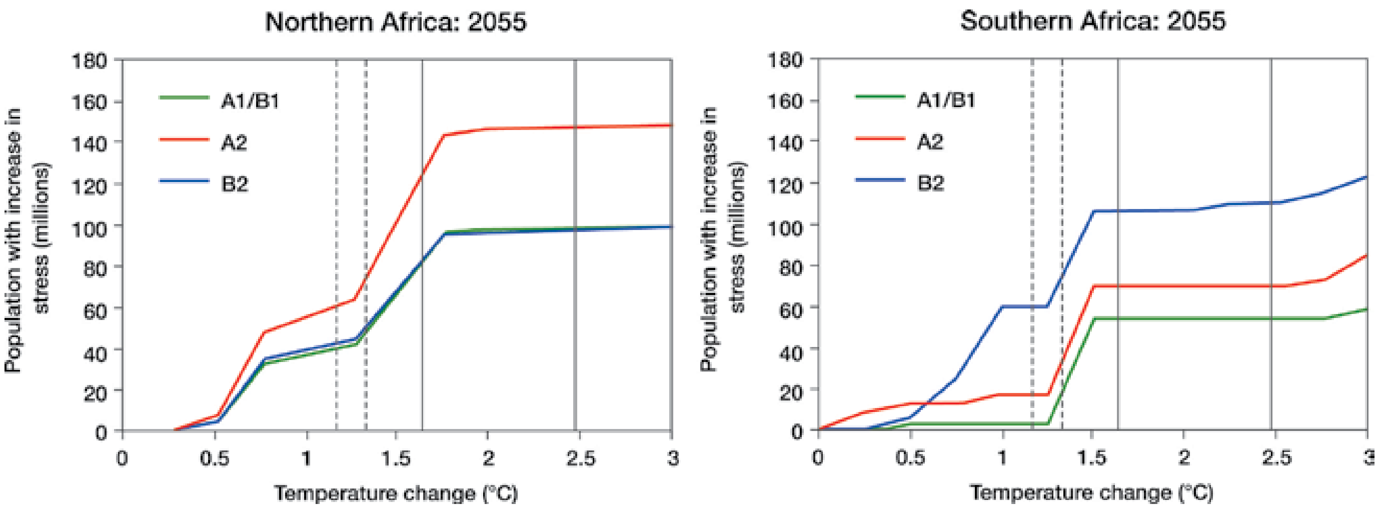


Figure 5.4: *Number of people (millions) living in watersheds exposed to an increase in water stress, compared to 1961–1990 (Arnell, 2006b). Water-stressed watersheds have runoff less than 1,000 m³/capita/yr, and populations are exposed to an increase in water stress when runoff reduces significantly, due to climate change. Scenarios are derived from HadCM3 and the red, green and blue lines relate to different population projections; note that projected hydrological changes vary substantially between different climate models in some regions. The steps in the function occur as more watersheds experience a significant decrease in runoff. [WGII Figure 9.3]*

5.1.3.3 Health

A considerable number of studies have linked climate change with health issues in the continent. For example, results from the Mapping Malaria Risk in Africa project (MARA/ARMA) indicate changes in the distribution of climate-suitable areas for malaria by 2020, 2050 and 2080 (Thomas et al., 2004). By 2050, and continuing into 2080, a large part of the western Sahel and much of southern-central Africa is shown to be *likely* to become unsuitable for malaria transmission. Other assessments (e.g., Hartmann et al., 2002), using sixteen climate change scenarios, show that, by 2100, changes in temperature and precipitation could alter the geographical distribution of malaria in Zimbabwe, with previously unsuitable areas of dense human population becoming suitable for transmission. [WGII 9.4.3]

Relatively few assessments of the possible future changes in animal health arising from climate variability and change have been undertaken. Changes in disease distribution, range, prevalence, incidence and seasonality can be expected. However, there is low certainty about the degree of change. Rift Valley Fever epidemics, evident during the 1997/98 El Niño event in East Africa and associated with flooding, could increase in regions subject to increases in flooding (Section 3.2.1.2). The number of extremely wet seasons in East Africa is projected to increase. Finally, heat stress and drought are *likely* to have a further negative impact on animal health and the production of dairy products (this has already been observed in the USA; see Warren et al., 2006). [WGI Table 11.1, 11.2.3; WGII 9.4.3, 5.4.3.1]

5.1.3.4 Agriculture

Impacts of climate change on growing periods and on agricultural systems and possible livelihood implications have been examined (e.g., Thornton et al., 2006). A recent study based on three scenarios indicates that crop net revenues would be *likely* to fall by as much as 90% by 2100, with small-scale farms being the most affected. However, there is the possibility that adaptation could reduce these negative effects (Benhin, 2006). [WGII 9.4.4]

A case study of climate change, water availability and agriculture in Egypt is provided in Box 5.2.

Not all changes in climate and climate variability would, however, be negative for agriculture. The growing seasons in certain areas, such as around the Ethiopian highlands, may lengthen under climate change. A combination of increased temperatures and rainfall changes may lead to the extension of the growing season, for example in some of the highland areas (Thornton et al., 2006). As a result of a reduction in frost in the highland zones of Mt. Kenya and Mt. Kilimanjaro, for example, it may be possible to grow more temperate crops, e.g., apples, pears, barley, wheat, etc. (Parry et al., 2004). [WGII 9.4.4]

Fisheries are another important source of revenue, employment, and protein. In coastal regions that have major lagoons or lake systems, changes in freshwater flows, and more intrusion of saltwaters into the lagoons, would affect species that are the basis of inland fisheries or aquaculture (Cury and Shannon, 2004). [WGII 9.4.4]

The impact of climate change on livestock in Africa has been examined (Seo and Mendelsohn, 2006). Decreased precipitation of 14% would be *likely* to reduce large farm livestock income by about 9% (–US$5 billion) due to a reduction in both the stock numbers and the net revenue per animal owned. [WGII 9.4.4]

Box 5.2: Climate, water availability and agriculture in Egypt. [WGII Box 9.2]

Egypt is one of the African countries that could be vulnerable to water stress under climate change. The water used in 2000 was estimated at about 70 km^3 which is already far in excess of the available resources (Gueye et al., 2005). A major challenge is to close the rapidly increasing gap between the limited water availability and the escalating demand for water from various economic sectors. The rate of water utilisation has already reached its maximum for Egypt, and climate change will exacerbate this vulnerability.

Agriculture consumes about 85% of the annual total water resource and plays a significant role in the Egyptian national economy, contributing about 20% of GDP. More than 70% of the cultivated area depends on low-efficiency surface irrigation systems, which cause high water losses, a decline in land productivity, waterlogging and salinity problems (El-Gindy et al., 2001). Moreover, unsustainable agricultural practices and improper irrigation management affect the quality of the country's water resources. Reductions in irrigation water quality have, in their turn, harmful effects on irrigated soils and crops.

Institutional water bodies in Egypt are working to achieve the following targets by 2017 through the National Improvement Plan (EPIQ, 2002; ICID, 2005):
- improving water sanitation coverage for urban and rural areas,
- wastewater management,
- optimising the use of water resources by improving irrigation efficiency and agriculture drainage-water reuse.

However, with climate change, an array of serious threats is apparent.
- Sea-level rise could impact on the Nile Delta and on people living in the delta and other coastal areas (Wahab, 2005).
- Temperature rises will be *likely* to reduce the productivity of major crops and increase their water requirements, thereby directly decreasing crop water-use efficiency (Abou-Hadid, 2006; Eid et al., 2006).
- There will probably be a general increase in irrigation demand (Attaher et al., 2006).
- There will also be a high degree of uncertainty about the flow of the Nile.
- Based on SRES scenarios, Egypt will be *likely* to experience an increase in water stress, with a projected decline in precipitation and a projected population of between 115 and 179 million by 2050. This will increase water stress in all sectors.
- Ongoing expansion of irrigated areas will reduce the capacity of Egypt to cope with future fluctuations in flow (Conway, 2005).

5.1.3.5 Biodiversity

Soil moisture reduction due to precipitation changes could affect natural systems in several ways. There are projections of significant extinctions in both plant and animals species. Over 5,000 plant species could be impacted by climate change, mainly due to the loss of suitable habitats. By 2050, the Fynbos Biome (*Ericaceae*-dominated ecosystem of South Africa, which is an IUCN 'hotspot') is projected to lose 51–61% of its extent due to decreased winter precipitation. The succulent Karoo Biome, which includes 2,800 plant species at increased risk of extinction, is projected to expand south-eastwards, and about 2% of the family *Proteaceae* are projected to become extinct. These plants are closely associated with birds that have specialised on feeding on them. Some mammal species, such as the zebra and nyala, which have been shown to be vulnerable to drought-induced changes in food availability, are widely projected to suffer losses. In some wildlife management areas, such as the Kruger and Hwange National Parks, wildlife populations are already dependant on water supplies supplemented by borehole water (Box 5.3). [WGII 4.4, 9.4.5, Table 9.1]

Box 5.3: Projected extinctions in the Kruger National Park, South Africa. [WGII Table 4.1]

In the Kruger National Park, South Africa, and for a global mean temperature increase 2.5–3.0°C above 1990 levels:
- 24–59% of mammals,
- 28–40% of birds,
- 13–70% of butterflies,
- 18–80% of other invertebrates, and
- 21–45% of reptiles would be committed to extinction.

In total, 66% of animal species would potentially be lost.

Many bird species are migrants from Europe and the Palaeo-Arctic region. Some species use the southern Sahel as a stopover stage before crossing the Sahara Desert. Drought-induced food shortage in the region would impair the migration success of such birds. As noted, the precipitation models for the Sahel are equivocal. [WGII 9.3.1] If the wet scenarios materialise, then the biodiversity of the sub-Saharan/Sahel region is in no imminent danger from water-stress-related impacts. On the other hand, the drier scenario would, on balance, lead to extensive extinctions, especially as competition between natural systems and human needs would intensify. [WGII 9.4.5]

Simulation results for raptors in southern Africa, using precipitation as the key environmental factor, suggest significant range reductions as their current ranges become drier. [WGII 4.4.3] In all, it is expected that about 25–40% of sub-Saharan African animal species in conservation areas would be endangered. [WGII 9.4.5]

5.1.4 Adaptation and vulnerability

Recent studies in Africa highlight the vulnerability of local groups that depend primarily on natural resources for their livelihoods, indicating that their resource base – already severely stressed and degraded by overuse – is expected to be further impacted by climate change (Leary et al., 2006). [WGII 17.1]

Climate change and variability have the potential to impose additonal pressures on water availability, accessibility, supply and demand in Africa. [WGII 9.4.1] It is estimated that around 25% (200 million) of Africa's population currently experiences water stress, with more countries expected to face high future risk (see Section 5.1.3.1). [WGII 9.ES] Moreover, it has been envisioned that, even without climate change, several countries, particularly in northern Africa, would reach the threshold level of their economically usable land-based water resources before 2025. [WGII 9.4.1] Frequent natural disasters, such as droughts and floods, have largely constrained agricultural development in Africa, which is heavily dependent on rainfall, leading to food insecurity in addition to a range of macro- and microstructural problems. [WGII 9.5.2]

ENSO has a significant influence on rainfall at interannual scales in Africa and may influence future climate variability. [WGI 3.7.4, 3.6.4, 11.2] However, a number of barriers hamper effective adaptation to variations in ENSO including: spatial and temporal uncertainties associated with forecasts of regional climate; the low level of awareness among decision makers of the local and regional impacts of El Niño; limited national capacities in climate monitoring and forecasting; and lack of co-ordination in the formulation of responses (Glantz, 2001). [WGII 17.2.2]

Regarding the impacts of climate variability and change on groundwater, little information is available, despite many countries (especially in northern Africa) being dependent on such water sources. [WGII 9.2.1]

Previous assessments of water impacts have not adequately covered the multiple future water uses and future water stress (e.g., Agoumi, 2003; Conway, 2005), and so more detailed research on hydrology, drainage and climate change is required. Future access to water in rural areas, drawn from low-order surface water streams, also needs to be addressed by countries sharing river basins (e.g., de Wit and Stankiewicz, 2006). [WGII 9.4.1]

Adaptive capacity and adaptation related to water resources are considered very important to the African continent. Historically, migration in the face of drought and floods has been identified as one of the adaptation options. Migration has also been found to present a source of income for those migrants, who are employed as seasonal labour. Other practices that contribute to adaptation include traditional and modern water-harvesting techniques, water conservation and storage, and planting of drought-resistant and early-maturing crops. The importance of building on traditional knowledge related to water harvesting and use has been highlighted as one of the most important adaptation requirements (Osman-Elasha et al., 2006), indicating the need for its incorporation into climate change policies to ensure the development of effective adaptation strategies that are cost-effective, participatory and sustainable. [WGII 9.5.1, Table 17.1]

Very little information exists regarding the cost of impacts and adaptation to climate change for water resources in Africa. However, an initial assessment in South Africa of adaptation costs in the Berg River Basin shows that the costs of not adapting to climate change can be much greater than those that may arise if flexible and efficient approaches are included in management options (see Stern, 2007). [WGII 9.5.2]

5.2 Asia

5.2.1 Context

Asia is a region where water distribution is uneven and large areas are under water stress. Among the forty-three countries of Asia, twenty have renewable annual per capita water resources in excess of 3,000 m^3, eleven are between 1,000 and 3,000 m^3, and six are below 1,000 m^3 (there are no data from the remaining six countries) (FAO, 2004a, b, c). [WGII Table 10.1] From west China and Mongolia to west Asia, there are large areas of arid and semi-arid lands. [WGII 10.2] Even in humid and sub-humid areas of Asia, water scarcity/stress is one of the constraints for sustainable development. On the other hand, Asia has a very high population that is growing at a fast rate, low development levels and weak coping capacity. Climate change is expected to exacerbate the water scarcity situation in Asia, together with multiple socio-economic stresses. [WGII 10.2]

5.2.2 Observed impacts of climate change on water

5.2.2.1 Freshwater resources

Inter-seasonal, interannual, and spatial variability in rainfall has been observed during the past few decades across all of Asia. Decreasing trends in annual mean rainfall were observed in Russia, north-east and north China, the coastal belts and arid plains of Pakistan, parts of north-east India, Indonesia, the Philippines and some areas of Japan. Annual mean rainfall exhibits increasing trends in western China, the Changjiang (River Yangtze) Basin and the south-eastern coast of China, the Arabian Peninsula, Bangladesh and along the western coasts of the Philippines. In South-East Asia, extreme weather events associated with El Niño have been reported to be more frequent and intense in the past 20 years (Trenberth and Hoar, 1997; Aldhous, 2004). It is important to note that substantial inter-decadal variability exists in both the Indian and the east Asian monsoons. [WGI 3.3.2, 3.7.1; WGII 10.2.2, 10.2.3]

Generally, the frequency of occurrence of more intense rainfall events in many parts of Asia has increased, causing severe floods, landslides, and debris and mud flows, while the number of rainy days and total annual amount of precipitation have decreased (Zhai et al., 1999; Khan et al., 2000; Shrestha et al., 2000; Izrael and Anokhin, 2001; Mirza, 2002; Kajiwara et al., 2003; Lal, 2003; Min et al., 2003; Ruosteenoja et al., 2003; Zhai and Pan, 2003; Gruza and Rankova, 2004; Zhai, 2004). However, there are reports that the frequency of extreme rainfall in some countries has exhibited a decreasing tendency (Manton et al., 2001; Kanai et al., 2004). [WGII 10.2.3]

The increasing frequency and intensity of droughts in many parts of Asia are attributed largely to rising temperatures, particularly during the summer and normally drier months, and during ENSO events (Webster et al. 1998; Duong, 2000; PAGASA, 2001; Lal, 2002, 2003; Batima, 2003; Gruza and Rankova, 2004; Natsagdorj et al., 2005). [WGI Box 3.6; WGII 10.2.3]

Rapid thawing of permafrost and decreasing depth of frozen soils [WGI 4.7.2], due largely to warming, has threatened many cities and human settlements, has caused more frequent landslides and degeneration of some forest ecosystems, and has resulted in an increase in lake water levels in the permafrost region of Asia (Osterkamp et al., 2000; Guo et al., 2001; Izrael and Anokhin, 2001; Jorgenson et al., 2001; Izrael et al., 2002; Fedorov and Konstantinov, 2003; Gavriliev and Efremov, 2003; Melnikov and Revson, 2003; Nelson, 2003; Tumerbaatar, 2003; ACIA, 2005). [WGII 10.2.4.2]

On average, Asian glaciers are melting at a rate that has been constant since at least the 1960s (Figure 2.6). [WGI 4.5.2] However, individual glaciers may vary from this pattern, and some are actually advancing and/or thickening – for example, in the central Karakorum – probably due to enhanced precipitation (Hewitt, 2005). [WGI 4.5.3] As a result of the ongoing melting of glaciers, glacial runoff and the frequency of glacial lake outbursts, causing mudflows and avalanches, have increased (Bhadra, 2002; WWF, 2005). [WGII 10.2.4.2]

Figure 5.5 shows the retreat (since 1780) of the Gangotri Glacier, the source of the Ganges, located in Uttarakhand, India. Although this retreat has been linked to anthropogenic climate change, no formal attribution studies have been carried out. It is worth noting that the tongue of this particular glacier is rather flat and heavily covered in debris. The shrinkage of tongues with these characteristics is difficult to relate to a particular climate signal, since the debris cover delays any signal. Flat tongues tend to collapse suddenly, with a sudden change in area, after thinning out for decades with relatively little areal change. [WGII 10.6.2]

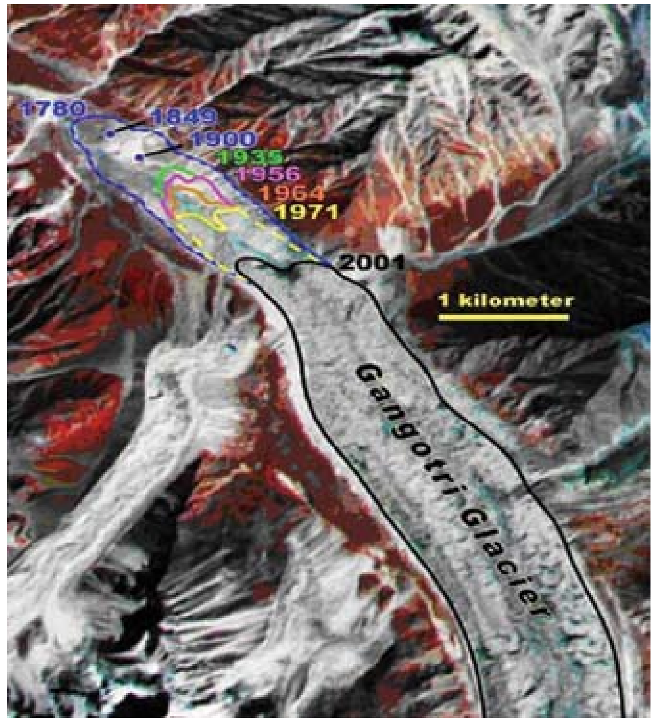


***Figure 5.5:** Composite satellite image showing how the Gangotri Glacier (source of the Ganges, located in Uttarakhand, India) terminus has retracted since 1780 (courtesy of NASA EROS Data Center, 9 September, 2001). [WGII Figure 10.6]*

In parts of China, temperature increases and decreases in precipitation, along with increasing water use, have caused water shortages that have led to drying up of lakes and rivers. In India, Pakistan, Nepal and Bangladesh, water shortages have been attributed to issues such as rapid urbanisation and industrialisation, population growth and inefficient water use, which are all aggravated by changing climate and its adverse impacts on demand, supply and water quality. In the countries situated in the Brahmaputra–Ganges–Meghna and Indus Basins, water shortages are also the result of the actions of upstream riverside-dwellers in storing water. In arid and semi-arid central and west Asia, changes in climate and its variability continue to challenge the ability of countries to meet growing demands for water (Abu-Taleb, 2000; Ragab and Prudhomme, 2002; Bou-Zeid and El-Fadel, 2002; UNEP/GRID-Arendal, 2002). The decreased precipitation and increased temperature commonly associated with ENSO have been reported to increase water shortages, particularly in parts of Asia where water resources are already under stress from growing water demands and inefficient water use (Manton et al., 2001). [WGII 10.2.4.2]

5.2.2.2 Agriculture

Production of rice, maize and wheat in the past few decades has declined in many parts of Asia due to increasing water stress, arising partly from increasing temperatures, increasing frequency of El Niño events and reductions in the number of rainy days (Wijeratne, 1996; Agarwal et al., 2000; Jin et al., 2001; Fischer et al., 2002a; Tao et al., 2003a, 2004). [WGII 10.2.4.1]

5.2.2.3 Biodiversity

With the gradual reduction in rainfall during the growing season for grass, aridity in central and west Asia has increased in recent years, reducing the growth of grasslands and increasing the bareness of the ground surface (Bou-Zeid and El-Fadel, 2002). Increasing bareness has led to increased reflection of solar radiation, such that more soil moisture evaporates and the ground becomes increasingly drier in a feedback process, thus adding to the acceleration of grassland degradation (Zhang et al., 2003). [WGII 10.2.4.4]

Precipitation decline and droughts in most delta regions of Pakistan, Bangladesh, India and China have resulted in drying of wetlands and severe degradation of ecosystems. The recurrent droughts from 1999 to 2001, as well as construction of upstream reservoirs and improper use of groundwater, have led to drying of the Momoge Wetland located in the Songnen Plain in north-eastern China (Pan et al., 2003). [WGII 10.2.4.4]

5.2.3 Projected impact of climate change on water and key vulnerabilities

5.2.3.1 Freshwater resources

Changes in seasonality and amount of water flow from river systems are expected, due to climate change. In some parts of Russia, climate change could significantly alter the variability of river runoff such that extremely low runoff events might occur much more frequently in the crop growing regions of the south-west (Peterson et al., 2002). Surface water availability from major rivers such as the Euphrates and Tigris might be affected by alteration of river flow. In Lebanon, the annual net usable water resource would decrease by 15% in response to a GCM-estimated average rise in temperature of 1.2°C under a doubled-CO_2 climate, while the flows in rivers would increase in winter and decrease in spring (Bou-Zeid and El-Fadel, 2002). The maximum monthly flow of the Mekong is projected to increase by 35–41% in the basin and by 16–19% in the delta, with the lower value estimated for the years 2010–2038 and the higher value for the years 2070–2099, compared with 1961–1990 levels. In contrast, the minimum monthly flows are estimated to decline by 17–24% in the basin and 26–29% in the delta (Hoanh et al., 2004) [WGII Box 5.3], suggesting that there could be increased flooding risks during the wet season and an increased possibility of water shortages in the dry season. [WGII 10.4.2.1]

Flooding could increase the habitat of brackish-water fisheries but could also seriously affect the aquaculture industry and infrastructure, particularly in heavily populated megadeltas. Reductions in dry-season flows may reduce recruitment of some species. In parts of central Asia, regional increases in temperature are expected to lead to an increased probability of events such as mudflows and avalanches that could adversely affect human settlements (Iafiazova, 1997). [WGII 10.4.2.1]

Saltwater intrusion in estuaries due to decreasing river runoff can be pushed 10–20 km further inland by rising sea levels (Shen et al., 2003; Yin et al., 2003; Thanh et al., 2004). Increases in water temperature and eutrophication in the Zhujiang and Changjiang Estuaries have led to formation of a bottom oxygen-deficient horizon and increased frequency and intensity of 'red tides' (Hu et al., 2001). Sea-level rises of 0.4–1.0 m can induce saltwater intrusion 1–3 km further inland in the Zhujiang Estuary (Huang and Xie, 2000). Increasing frequency and intensity of droughts in the catchment area would lead to more serious and frequent saltwater intrusion in the estuary (Xu, 2003; Thanh et al., 2004; Huang et al., 2005) and thus deteriorate surface water and groundwater quality. [WGII 10.4.2.1, 10.4.3.2]

Consequences of enhanced snow and glacier melt, as well as rising snow lines, would be unfavourable for downstream agriculture in several countries of south and central Asia. The volume and rate of snowmelt in spring is projected to accelerate in north-western China and western Mongolia and the thawing time could advance, which will increase some water sources and may lead to flood in spring, but significant shortages in water availability for livestock are projected by the end of this century (Batima et al., 2004, 2005). [WGII 10.4.2, 10.6]

It is expected that, in the medium term, climate-change-driven enhanced snow- or glacier melt will lead to floods. Such floods quite often are caused by rising river water levels due to blockage of the channel by drifting ice. [WGII 10.4.2, 10.6]

A projected increase in surface air temperature in north-western China is, by linear extrapolation of observed changes, expected to result in a 27% decline in glacier area, a 10–15% decline in frozen soil area, an increase in flood and debris flow, and more severe water shortages by 2050 compared with 1961–1990 (Qin, 2002). The duration of seasonal snow cover in alpine areas – namely the Tibet Plateau, Xinjiang and Inner Mongolia – is expected to shorten, leading to a decline in volume and resulting in severe spring droughts. Between 20% and 40% reductions in runoff per capita in Ningxia, Xinjiang and Qinghai Provinces are *likely* by the end of the 21st century (Tao et al., 2005). However, pressure on water resources due to increasing population and socio-economic development is *likely* to grow. Higashi et al. (2006) project that the future flood risk in Tokyo (Japan) between 2050 and 2300 under the SRES A1B scenario is *likely* to be 1.1 to 1.2 times higher than the present condition. [WGII 10.4.2.3]

The gross per capita water availability in India is projected to decline from about 1,820 m^3/yr in 2001 to as little as 1,140 m^3/yr in 2050, as a result of population growth (Gupta and Deshpande, 2004). Another study indicates that India will reach a state of water stress before 2025, when the availability is projected to fall below 1,000 m^3 per capita (CWC, 2001). These changes are due to climatic and demographic factors. The relative contribution of these factors is not known. The projected decrease in winter precipitation over the Indian sub-continent would imply less storage and greater water stress during the lean monsoon period. Intense rain occurring over fewer days, which implies increased frequency of floods during the monsoon, may also result in reduced groundwater recharge potential. Expansion of areas under severe water stress will be one of the most pressing environmental problems in South and South-East Asia in the foreseeable future, as the number of people living under severe water stress is *likely* to increase substantially in absolute terms. It is estimated that, under the full range of SRES scenarios, from 120 million to 1.2 billion, and from 185 million to 981 million people will experience increased water stress by the 2020s and the 2050s, respectively (Arnell, 2004). The decline in annual flow of the Red River by 13–19% and that of the Mekong River by 16–24% by the end of the 21st century is projected, and would contribute to increasing water stress (ADB, 1994). [WGII 10.4.2]

5.2.3.2 Energy

Changes in runoff could have a significant effect on the power output of hydropower-generating countries such as Tajikistan, which is the third largest hydro-electricity producer in the world (World Bank, 2002). [WGII 10.4.2]

5.2.3.3 Agriculture

Agricultural irrigation demand in arid and semi-arid regions of Asia is estimated to increase by at least 10% for an increase in temperature of 1°C (Fischer et al., 2002a; Liu, 2002). Based on a study by Tao et al. (2003b), rain-fed crops in the plains of north and north-east China could face water-related challenges in future decades due to increases in water demand and soil-moisture deficit associated with projected declines in precipitation. Note, however, that more than two-thirds of the models ensembled in Figures 2.8 and 2.10 show an increase in precipitation and runoff for this region. In north China, irrigation from surface water and groundwater sources is projected to meet only 70% of the water requirement for agricultural production, due to the effects of climate change and increasing demand (Liu et al., 2001; Qin, 2002). [WGII 10.4.1] Enhanced variability in hydrological characteristics will be *likely* to continue to affect grain supplies and food security in many nations of Asia. [WGII 10.4.1.2]

5.2.4 Adaptation and vulnerability

There are different current water vulnerabilities in Asian countries. Some countries which are not currently facing high risk are expected to face a future risk of water stress, with various capacities for adaptation. Coastal areas, especially heavily populated megadelta regions in south, east and south-east Asia, are expected to be at greatest risk of increased river and coastal flooding. In southern and eastern Asia, the interaction of climate change impacts with rapid economic and population growth, and migration from rural to urban areas, is expected to affect development. [WGII 10.2.4, 10.4, 10.6]

The vulnerability of a society is influenced by its development path, physical exposures, the distribution of resources, prior stresses, and social and government institutions. All societies have inherent abilities to deal with certain variations in climate, yet adaptive capacities are unevenly distributed, both across countries and within societies. The poor and marginalised have historically been most at risk, and are most vulnerable to the impacts of climate change. Recent analyses in Asia show that marginalised, primary-resource-dependent livelihood groups are particularly vulnerable to climate change impacts if their natural resource base is severely stressed and degraded by overuse, or if their governance systems are not capable of responding effectively (Leary et al., 2006). [WGII 17.1] There is growing evidence that adaptation is occurring in response to observed and anticipated climate change. For example, climate change forms part of the design consideration in infrastructure projects such as coastal defence in the Maldives and prevention of glacial lake outburst flooding in Nepal (see Box 5.4). [WGII 17.2, 17.5, 16.5]

In some parts of Asia, the conversion of cropland to forest (grassland), restoration and re-establishment of vegetation, improvement of the tree and herb varieties, and selection and cultivation of new drought-resistant varieties could be effective measures to prevent water scarcity due to climate change. Water-saving schemes for irrigation could be used to avert the water scarcity in regions already under water stress (Wang, 2003). In north Asia, recycling and reuse of municipal wastewater (Frolov et al., 2004) and increasing efficiency of water use for irrigation and other purposes (Alcamo et al., 2004) will be *likely* to help avert water scarcity. [WGII 10.5.2]

There are many adaptation measures that could be applied in various parts of Asia to minimise the impacts of climate change on water resources, several of which address the existing inefficiency in the use of water:

- modernisation of existing irrigation schemes and demand management aimed at optimising physical and economic efficiency in the use of water resources and recycled water in water-stressed countries;
- public investment policies that improve access to available water resources, encourage integrated water management and respect for the environment, and promote better practices for the sensible use of water in agriculture;
- the use of water to meet non-potable water demands. After treatment, recycled water can also be used to create or enhance wetlands and riparian habitats. [WGII 10.5.2]

Effective adaptation and adaptive capacity, particularly in developing Asian countries, will continue to be limited by various ecological, social and economic, technical, institutional and political constraints. Water recycling is a sustainable approach towards adaptation to climate change and can be cost-effective in the long term. However, the treatment of wastewater for reuse that is now being practised in Singapore, and the installation of distribution systems, can initially be expensive compared to water supply alternatives such as the use of imported water or groundwater. Nevertheless, they are

Box 5.4: Tsho Rolpa Risk Reduction Project in Nepal as observed anticipatory adaptation. [WGII Box 17.1]

The Tsho Rolpa is a glacial lake located at an altitude of about 4,580 m in Nepal. Glacier shrinkage increased the size of the Tsho Rolpa from 0.23 km^2 in 1957/58 to 1.65 km^2 in 1997 (Figure 5.6). The 90–100 million m^3 of water contained by the lake at this time were only held back by a moraine dam – a hazard that required urgent action to reduce the risk of a catastrophic glacial lake outburst flood (GLOF).

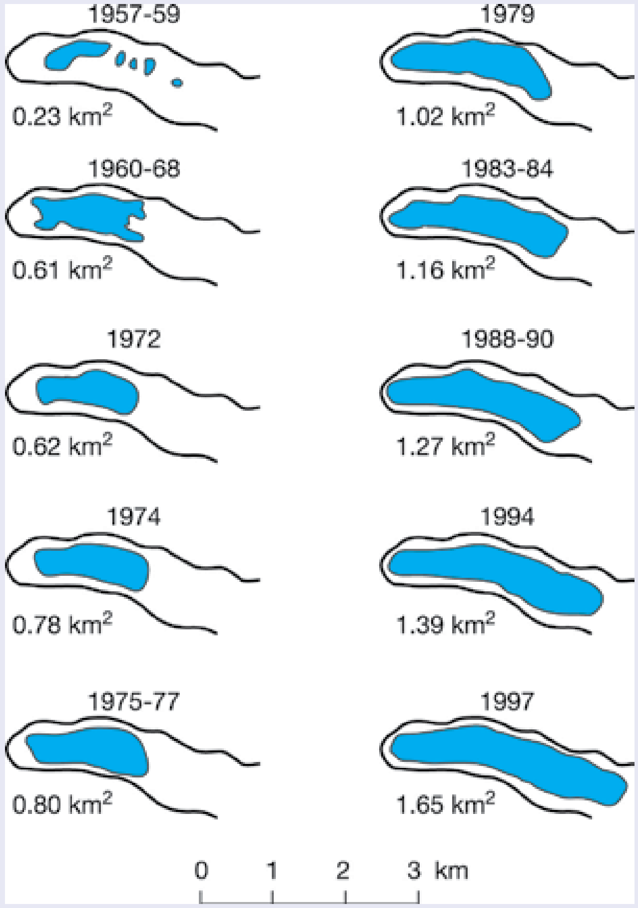


Figure 5.6: *Changes in the area of the Tsho Rolpa over time.*

If the dam were breached, one-third or more of the water could flood downstream. Among other considerations, this posed a major risk to the Khimti hydropower plant, which was under construction downstream. These concerns spurred the Government of Nepal, with the support of international donors, to initiate a project in 1998 to lower the level of the lake through drainage. An expert group recommended that, to reduce the risk of a GLOF, the lake should be lowered three metres by cutting a channel in the moraine. A gate was constructed to allow for controlled release of water. Meanwhile, an early-warning system was established in nineteen villages downstream in case a Tsho Rolpa GLOF should occur despite these efforts. Local villagers were actively involved in the design of the system, and safety drills are carried out periodically. In 2002, the four-year construction project was completed at a cost of US$3.2 million. Clearly, reducing GLOF risks involves substantial costs and is time-consuming, as complete prevention of a GLOF would require further drainage to lower the lake level.

The case of Tsho Rolpa has to be seen in a broader context. The frequency of glacial lake outburst floods (GLOFs) in the Himalayas of Nepal, Bhutan and Tibet has increased from 0.38 events/yr in the 1950s to 0.54 events/yr in the 1990s. [WGII 1.3.1.1]

Sources: Mool et al. (2001), OECD (2003), Shrestha and Shrestha (2004).

potentially important adaptation options in many countries of Asia. Reduction of water wastage and leakage could be practised in order to cushion decreases in water supply due to declines in precipitation and increases in temperature. The use of market-oriented approaches to reduce wasteful water use could also be effective in reducing adverse climate change impacts on water resources. In rivers such as the Mekong, where wet-season discharge is projected to increase and the dry-season flows projected to decrease, planned water management interventions such as dams and reservoirs could marginally decrease wet-season flows and substantially increase dry-season flows. [WGII 10.5.2, 10.5.7]

5.3 Australia and New Zealand

5.3.1 Context

Although Australia and New Zealand are very different hydrologically and geologically, both are already experiencing water supply impacts from recent climate change, due to natural variability and to human activity. The strongest regional driver of natural climate variability is the El Niño–Southern Oscillation cycle (Section 2.1.7). Since 2002, virtually all of the eastern states and the south-west region of Australia have moved into drought. This drought is at least comparable to the so-called 'Federation droughts' of 1895 and 1902, and has generated considerable debate about climate change and its impact on water resources, and sustainable water management. [WGII 11.2.1, 11.2.4]

Increases in water demand have placed stress on supply capacity for irrigation, cities, industry and environmental flows. Increased demand since the 1980s in New Zealand has been due to agricultural intensification (Woods and Howard-Williams, 2004). The irrigated area of New Zealand has increased by around 55% each decade since the 1960s (Lincoln Environmental, 2000). From 1985 to 1996, Australian water demand increased by 65% (NLWRA, 2001). In Australia, dryland salinity, alteration of river flows, over-allocation and inefficient use of water resources, land clearing, the intensification of agriculture and fragmentation of ecosystems are major sources of environmental stress (SOE, 2001; Cullen, 2002). In the context of projected climate change, water supply is one of the most vulnerable sectors in Australia and is expected to be a major issue in parts of New Zealand. [WGII 11.ES, 11.2.4, 11.7]

5.3.2 Observed changes

The winter-rainfall-dominated region of south-west Western Australia has experienced a substantial decline in the May–July rainfall since the mid-20th century. The effects of the decline on natural runoff have been severe, as evidenced by a 50% drop in annual inflows to reservoirs supplying the city of Perth (Figure 5.7). Similar pressures have been imposed on local groundwater resources and wetlands. This has been accompanied by a 20% increase in domestic usage in 20 years, and a population growth of 1.7% per year (IOCI, 2002). Although no formal attribution studies were available at the time of the AR4, climate simulations indicated that at least some of the observed drying was related

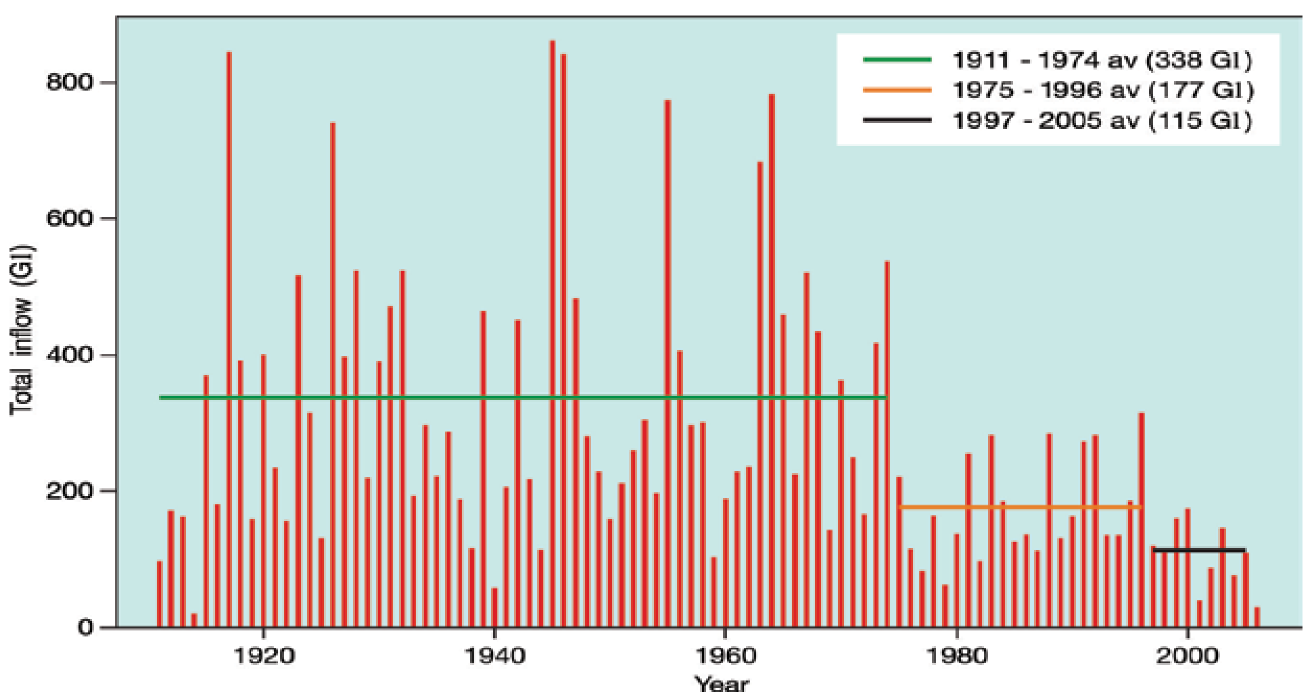


Figure 5.7: *Annual inflow to Perth Water Supply System from 1911 to 2006. Horizontal lines show averages. Source: http://www.watercorporation.com.au/D/dams_streamflow.cfm (courtesy of the Water Corporation of Western Australia). [WGII Figure 11.3]*

to the enhanced greenhouse effect (IOCI, 2002). In recent years, an intense multi-year drought has emerged in eastern and other parts of southern Australia. For example, the total inflow to the Murray River over the five years prior to 2006 was the lowest five-year sequence on record. [WGII 11.6]

5.3.3 Projected changes

5.3.3.1 Water

Ongoing water security problems are *very likely* to increase by 2030 in southern and eastern Australia, and parts of eastern New Zealand that are distant from major rivers. [WGII 11.ES] The Murray-Darling Basin is Australia's largest river basin, accounting for about 70% of irrigated crops and pastures (MDBC, 2006). For the SRES A1 and B1 emission scenarios and a wide range of GCMs, annual streamflow in the Basin is projected to fall 10–25% by 2050 and 16–48% by 2100, with salinity changes of −8 to +19% and −25 to +72%, respectively (Beare and Heaney, 2002). [WGII Table 11.5] Runoff in twenty-nine Victorian catchments is projected to decline by 0–45% (Jones and Durack, 2005). For the A2 scenario, projections indicate a 6–8% decline in annual runoff in most of eastern Australia, and 14% decline in south-west Australia, in the period 2021–2050 relative to 1961–1990 (Chiew et al., 2003). A risk assessment for the city of Melbourne using ten climate models (driven by the SRES B1, A1B and A1F scenarios) indicated average streamflow declines of 3–11% by 2020 and 7–35% by 2050; however, planned demand-side and supply-side actions may alleviate water shortages through to 2020 (Howe et al., 2005). Little is known about future impacts on groundwater in Australia. [WGII 11.4.1]

In New Zealand, proportionately more runoff is *very likely f*rom South Island rivers in winter, and less in summer (Woods and Howard-Williams, 2004). This is *very likely* to provide more water for hydro-electric generation during the winter peak demand period, and reduce dependence on hydro-storage lakes to transfer generation capacity into the next winter. However, industries dependent on irrigation (e.g., dairy, grain production, horticulture) are *likely* to experience negative effects due to lower water availability in spring and summer, their time of peak demand. Increased drought frequency is *very likely* in eastern areas, with potential losses in agricultural production from unirrigated land (Mullan et al., 2005). The effects of climate change on flood and drought frequency are *virtually certain* to be modulated by phases of the ENSO and IPO (McKerchar and Henderson, 2003). The groundwater aquifer for Auckland City has spare capacity to accommodate recharge under all the scenarios examined (Namjou et al., 2006). Base flows in principal streams and springs are *very unlikely* to be compromised unless many dry years occur in succession. [WGII 11.4.1.1]

5.3.3.2 Energy

In Australia and New Zealand, climate change could affect energy production in regions where climate-induced reductions in water supplies lead to reductions in feed water for hydropower turbines and cooling water for thermal power plants. In New Zealand, increased westerly wind speed is *very likely* to enhance wind generation and spillover precipitation into major South Island hydro-catchments, and to increase winter rain in the Waikato catchment (Ministry for the Environment, 2004). Warming is *virtually certain* to increase melting of snow, the ratio of rainfall to snowfall, and river flows in winter and early spring. This is *very likely* to assist hydro-electric generation at the time of peak energy demand for heating. [WGII 11.4.10]

5.3.3.3 Health

There are *likely* to be alterations in the geographical range and seasonality of some mosquito-borne infectious diseases, e.g., Ross River disease, dengue and malaria. Fewer, but heavier, rainfall events are *likely* to affect mosquito breeding and increase the variability in annual rates of Ross River disease, particularly in temperate and semi-arid areas (Woodruff et al., 2002, 2006). Dengue is a substantial threat in Australia; the climate of the far north already supports *Aedes aegypti* (the major mosquito vector of the dengue virus), and outbreaks of dengue have occurred with increasing frequency and magnitude in far-northern Australia over the past decade. Malaria is *unlikely* to establish unless there is a dramatic deterioration in the public health response (McMichael et al., 2003). [WGII 11.4.11]

Eutrophication is a major water-quality problem (Davis, 1997; SOE, 2001). Toxic algal blooms are *likely* to appear more frequently and be present for longer due to climate change. They can pose a threat to human health for both recreation and consumptive water use, and can kill fish and livestock (Falconer, 1997). Simple, resource-neutral, adaptive management strategies, such as flushing flows, can substantially reduce their occurrence and duration in nutrient-rich, thermally stratified water bodies (Viney et al., 2003). [WGII 11.4.1]

5.3.3.4 Agriculture

Large shifts in the geographical distribution of agriculture and its services are *very likely*. Farming of marginal land in drier regions is *likely* to become unsustainable due to water shortages, new biosecurity hazards, environmental degradation and social disruption. [WGII 11.7] Cropping and other agricultural industries reliant on irrigation are *likely* to be threatened where irrigation water availability is reduced. For maize in New Zealand, a reduction in growth duration reduces crop water requirements, providing closer synchronisation of development with seasonal climatic conditions (Sorensen et al., 2000). The distribution of viticulture in both countries is *likely* to change depending upon suitability compared to high-yield pasture and silviculture, and upon irrigation water availability and cost (Hood et al., 2002; Miller and Veltman, 2004; Jenkins, 2006). [WGII 11.4.3]

5.3.3.5 Biodiversity

Impacts on the structure, function and species composition of many natural ecosystems are *likely* to be significant by 2020, and are *virtually certain* to exacerbate existing stresses such as invasive species and habitat loss (e.g., for migratory birds), increase the probability of species extinctions, degrade many natural systems and cause a reduction in ecosystem services for water supply. The impact of climate change on water resources will also interact with other stressors such as invasive species and habitat fragmentation. Saltwater intrusion as a result of sea-level rise, decreases in river flows, and increased drought frequency are *very likely* to alter species composition of freshwater habitats, with consequent impacts on estuarine and coastal fisheries (Bunn and Arthington, 2002; Hall and Burns, 2002; Herron et al., 2002; Schallenberg et al., 2003). [WGII 11.ES, 11.4.2]

5.3.4 Adaptation and vulnerability

Planned adaptation can greatly reduce vulnerability, and opportunities lie in the inclusion of risks due to climate change on the demand as well as the supply side (Allen Consulting Group, 2005). In major cities such as Perth, Brisbane, Sydney, Melbourne, Adelaide, Canberra and Auckland, concerns about population pressures, ongoing drought in southern and eastern Australia, and the impact of climate change are leading water planners to consider a range of adaptation options. While some adaptation has already occurred in response to observed climate change (e.g., ongoing water restrictions, water recycling, seawater desalination) (see Table 5.2) [WGII Table 11.2, 11.6], both countries have taken notable steps in building adaptive capacity by increasing support for research and knowledge, expanding assessments of the risks of climate change for decision makers, infusing climate change into policies and plans, promoting awareness, and dealing more effectively with climate issues. However, there remain environmental, economic, informational, social, attitudinal and political barriers to the implementation of adaptation. [WGII 11.5]

In urban catchments, storm and recycled water could be used to augment supply, although existing institutional arrangements and technical systems for water distribution constrain implementation. Moreover, there is community resistance to the use of recycled water for human consumption (e.g., in such cities as Toowoomba in Queensland, and Goulburn in New South Wales). Installation of rainwater tanks is another adaptation response and is now actively pursued through incentive policies and rebates. For rural activities, more flexible arrangements for allocation are required, via the expansion of water markets, where trading can increase water-use efficiency (Beare and Heaney, 2002). Substantial progress is being made in this

Table 5.2: *Examples of government adaptation strategies to cope with water shortages in Australia. [WGII Table 11.2] Note that the investment figures were accurate at the time the Fourth Assessment went to press in 2007, and do not reflect later developments.*

Government	Strategy	Investment	Source
Australia	Drought aid payments to rural communities	US$0.7 billion from 2001 to 2006	DAFF, 2006b
Australia	National Water Initiative, supported by the Australian Water Fund	US$1.5 billion from 2004 to 2009	DAFF, 2006a
Australia	Murray-Darling Basin Water Agreement	US$0.4 billion from 2004 to 2009	DPMC, 2004
Victoria	Melbourne's Eastern Treatment Plant to supply recycled water	US$225 million by 2012	Melbourne Water, 2006
Victoria	New pipeline from Bendigo to Ballarat, water recycling, interconnections between dams, reducing channel seepage, conservation measures	US$153 million by 2015	Premier of Victoria, 2006
Victoria	Wimmera Mallee pipeline replacing open irrigation channels	US$376 million by 2010	Vic DSE, 2006
NSW	NSW Water Savings Fund supports projects which save or recycle water in Sydney	US$98 million for Round 3, plus more than US$25 million to 68 other projects	DEUS, 2006
Queensland (Qld)	Qld Water Plan 2005 to 2010 to improve water-use efficiency and quality, recycling, drought preparedness, new water pricing	Includes US$182 million for water infrastructure in south-east Qld, and US$302 million to other infrastructure programmes	Queensland Government, 2005
South Australia	Water Proofing Adelaide project is a blueprint for the management, conservation and development of Adelaide's water resources to 2025	N/A	Government of South Australia, 2005
Western Australia (WA)	State Water Strategy (2003) and State Water Plan (proposed) WA Water Corporation doubled supply from 1996 to 2006	US$500 million spent by WA Water Corporation from 1996 to 2006, plus US$290 million for the Perth desalination plant	Government of Western Australia, 2003, 2006; Water Corporation, 2006

regard. Under the National Water Initiative, states, territories and the Australian Government are now committed to pursuing best-practice water pricing and institutional arrangements to achieve consistency in water charging. [WGII 11.5]

When climate change impacts are combined with other non-climate trends, there are some serious implications for sustainability in both Australia and New Zealand. In some river catchments, where increasing urban and rural water demand has already exceeded sustainable levels of supply, ongoing and proposed adaptation strategies [WGII 11.2.5] are *likely* to buy some time. Continued rates of coastal development are *likely* to require tighter planning and regulation if such developments are to remain sustainable. [WGII 11.7]

5.4 Europe

5.4.1 Context

Europe is well watered, with numerous permanent rivers, many of which flow outward from the central part of the continent. It also has large areas with low relief. The main types of climate in Europe are maritime, transitional, continental, polar and Mediterranean; the major vegetation types are tundra, coniferous taiga (boreal forest), deciduous-mixed forest, steppe and Mediterranean. A relatively large proportion of Europe is farmed, with about one-third of the area being classified as arable and cereals being the predominant crop. [WGII TAR 13.1.2.1]

The sensitivity of Europe to climate change has a distinct north–south gradient, with many studies indicating that southern Europe will be the more severely affected (EEA, 2004). The already hot and semi-arid climate of southern Europe is expected to become still warmer and drier, threatening its waterways, hydropower, agricultural production and timber harvests. In central and eastern Europe, summer precipitation is projected to decrease, causing higher water stress. Northern countries are also vulnerable to climate change, although in the initial stages of warming there may be some benefits in terms of, for example, increased crop yields and forest growth. [WGII 12.2.3, SPM]

Key environmental pressures relate to biodiversity, landscape, soil and land degradation, forest degradation, natural hazards, water management, and recreational environments. Most ecosystems in Europe are managed or semi-managed; they are often fragmented and under stress from pollution and other human impacts. [WGII TAR 13.1.2.1]

5.4.2 Observed changes

Mean winter precipitation increased over the period 1946–1999 across most of Atlantic- and northern Europe (Klein Tank et al., 2002) and this has to be interpreted, in part, in the context of winter NAO changes (Scaife et al., 2005). In the Mediterranean area, yearly precipitation trends over the period 1950–2000 were negative in the eastern part (Norrant and Douguédroit, 2006). An increase in mean precipitation per wet day is observed in most parts of the continent, even in some areas which are getting drier (Frich et al., 2002; Klein Tank et al., 2002; Alexander et al., 2006). As a result of these and other changes in the hydrological and thermal regimes (cf. Auer et al., 2007), observed impacts have been documented in other sectors, and some of these are set out in Table 5.3. [WGI Chapter 3; WGII 12.2.1]

5.4.3 Projected changes

5.4.3.1 Water

Generally, for all scenarios, projected mean annual precipitation increases in northern Europe and decreases further south. However, the change in precipitation varies substantially from season to season and across regions in response to changes in large-scale circulation and water vapour loading. Räisänen et al. (2004) project that summer precipitation would decrease

Table 5.3: *Attribution of recent changes in natural and managed ecosystems to recent temperature and precipitation trends. [Selected from WGII Table 12.1]*

Region	Observed change	Reference
Terrestrial ecosystems		
Fennoscandian mountains and sub-Arctic	Disappearance of some types of wetlands (palsa mires) in Lapland; increased species richness and frequency at altitudinal margin of plant life	Klanderud and Birks, 2003; Luoto et al., 2004
Agriculture		
Parts of northern Europe	Increased crop stress during hotter drier summers; increased risk to crops from hail	Viner et al., 2006
Cryosphere		
Russia	Decrease in thickness and areal extent of permafrost and damages to infrastructure	Frauenfeld et al., 2004; Mazhitova et al., 2004
Alps	Decrease in seasonal snow cover (at lower elevations)	Laternser and Schneebeli, 2003; Martin and Etchevers, 2005
Europe	Decrease in glacier volume and area (except some glaciers in Norway)	Hoelzle et al., 2003

substantially (in some areas up to 70% in the SRES A2 scenario) in southern and central Europe, and to a smaller degree up to central Scandinavia. Giorgi et al. (2004) identified enhanced anticyclonic circulation in summer over the north-eastern Atlantic, which induces a ridge over western Europe and a trough over eastern Europe. This blocking structure deflects storms northward, causing a substantial and widespread decrease of precipitation (up to 30–45%) over the Mediterranean Basin as well as western and central Europe. [WGI Table 11.1; WGII 12.3.1.1]

It is projected that climate change will have a range of impacts on water resources (Table 5.3). Annual runoff increases are projected in Atlantic- and northern Europe (Werritty, 2001; Andréasson et al., 2004), and decreases in central, Mediterranean and eastern Europe (Chang et al., 2002; Etchevers et al., 2002; Menzel and Bürger, 2002; Iglesias et al., 2005). Annual average runoff is projected to increase in northern Europe (north of 47°N) by approximately 5–15% up to the 2020s and by 9–22% up to the 2070s, for the A2 and B2 scenarios and climate scenarios from two different climate models (Alcamo et al., 2007). Meanwhile, in southern Europe (south of 47°N), runoff is projected to decrease by 0–23% up to the 2020s and by 6–36% up to the 2070s (for the same set of assumptions). Groundwater recharge is *likely* to be reduced in central and eastern Europe (Eitzinger et al., 2003), with a larger reduction in valleys (Krüger et al., 2002) and lowlands, e.g., in the Hungarian steppes: (Somlyódy, 2002). [WGII 12.4.1, Figure 12.1]

Flow seasonality increases, with higher flows in the peak flow season and either lower flows during the low-flow season or extended dry periods (Arnell, 2003, 2004). [WGII 3.4.1] Studies show an increase in winter flows and decrease in summer flows in the Rhine (Middelkoop and Kwadijk, 2001), Slovakian rivers (Szolgay et al., 2004), the Volga, and central and eastern Europe (Oltchev et al., 2002). Initially, glacier retreat is projected to enhance the summer flow in the rivers of the Alps. However, when glaciers shrink, summer flow is projected to be reduced (Hock et al., 2005) by up to 50% (Zierl and Bugmann, 2005). Summer low flow is projected to decrease by up to 50% in central Europe (Eckhardt and Ulbrich, 2003), and by up to 80% in some rivers in southern Europe (Santos et al., 2002). [WGII 12.4.1]

The regions most prone to an increase in drought risk are the Mediterranean and some parts of central and eastern Europe, where the highest increase in irrigation water demand is projected (Döll, 2002; Donevska and Dodeva, 2004). This calls for developing sustainable land-use planning. Irrigation requirements are *likely* to become substantial in countries (e.g., in Ireland) where it now hardly exists (Holden et al., 2003). It is *likely* that, due to both climate change and increasing water withdrawals, the area affected by severe water stress (withdrawal/availability higher than 40%) will increase and lead to increasing competition for available water resources (Alcamo et al., 2003b; Schröter et al., 2005). [WGII 12.4.1]

Future risk of floods and droughts (see Table 5.4). Flood risk is projected to increase throughout the continent. The regions most prone to a rise in flood frequencies are eastern Europe, then northern Europe, the Atlantic coast and central Europe, while projections for southern and south-eastern Europe show significant increases in drought frequencies. In some regions, both the risks of floods and droughts are projected to increase simultaneously. [WGII Table 12.4]

Christensen and Christensen (2003), Giorgi et al. (2004), Kjellström (2004) and Kundzewicz et al. (2006) all found a substantial increase in the intensity of daily precipitation events. This holds even for areas with a decrease in mean precipitation, such as central Europe and the Mediterranean. The impact of this change over the Mediterranean region during summer is not clear due to the strong convective rainfall component and its great spatial variability (Llasat, 2001). [WGII 12.3.1.2]

The combined effects of higher temperatures and reduced mean summer precipitation would enhance the occurrence of

Table 5.4: *Impact of climate change on drought and flood occurrence in Europe for various time slices and under various scenarios based on the ECHAM4 and HadCM3 models. [WGII Table 12.2]*

Time slice	Water availability and droughts	Floods
2020s	Increase in annual runoff in northern Europe by up to 15% and decrease in the South by up to 23%[a]	Increasing risk of winter flood in northern Europe and of flash flood in all of Europe
	Decrease in summer flow[d]	Risk of snowmelt flood shifts from spring to winter[c]
2050s	Decrease in annual runoff by up to 20–30% in south-eastern Europe[b]	
2070s	Increase in annual runoff in the North by up to 30% and decrease by up to 36% in the South[a]	Today's 100-year floods are projected to occur more frequently in northern and north-eastern Europe (Sweden, Finland, N. Russia), in Ireland, in central and E. Europe (Poland, Alpine rivers), in Atlantic parts of S. Europe (Spain, Portugal); less frequently in large parts of S. Europe[c]
	Decrease in summer low flow by up to 80%[b, d]	
	Decreasing drought risk in N. Europe, increasing drought risk in W. and S. Europe. By the 2070s, today's 100-year droughts are projected to return, on average, every 10 (or fewer) years in parts of Spain and Portugal, western France, the Vistula Basin in Poland, and western Turkey[c]	

[a] Alcamo et al., 2007; [b] Arnell, 2004, [c] Lehner et al., 2006, [d] Santos et al., 2002.

heatwaves and droughts. Schär et al. (2004) conclude that the future European summer climate would experience a pronounced increase in year-to-year variability and thus a higher incidence of heatwaves and droughts. The Mediterranean and even much of eastern Europe may experience an increase in dry periods by the late 21st century (Polemio and Casarano, 2004). According to Good et al. (2006), the longest yearly dry spell would increase by as much as 50%, especially over France and central Europe. However, there is some recent evidence (Lenderink et al., 2007) that some of these projections for droughts and heatwaves may be slightly overestimated due to the parameterisation of soil moisture in regional climate models. Decreased summer precipitation in southern Europe, accompanied by rising temperatures, which enhances evaporative demand, would inevitably lead to reduced summer soil moisture (cf. Douville et al., 2002) and more frequent and more intense droughts. [WGII 3.4.3, 12.3.1]

Studies indicate a decrease in peak snowmelt floods by the 2080s in parts of the UK (Kay et al., 2006b), but the impact of climate change on flood regime can be both positive or negative, highlighting the uncertainty still remaining in climate change impacts (Reynard et al., 2004). Palmer and Räisänen (2002) analysed the modelled differences in winter precipitation between the control run and an ensemble with transient increase in CO_2 and calculated around the time of CO_2 doubling. Over Europe, a considerable increase in the risk of a very wet winter was found. The probability of total boreal winter precipitation exceeding two standard deviations above normal was found to increase considerably (even five- to seven-fold) over large areas of Europe, with *likely* consequences on winter flood hazard. [WGII 3.4.3]

5.4.3.2 Energy
Hydropower is a key renewable energy source in Europe (19.8% of the electricity generated). By the 2070s, hydropower potential for the whole of Europe is expected to decline by 6%, translated into a 20–50% decrease around the Mediterranean, a 15–30% increase in northern and eastern Europe, and a stable hydropower pattern for western and central Europe (Lehner et al., 2005). Biofuel production is largely determined by the supply of moisture and the length of the growing season (Olesen and Bindi, 2002). [WGII 12.4.8.1]

5.4.3.3 Health
Climate change is also *likely* to affect water quality and quantity in Europe, and hence the risk of contamination of public and private water supplies (Miettinen et al., 2001; Hunter, 2003; Elpiner, 2004; Kovats and Tirado, 2006). Both extreme rainfall and droughts can increase the total microbial loads in freshwater and have implications for disease outbreaks and water-quality monitoring (Howe et al., 2002; Kistemann et al., 2002; Opopol et al. 2003; Knight et al., 2004; Schijven and de Roda Husman, 2005). [WGII 12.4.11]

5.4.3.4 Agriculture
The predicted increase in extreme weather events (e.g., spells of high temperature and droughts) (Meehl and Tebaldi, 2004; Schär et al., 2004; Beniston et al., 2007) is projected to increase yield variability (Jones et al., 2003b) and to reduce average yield (Trnka et al., 2004). In particular, in the European Mediterranean region, increases in the frequency of extreme climate events during specific crop development stages (e.g., heat stress during the flowering period, rainy days during sowing dates), together with higher rainfall intensity and longer dry spells, is *likely* to reduce the yield of summer crops (e.g., sunflower). [WGII 12.4.7.1]

5.4.3.5 Biodiversity
Many systems, such as the permafrost areas in the Arctic and ephemeral (short-lived) aquatic ecosystems in the Mediterranean, are projected to disappear. [WGII 12.4.3]

Loss of permafrost in the Arctic (ACIA, 2004) will be *likely* to cause a reduction in some types of wetlands in the current permafrost zone (Ivanov and Maximov, 2003). A consequence of warming could be a higher risk of algal blooms and increased growth of toxic cyanobacteria in lakes (Moss et al., 2003; Straile et al., 2003; Briers et al., 2004; Eisenreich, 2005). Higher precipitation and reduced frost may enhance nutrient loss from cultivated fields and result in higher nutrient loadings (Bouraoui et al., 2004; Kaste et al., 2004; Eisenreich, 2005), leading to intensive eutrophication of lakes and wetlands (Jeppesen et al., 2003). Higher temperatures will also reduce dissolved oxygen saturation levels and increase the risk of oxygen depletion (Sand-Jensen and Pedersen, 2005). [WGII 12.4.5]

Higher temperatures are *likely* to lead to increased species richness in freshwater ecosystems in northern Europe and decreases in parts of south-western Europe (Gutiérrez Teira, 2003). [WGII 12.4.6]

5.4.4 Adaptation and vulnerability

Climate change will pose two major water management challenges in Europe: increasing water stress mainly in south-eastern Europe, and increasing risk of floods throughout most of the continent. Adaptation options to cope with these challenges are well documented (IPCC, 2001b). Reservoirs and dykes are *likely* to remain the main structural measures to protect against floods in highland and lowland areas, respectively (Hooijer et al., 2004). However, other planned adaptation options are becoming more popular, such as expanded floodplain areas (Helms et al., 2002), emergency flood reservoirs (Somlyódy, 2002), preserved areas for flood water (Silander et al., 2006), and flood forecasting and warning systems, especially for flash floods. Multi-purpose reservoirs serve as an adaptation measure for both floods and droughts. [WGII 12.5.1]

To adapt to increasing water stress, the most common and planned strategies remain supply-side measures such as impounding rivers to form instream reservoirs (Santos et al., 2002; Iglesias et al., 2005). However, new reservoir construction is being increasingly constrained in Europe by environmental regulations (Barreira, 2004) and high investment costs (Schröter et al., 2005). Other supply-side approaches, such as wastewater reuse and desalination, are being more widely considered, but their popularity is dampened, respectively, by health concerns in using wastewater (Geres, 2004), and the high energy costs of desalination (Iglesias et al., 2005). Some planned demand-side strategies are also feasible (AEMA, 2002), such as household, industrial and agricultural water conservation, reducing leaky municipal and irrigation water systems (Donevska and Dodeva, 2004; Geres, 2004), and water pricing (Iglesias et al., 2005). Irrigation water demand may be reduced by introducing crops that are more suited to a changing climate. An example of a unique European approach to adapting to water stress is that regional- and watershed-level strategies to adapt to climate change are being incorporated into plans for integrated water management (Kabat et al., 2002; Cosgrove et al., 2004; Kashyap, 2004), while national strategies are being designed to fit into existing governance structures (Donevska and Dodeva, 2004). [WGII 12.5.1]

Adaptation procedures and risk management practices for the water sector are being developed in some countries and regions (e.g., the Netherlands, the UK and Germany) that recognise the uncertainty of projected hydrological changes. [WGII 3.ES, 3.2, 3.6]

5.5 Latin America

5.5.1 Context

Population growth continues, with consequences for food demand. Because the economies of most Latin American countries depend on agricultural productivity, regional variation in crop yields is a very relevant issue. Latin America has a large variety of climate as result of its geographical configuration. The region also has large arid and semi-arid areas. The climatic spectrum ranges from cold, icy high elevations to temperate and tropical climate. Glaciers have generally receded in the past decades, and some very small glaciers have already disappeared.

The Amazon, the Parana-Plata and Orinoco together carry into the Atlantic Ocean more than 30% of the renewable freshwater of the world. However, these water resources are poorly distributed, and extensive zones have very limited water availability (Mata et al., 2001). There are stresses on water availability and quality where low precipitation or higher temperatures occur. Droughts that are statistically linked to ENSO events generate rigorous restrictions on the water resources of many areas in Latin America.

5.5.2 Observed changes

5.5.2.1 Water

Over the past three decades, Latin America has been subject to climate-related impacts, some of them linked with ENSO events.

- Increases in climate extremes such as floods, droughts and landslides (e.g., heavy precipitation in Venezuela (1999 and 2005); the flooding in the Argentinean Pampas (2000 and 2002), the Amazon drought (2005), destructive hail storms in Bolivia (2002) and in Buenos Aires (2006), Cyclone Catarina in the South Atlantic (2004), and the record hurricane season of 2005 in the Caribbean region). The occurrence of climate-related disasters increased by 2.4 times between the periods 1970–1999 and 2000–2005, continuing the trend observed during the 1990s. Only 19% of the events between 2000 and 2005 have been economically quantified, representing losses of nearly US$20 billion (Nagy et al., 2006). [WGII 13.2.2]
- Stress on water availability: droughts related to La Niña created severe restrictions for the water supply and irrigation demands in central western Argentina and in central Chile. Droughts related to El Niño reduced the flow of the Cauca River in Colombia. [WGII 13.2.2]
- Increases in precipitation were observed in southern Brazil, Paraguay, Uruguay, north-east Argentina (Pampas), and parts of Bolivia, north-west Peru, Ecuador and north-west Mexico. The higher precipitation provoked a 10% increase in flood frequency in the Amazon River at Obidos; a 50% increase in streamflow in the rivers of Uruguay, Parana and Paraguay; and more floods in the Mamore Basin in Bolivian Amazonia. An increase in intense rainfall events and consecutive dry days was also observed over the region. Conversely, a declining trend in precipitation was observed in Chile, south-western Argentina, north-eastern Brazil, southern Peru and western Central America (e.g., Nicaragua). [WGII 13.2.4.1]
- A sea-level rise rate of 2–3 mm/yr during the last 10–20 years in south-eastern South America. [WGII 13.2.4.1]
- Glaciers in the tropical Andes of Bolivia, Peru, Ecuador and Colombia have decreased in area by amounts similar to global changes since the end of the Little Ice Age (see Figure 5.9). The smallest glaciers have been affected the most (see Box 5.5). The reasons for these changes are not the same as those in mid- and high latitudes, being related to complex and spatially varying combinations of higher temperatures and changes in atmospheric moisture content. [WGI 4.5.3]

Further indications of observed trends in hydrological variables are given in Table 5.5 and Figure 5.8.

5.5.2.2 Energy

Hydropower is the main electrical energy source for most countries in Latin America, and is vulnerable to large-scale and persistent rainfall anomalies due to El Niño and La Niña, as observed in Argentina, Colombia, Brazil, Chile, Peru, Uruguay and Venezuela. A combination of increased energy demand and droughts caused a virtual breakdown of hydro-electricity in most of Brazil in 2001 and contributed to a reduction in GDP (Kane, 2002). Glacier retreat is also affecting hydropower generation, as observed in the cities of La Paz and Lima. [WGII 13.2.2, 13.2.4]

5.5.2.3 Health

There are linkages between climate-related extreme events and health in Latin America. Droughts favour epidemics in

Table 5.5: *Some recent trends in hydrological variables. [WGII Table 13.1, Table 13.2, Table 13.3]*

Current trends in precipitation (WGII Table 13.2)		
Precipitation (change shown in % unless otherwise indicated)	**Period**	**Change**
Amazonia – northern/southern (Marengo, 2004)	1949–1999	-11 to -17 / -23 to +18
Bolivian Amazonia (Ronchail et al., 2005)	since 1970	+15
Argentina – central and north-east (Penalba and Vargas, 2004)	1900–2000	+1 SD to +2 SD
Uruguay (Bidegain et al., 2005)	1961–2002	+ 20
Chile – central (Camilloni, 2005)	last 50 years	-50
Colombia (Pabón, 2003)	1961–1990	-4 to +6

Selected hydrological extremes and their impacts, 2004–2006 (WGII Table 13.1)	
Heavy rains Sep. 2005	Colombia: 70 deaths, 86 injured, 6 disappeared and 140,000 flood victims (NOAA, 2005).
Heavy rains Feb. 2005	Venezuela: heavy precipitation (mainly on central coast and in Andean mountains), severe floods and heavy landslides. Losses of US$52 million; 63 deaths and 175,000 injuries (UCV, 2005; DNPC, 2005/2006).
Droughts 2004–2006	Argentina – Chaco: losses estimated at US$360 million; 120,000 cattle lost, 10,000 evacuees in 2004 (SRA, 2005). Also in Bolivia and Paraguay: 2004/05. Brazil – Amazonia: severe drought affected central and south-western Amazonia, probably associated with warm sea surface temperatures in the tropical North Atlantic (http://www.cptec.inpe.br/). Brazil – Rio Grande do Sul: reductions of 65% and 56% in soybean and maize production (http://www.ibge.gov.br/home/ In English: http://www.ibge.gov.br/english/).

Glacier retreat trends (WGII Table 13.3)	
Glaciers/Period	*Changes/Impacts*
Peru[a,b] last 35 years	22% reduction in glacier total area (cf. Figure 5.9); reduction of 12% in freshwater in the coastal zone (where 60% of the country's population live). Estimated water loss almost 7,000 × 10^6 m^3
Peru[c] last 30 years	Reduction up to 80% of glacier surface from very small glaciers; loss of 188 × 10^6 m^3 in water reserves during the last 50 years.
Colombia[d] 1990–2000	82% reduction in glaciers; under the current climate trends, Colombia's glaciers are expected to disappear completely within the next 100 years.
Ecuador[e] 1956–1998	There has been a gradual decline in glacier length; reduction of water supply for irrigation, clean water supply for the city of Quito.
Bolivia[f] since mid-1990s	Projected glacier shrinkage in Bolivia indicates adverse consequences for water supply and hydropower generation for the city of La Paz. Also see Box 5.5.

[a] Vásquez, 2004; [b] Mark and Seltzer, 2003; [c] NC-Perú, 2001; [d] NC-Colombia, 2001; [e] NC-Ecuador, 2000; [f] Francou et al., 2003.

Colombia and Guyana, while floods engender epidemics in the dry northern coastal region of Peru (Gagnon et al., 2002). Annual variations in dengue/dengue haemorrhagic fever in Honduras and Nicaragua appear to be related to climate-driven fluctuations in vector densities (temperature, humidity, solar radiation and rainfall) (Patz et al., 2005). Flooding produced outbreaks of *leptospirosis* in Brazil, particularly in densely populated areas without adequate drainage (Ko et al., 1999; Kupek et al., 2000). The distribution of *schistosomiasis* is probably linked to climatic factors. Concerning diseases transmitted by rodents, there is good evidence that some increases in occurrence are observed during/after heavy rainfall and flooding because of altered patterns of human–pathogen–rodent contact. In some coastal areas of the Gulf of Mexico, an increase in sea surface temperature and precipitation has been associated with an increase in dengue transmission cycles (Hurtado-Díaz et al., 2006). [WGII 13.2.2, 8.2.8.3]

5.5.2.4 *Agriculture*

As a result of high rainfall and humidity caused by El Niño, several fungal diseases in maize, potato, wheat and bean are observed in Peru. Some positive impacts are reported for the Argentinean Pampas region, where increases in precipitation led to increases in crop yields close to 38% in soybean, 18% in maize, 13% in wheat, and 12% in sunflower. In the same way, pasture productivity increased by 7% in Argentina and Uruguay. [WGII 13.2.2, 13.2.4]

5.5.2.5 *Biodiversity*

There are few studies assessing the effects of climate change on biodiversity, and in all of them it is difficult to differentiate the effects caused by climate change from those arising from other factors. Tropical forests of Latin America, particularly those of Amazonia, are increasingly susceptible to fire occurrences due to increased El Niño-related droughts and to land-use change

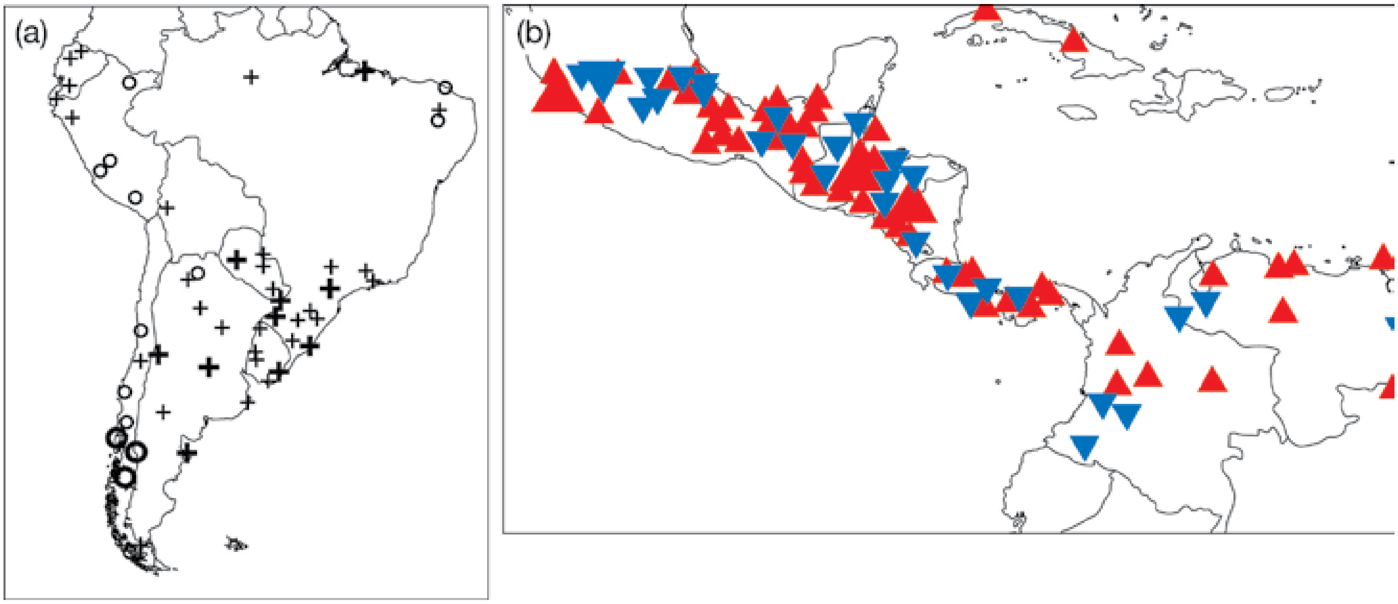


Figure 5.8: *Trends in annual rainfall in (a) South America (1960–2000). An increase is shown by a plus sign, a decrease by a circle; bold values indicate significance at P ≤ 0.05 (reproduced from Haylock et al. (2006) with permission from the American Meteorological Society). (b) Central America and northern South America (1961–2003). Large red triangles indicate positive significant trends, small red triangles indicate positive non-significant trends, large blue triangles indicate negative significant trends, and small blue triangles indicate negative non-significant trends (reproduced from Aguilar et al. (2005) with permission from the American Geophysical Union. [WGII Figure 13.1]*

(deforestation, selective logging and forest fragmentation). [WGII 13.2.2]

In relation to biodiversity, populations of toads and frogs in cloud forests were found to be affected after years of low precipitation. In Central and South America, links between higher temperatures and frog extinctions caused by a skin disease (*Batrachochytrium dendrobatidis*) were found. One study considering data from 1977–2001 showed that coral cover on Caribbean reefs decreased by 17% on average in the year following a hurricane, with no evidence of recovery for at least eight post-impact years. [WGII 13.2.2]

5.5.3 Projected changes

5.5.3.1 Water and climate

With *medium confidence*, the projected mean warming for Latin America for 2100, according to different climate models, ranges from 1ºC to 4ºC for the B2 emissions scenario and from 2ºC to 6ºC for the A2 scenario. Most GCM projections indicate larger (positive or negative) rainfall anomalies for the tropical region and smaller ones for the extra-tropical part of South America. In addition, extreme dry seasons are projected to become more frequent in Central America, for all seasons. Beyond these results there is relatively little agreement between models on changes in the frequency of extreme seasons for precipitation. For daily precipitation extremes, one study based on two AOGCMs suggests an increase in the number of wet days over parts of south-eastern South America and central Amazonia, and weaker daily precipitation extremes over the coast of north-east Brazil. [WGI Table 11.1, 11.6; WGII 13.ES, 13.3.1]

The number of people living in already water-stressed watersheds (i.e., having supplies less than 1,000 m^3/capita/yr) in the absence of climate change is estimated at 22.2 million (in 1995). Under the SRES scenarios, this number is estimated to increase to between 12 and 81 million in the 2020s and to between 79 and 178 million in the 2050s (Arnell, 2004). These estimates do not take into account the number of people moving out of water stress, which is shown in Table 5.6. The current vulnerabilities observed in many regions of Latin American countries will be increased by the joint negative effect of growing demands due to an increasing population rate for water supply and irrigation, and the expected drier conditions in many basins. Therefore, taking into account the number of people experiencing decreased water stress, there is still a net increase in the number of people becoming water-stressed. [WGII 13.4.3]

5.5.3.2 Energy

Expected further glacier retreat is projected to impact the generation of hydro-electricity in countries such as Colombia and Peru (UNMSM, 2004). Some small tropical glaciers have already disappeared, and others are *likely* to do so within the next few decades, with potential effects on hydropower generation (Ramírez et al., 2001). [WGI 4.5.3; WGII 13.2.4]

5.5.3.3 Health

Around 262 million people, representing 31% of the Latin American population, live in malaria risk areas (i.e., tropical and sub-tropical regions) (PAHO, 2003). Based on SRES emissions scenarios and socio-economic scenarios, some projections indicate decreases in the length of the transmission season of

Box 5.5: Changes in South American glaciers. [WGII Box 1.1]

A general glacier shrinkage in the tropical Andes has been observed and, as in other mountain ranges, the smallest glaciers are more strongly affected [WGI 4.5.3], with many of them having already disappeared during the last century. As for the largely glacier-covered mountain ranges such as the Cordillera Blanca in Peru and the Cordillera Real in Bolivia, total glacier area has shrunk by about one-third of the Little Ice Age extent (Figure 5.9).

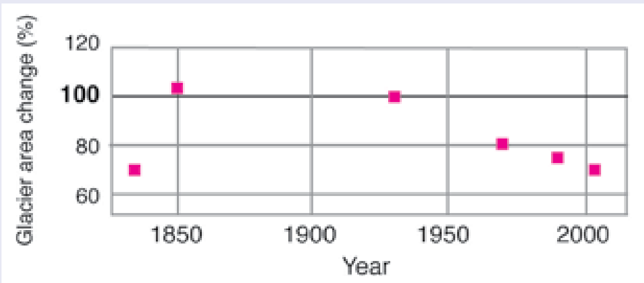


Figure 5.9: *Extent (%) of the total surface area of glaciers of the tropical Cordillera Blanca, Peru, relative to their extent around 1925 (=100) (Georges, 2004). The area of glacier in the Cordillera Blanca in 1990 was 620 km². [Extracted from WGI Figure 4.16]*

The Chacaltaya Glacier in Bolivia (16°S) is a typical example of a disintegrating, and most probably disappearing, small glacier. Its area in 1940 was 0.22 km², and this has currently (in 2005) reduced to less than 0.01 km² (Figure 5.10) (Ramírez et al., 2001; Francou et al., 2003; Berger et al., 2005). Over the period 1992 to 2005, the glacier suffered a loss of 90% of its surface area, and 97% of its volume of ice (Berger et al., 2005). A linear extrapolation from these observed numbers indicates that it may disappear completely before 2010 (Coudrain et al., 2005). Although, in the tropics, glacier mass balance responds sensitively to changes in precipitation and humidity [WGI 4.5.3], the shrinkage of Chacaltaya is consistent with an ascent of the 0°C isotherm of about 50 m/decade in the tropical Andes since the 1980s (Vuille et al., 2003).

With a mean altitude of 5,260 m above sea level, the glacier was the highest skiing station in the world until a few years ago. The ongoing shrinkage of the glacier during the 1990s has led to its near disappearance, and as a consequence Bolivia has lost its only ski resort (Figure 5.10).

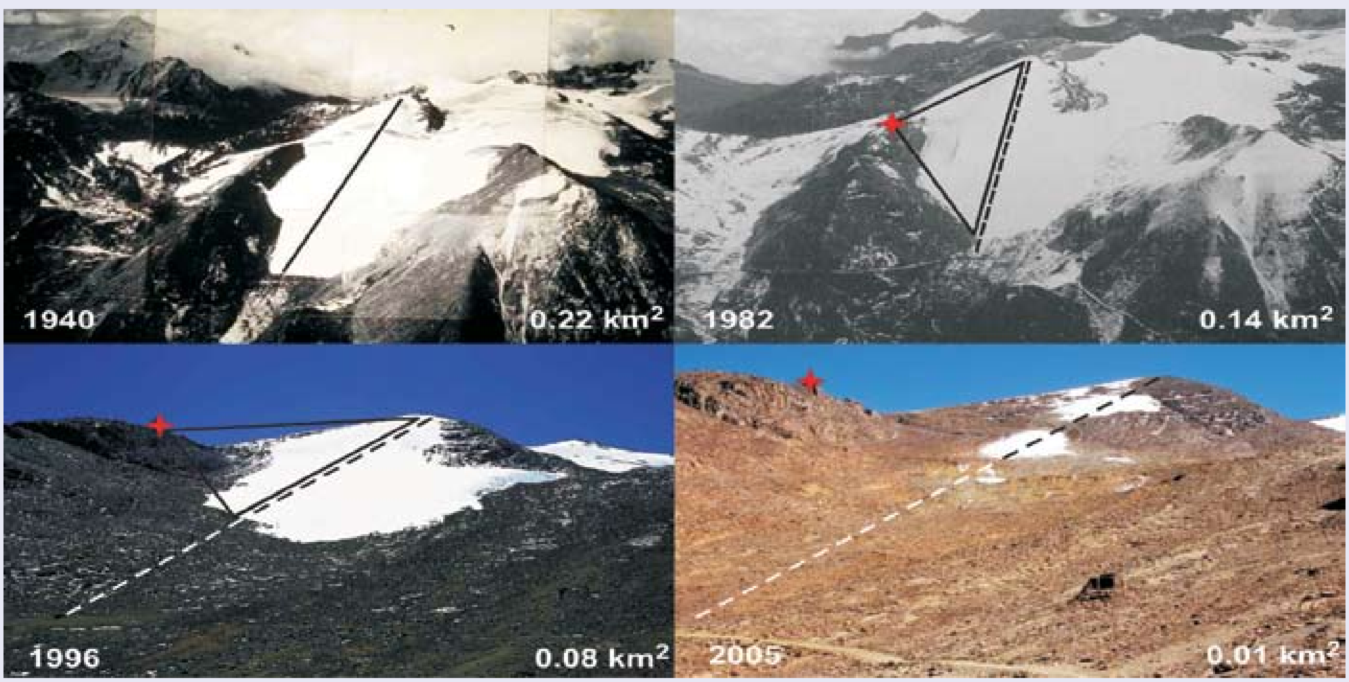


Figure 5.10: *Areal extent of Chacaltaya Glacier, Bolivia, from 1940 to 2005. By 2005, the glacier had separated into three distinct small bodies. The position of the ski hut, which did not exist in 1940, is indicated with a red cross. The ski lift had a length of about 800 m in 1940 and about 600 m in 1996 (shown by a continuous line in 1940 and a broken line in all other panels) and was normally installed during the precipitation season. After 2004, skiing was no longer possible. Photo credits: Francou and Vincent (2006) and Jordan (1991). [WGII Figure 1.1]*

Table 5.6: *Increase in the numbers of people living in water-stressed watersheds in Latin America (million) based on the HadCM3 GCM (Arnell, 2004). [WGII Table 13.6]*

Scenario and GCM	1995	2025		2055	
		Without climate change	With climate change	Without climate change	With climate change
A1	22.2	35.7	21.0	54.0	60.0
A2	22.2	55.9	37.0–66.0	149.3	60.0–150.0
B1	22.2	35.7	22.0	54.0	74.0
B2	22.2	47.3	7.0–77.0	59.4	62.0

malaria in many areas where reductions in precipitation are projected, such as the Amazon and Central America. The results report additional numbers of people at risk in areas around the southern limit of the disease distribution in South America (van Lieshout et al., 2004). Nicaragua and Bolivia have predicted a possible increase in the incidence of malaria in 2010, reporting seasonal variations (Aparicio, 2000; NC-Nicaragua, 2001). The increase in malaria and population at risk could affect the costs of health services, including treatment and social security payments. [WGII 13.4.5]

Other models project a substantial increase in the number of people at risk of dengue due to changes in the geographical limits of transmission in Mexico, Brazil, Peru and Ecuador (Hales et al., 2002). Some models project changes in the spatial distribution (dispersion) of the cutaneous *leishmaniasis* vector in Peru, Brazil, Paraguay, Uruguay, Argentina and Bolivia (Aparicio, 2000; Peterson and Shaw, 2003), as well as the monthly distribution of the dengue vector (Peterson et al., 2005). [WGII 13.4.5]

5.5.3.4 Agriculture

Several studies using crop simulation models, under climate change, for commercial crops, were run for the Latin America region. The number of people at risk of hunger under SRES emissions scenario A2 is projected to increase by 1 million in 2020, while it is projected that there will be no change for 2050 and that the number will decrease by 4 million in 2080. [WGII Table 13.5, 13.4.2]

5.5.3.5 Biodiversity

Through a complex set of alterations comprising a modification in rainfall and runoff, a replacement of tropical forest by savannas is expected in eastern Amazonia and the tropical forests of central and southern Mexico, along with replacement of semi-arid by arid vegetation in parts of north-east Brazil and most of central and northern Mexico due to the synergistic effects of both land-use and climate changes. By the 2050s, 50% of agricultural lands are *very likely* to be subjected to desertification and salinisation in some areas. [WGII 13.ES, 13.4.1, 13.4.2]

5.5.4 Adaptation and vulnerability

5.5.4.1 Past and current adaptation

The lack of adequate adaptation strategies to cope with the hazards and risks of floods and droughts in Latin American countries is due to low gross national product (GNP), the increasing population settling in vulnerable areas (prone to flooding, landslides or drought), and the absence of the appropriate political, institutional and technological frameworks (Solanes and Jouravlev, 2006). Nevertheless, some communities and cities have organised themselves, becoming active in disaster prevention (Fay et al., 2003b). Many poor inhabitants have been encouraged to relocate from flood-prone areas to safer places. With the assistance of IRDB and IDFB loans, they built new homes, e.g., resettlements in the Paraná River Basin of Argentina, after the 1992 flood (IRDB, 2000). In some cases, a change in environmental conditions affecting the typical economy of the Pampas has led to the introduction of new production activities through aquaculture, using natural regional fish species such as pejerrey (*Odontesthes bonariensis*) (La Nación, 2002). Another example, in this case related to the adaptive capacity of people to water stresses, is provided by 'self-organisation' programmes for improving water supply systems in very poor communities. The organisation Business Partners for Development Water and Sanitation Clusters has been working on four 'focus' plans in Latin America: Cartagena (Colombia), La Paz and El Alto (Bolivia), and some underprivileged districts of Gran Buenos Aires (Argentina) (The Water Page, 2001; Water 21, 2002). Rainwater cropping and storage systems are important features of sustainable development in the semi-arid tropics. In particular, there is a joint project developed in Brazil by the NGO Network Articulação no Semi-Árido (ASA) Project, called the P1MC Project, for one million cisterns to be installed by civilian society in a decentralised manner. The plan is to supply drinking water to one million rural households in the perennial drought areas of the Brazilian semi-arid tropics (BSATs). During the first stage, 12,400 cisterns were built by ASA and the Ministry of Environment of Brazil and a further 21,000 were planned by the end of 2004 (Gnadlinger, 2003). In Argentina, national safe water programmes for local communities in arid regions of Santiago del Estero Province installed ten rainwater catchments and storage systems between 2000 and 2002 (Basán Nickisch, 2002). [WGII 13.2.5]

5.5.4.2 Adaptation: practices, options and constraints

Water management policies in Latin America need to be relevant and should be included as a central point for adaptation criteria. This will enhance the region's capability to improve its management of water availability. Adaptation to drier conditions in approximately 60% of the Latin America region will need large investments in water supply systems. Managing trans-basin diversions has been the solution in many areas (e.g., Yacambu Basin in Venezuela, Alto Piura and Mantaro Basin in Peru). Water conservation practices, water recycling and optimisation of water consumption have been recommended during water-stressed periods (COHIFE, 2003) (see Box 5.6). [WGII 13.5]

Box 5.6: Adaptation capacity of the South American highlands pre-Colombian communities. [WGII Box 13.2]

The subsistence of indigenous civilisations in the Americas relied on the resources cropped under the prevailing climate conditions around their settlements. In the highlands of today's Latin America, one of the most critical limitations affecting development was, and currently is, the irregular distribution of water. This situation is the result of the particularities of atmospheric processes and extremes, the rapid runoff in the deep valleys, and the changing soil conditions. Glacier melt was, and still is, a reliable source of water during dry seasons. However, the streams run into the valleys within bounded water courses, bringing water only to certain locations. Since the rainfall seasonality is strong, runoff from glaciers is the major dependable source of water during the dry season. Consequently, the pre-Colombian communities developed different adaptive actions to satisfy their requirements. Today, the problem of achieving the necessary balance between water availability and demand is practically the same, although the scale might be different.

Under such limitations, from today's Mexico to northern Chile and Argentina, the pre-Colombian civilisations developed the necessary capacity to adapt to the local environmental conditions. Such capacity involved their ability to solve some hydraulic problems and foresee climate variations and seasonal rain periods. On the engineering side, their developments included the use of captured rainwater for cropping, filtration and storage; and the construction of surface and underground irrigation channels, including devices to measure the quantity of water stored (Figure 5.11) (Treacy, 1994; Wright and Valencia Zegarra, 2000; Caran and Nelly, 2006). They were also able to interconnect river basins from the Pacific and Atlantic watersheds, in the Cumbe valley and in Cajamarca (Burger, 1992).

Figure 5.11: *Nasca (southern coast of Peru) system of water cropping for underground aqueducts and feeding the phreatic layers.*

Other capacities were developed to foresee climatic variations and seasonal rain periods, to organise their sowing schedules, and to programme their yields (Orlove et al., 2000). These efforts enabled the subsistence of communities which, at the peak of the Inca civilisation, included some 10 million people in what is today Peru and Ecuador.

Their engineering capacities also enabled the rectification of river courses, as in the case of the Urubamba River, and the building of bridges, either hanging ones or with pillars cast in the river bed. They also used running water for leisure and worship purposes, as seen today in the 'Baño del Inca' (the spa of the Incas), fed from geothermal sources, and the ruins of a musical garden at Tampumacchay in the vicinity of Cusco (Cortazar, 1968). The priests of the Chavin culture used running water flowing within tubes bored into the structure of the temples in order to produce a sound like the roar of a jaguar; the jaguar being one of their deities (Burger, 1992). Water was also used to cut stone blocks for construction. As seen in Ollantaytambo, on the way to Machu Picchu, these stones were cut in regular geometric shapes by leaking water into cleverly made interstices and freezing it during the Altiplano night, at below-zero temperatures. They also acquired the capacity to forecast climate variations, such as those from El Niño (Canziani and Mata, 2004), enabling the most convenient and opportune organisation of their foodstuff production. In short, they developed pioneering efforts to adapt to adverse local conditions and define sustainable development paths.

Today, under the vagaries of weather and climate, exacerbated by the increasing greenhouse effect and the shrinkage of the glaciers (Carey, 2005; Bradley et al., 2006), it would be extremely useful to revisit and update such adaptation measures. Education and training of present community members on the knowledge and technical abilities of their ancestors would be a way forward. ECLAC's procedures for the management of sustainable development (Dourojeanni, 2000), when considering the need to manage the extreme climate conditions in the highlands, refer back to the pre-Colombian irrigation strategies.

Problems in education and public health services are fundamental barriers to adaptation; for example, in the case of extreme events (e.g., floods or droughts) mainly in poor rural areas (Villagrán de León et al., 2003). [WGII 13.5]

5.6 North America

5.6.1 Context and observed change

Climate change will constrain North America's already over-allocated water resources, thereby increasing competition among agricultural, municipal industrial, and ecological uses (*very high confidence*). Some of the most important societal and ecological impacts of climate change that are anticipated in this region stem from changes in surface and groundwater hydrology. Table 5.7 outlines the changes observed in North America during the past century, which illustrate the wide range of effects of a warming climate on water resources. [WGII 14.ES]

As the rate of warming accelerates during the coming decades, changes can be anticipated in the timing, volume, quality and spatial distribution of freshwater available for human settlements, agriculture and industrial users in most regions of North America. While some of the water resource changes listed above hold true for much of North America, 20th-century trends suggest a high degree of regional variability in the impacts of climate change on runoff, streamflow and groundwater recharge. Variations in wealth and geography also contribute to an uneven distribution of *likely* impacts, vulnerabilities, and capacities to adapt in both Canada and the USA. [WGII 14.ES, 14.1]

Table 5.7: *Observed changes in North American water resources during the past century (↑ = increase, ↓ = decrease).*

Water resource change	Examples from AR4
1–4 week earlier peak streamflow due to earlier warming-driven snowmelt	US West and US New England regions, Canada [WGII 1.3, 14.2]
↓ Proportion of precipitation falling as snow	Western Canada and prairies, US West [WGII 14.2, WGI 4.2]
↓ Duration and extent of snow cover	Most of North America [WGI 4.2]
↑ Annual precipitation	Most of North America [WGI 3.3]
↓ Mountain snow water equivalent	Western North America [WGI 4.2]
↓ Annual precipitation	Central Rockies, south-western USA, Canadian prairies and eastern Arctic [WGII 14.2]
↑ Frequency of heavy precipitation events	Most of USA [WGII 14.2]
↓ Runoff and streamflow	Colorado and Columbia River Basins [WGII 14.2]
Widespread thawing of permafrost	Most of northern Canada and Alaska [WGII 14.4, 15.7]
↑ Water temperature of lakes (0.1–1.5°C)	Most of North America [WGII 1.3]
↑ Streamflow	Most of the eastern USA [WGII 14.2]
Glacial shrinkage	US western mountains, Alaska and Canada [WGI 4.ES, 4.5]
↓ Ice cover	Great Lakes, Gulf of St. Lawrence [WGII 4.4, 14.2]
Salinisation of coastal surfacewaters	Florida, Louisiana [WGII 6.4]
↑ Periods of drought	Western USA, southern Canada [WGII 14.2]

5.6.2 Projected change and consequences

5.6.2.1 Freshwater resources

Simulated future annual runoff in North American catchments varies by region, general circulation model (GCM) and emissions scenario. Annual mean precipitation is projected to decrease in the south-western USA but increase over most of the remainder of North America up to 2100. [WGI 11.5.3.2; WGII 14.3.1] Increases in precipitation in Canada are projected to be in the range of +20% for the annual mean and +30% for winter, under the A1B scenario. Some studies project widespread increases in extreme precipitation [WGI 11.5.3.3; WGII 14.3.1], but also droughts associated with greater temporal variability in precipitation. In general, projected changes in precipitation extremes are larger than changes in mean precipitation. [WGI 10.3.6.1; WGII 14.3.1]

Warming and changes in the form, timing and amount of precipitation will be *very likely* to lead to earlier melting and significant reductions in snowpack in the western mountains by the middle of the 21st century. In projections for mountain snowmelt-dominated watersheds, snowmelt runoff advances, winter and early spring flows increase (raising flooding potential), and summer flows decrease substantially. [WGII 14.4] Hence, over-allocated water systems of the western USA and Canada that rely on capturing snowmelt runoff could be especially vulnerable, as are those systems that rely upon runoff from glaciers. [WGII 14.2, 15.2]

In British Columbia, projected impacts include increased winter precipitation, more severe spring floods on the coast and the interior, and more summer droughts along the south coast and southern interior, which would decrease streamflow in these areas and affect both fish survival and water supplies in the summer, when demand is the highest. In the Great Lakes, projected impacts associated with lower water levels are *likely* to exacerbate challenges relating to water quality, navigation, recreation, hydropower generation, water transfers and bi-national relationships. [WGII 14.2, 14.4] Many, but not all, assessments project lower net basin supplies and water levels for the Great Lakes–St. Lawrence Basin. [WGII 14.ES, 14.2]

With climate change, availability of groundwater is *likely* to be influenced by three key factors: *withdrawals* (reflecting development, demand, and availability of other sources), *evapotranspiration* (increases with temperature) and *recharge* (determined by temperature, timing and amount of precipitation, and surface water interactions). Simulated annual groundwater base flows and aquifer levels respond to temperature, precipitation and pumping – decreasing in scenarios that are drier or have higher pumping and increasing in scenarios that are wetter. In some cases there are base flow shifts; increasing in winter and decreasing in spring and early summer. [WGII 14.4.1] Increased evapotranspiration or groundwater pumping in semi-arid and arid regions of North America may lead to salinisation of shallow aquifers. [WGII 3.4] In addition, climate change is *likely* to increase the occurrence of saltwater intrusion into coastal aquifers as sea level rises. [WGII 3.4.2]

5.6.2.2 Energy

Hydropower production is known to be sensitive to total runoff, to its timing, and to reservoir levels. During the 1990s, for example, Great Lakes levels fell as a result of a lengthy drought, and in 1999 hydropower production was down significantly both at Niagara and Sault St. Marie (CCME, 2003). [WGII 4.2] For a 2–3°C warming in the Columbia River Basin and British Columbia Hydro service areas, the hydro-electric supply under worst-case water conditions for winter peak demand will be *likely* to increase (*high confidence*). Similarly, Colorado River hydropower yields will be *likely* to decrease significantly (Christensen et al., 2004), as will Great Lakes hydropower (Moulton and Cuthbert, 2000; Lofgren et al., 2002; Mirza, 2004). Lower Great Lake water levels could lead to large economic losses (Canadian $437–660 million/yr), with increased water levels leading to small gains (Canadian $28–42 million/yr) (Buttle et al., 2004; Ouranos, 2004). Northern Québec hydropower production would be *likely* to benefit from greater precipitation and more open water conditions, but hydro plants in southern Québec would be *likely* to be affected by lower water levels. Consequences of changes in seasonal distribution of flows and in the timing of ice formation are uncertain (Ouranos, 2004). [WGII 3.5, 14.4.8]

Solar resources could be affected by future changes in cloudiness, which could slightly increase the potential for solar energy in North America south of 60°N (based on many models and the A1B emissions scenario for 2080–2099 *versus* 1980–1999). [WGI Figure 10.10] Pan et al. (2004), however, projected the opposite; that increased cloudiness will decrease the potential output of photovoltaics by 0–20% (based on the HadCM2 and RegCM2[24] models with an idealised scenario of CO_2 increase). [WGII 14.4.8] Bioenergy potential is climate-sensitive through direct impacts on crop growth and availability of irrigation water. Bioenergy crops are projected to compete successfully for agricultural acreage at a price of US$33/$10^6$ g, or about US$1.83/$10^9$ joules (Walsh et al., 2003). Warming and precipitation increases are expected to allow the bioenergy crop, switchgrass, to compete effectively with traditional crops in the central USA (based on the RegCM2 model and doubled CO_2 concentration) (Brown et al., 2000). [WGII 14.4.8]

5.6.2.3 Health

Water-borne disease outbreaks from all causes are distinctly seasonal in North America, clustered in key watersheds, and associated with heavy precipitation (in the USA: Curriero et al., 2001) or with extreme precipitation and warmer temperatures (in Canada: Thomas et al., 2006). Heavy runoff after severe rainfall can also contaminate recreational waters and increase the risk of human illness (Schuster et al., 2005) through higher bacterial counts. This association is often strongest at beaches close to rivers (Dwight et al., 2002). Water-borne diseases and degraded water quality are *very likely* to increase with more heavy precipitation. Food-borne diseases also show some relationship with temperature trends. In Alberta, ambient temperature is strongly, but non-linearly, associated with the occurrence of enteric pathogens (Fleury et al., 2006). [WGII 14.ES, 14.2.5]

An increase in intense tropical cyclone activity is *likely*. [WGI SPM] Storm surge flooding is already a problem along the Gulf of Mexico and South Atlantic coasts of North America. The death toll from Hurricane Katrina in 2005 is estimated at 1,800 [WGII 6.4.2], with some deaths and many cases of diarrhoeal illness associated with contamination of water supplies (CDC, 2005; Manuel, 2006). [WGII 8.2.2; see also Section 4.5 regarding riverine flooding]

5.6.2.4 Agriculture

Research since the TAR supports the conclusion that moderate climate change will be *likely* to increase yields of North American rain-fed agriculture, but with smaller increases and more spatial variability than in earlier estimates (*high confidence*) (Reilly, 2002). Many crops that are currently near climate thresholds, however, are projected to suffer decreases in yields, quality, or both, with even modest warming (*medium confidence*) (Hayhoe et al., 2004; White et al., 2006). [WGII 14.4.4]

The vulnerability of North American agriculture to climatic change is multidimensional and is determined by interactions between pre-existing conditions, indirect stresses stemming from climate change (e.g., changes in pest competition, water availability), and the sector's capacity to cope with multiple, interacting factors, including economic competition from other regions as well as improvements in crop cultivars and farm management (Parson et al., 2003). Water availability is the major factor limiting agriculture in south-east Arizona, but farmers in the region perceive that technologies and adaptations such as crop insurance have recently decreased vulnerability (Vasquez-Leon et al., 2003). Areas with marginal financial and resource endowments (e.g., the US northern plains) are especially vulnerable to climate change (Antle et al., 2004). Unsustainable land-use practices will tend to increase the

[24] See Appendix I for model descriptions.

vulnerability of agriculture in the US Great Plains to climate change (Polsky and Easterling, 2001). [WGII 14.4.4; see also Section 4.2.2] Heavily utilised groundwater-based systems in the south-west USA are *likely* to experience additional stress from climate change that leads to decreased recharge (*high confidence*), thereby impacting agricultural productivity. [WGII 14.4.1]

Decreases in snow cover and more winter rain on bare soil are *likely* to lengthen the erosion season and enhance erosion, increasing the potential for water quality impacts in agricultural areas. Soil management practices (e.g., crop residue, no-till) in the North American grainbelt may not provide sufficient erosion protection against future intense precipitation and associated runoff (Hatfield and Pruger, 2004; Nearing et al., 2004). [WGII 14.4.1]

5.6.2.5 Biodiversity

A wide range of species and biomes could be affected by the projected changes in rainfall, soil moisture, surface water levels and streamflow in North America during the coming decades.

The lowering of lake and pond water levels, for example, can lead to reproductive failure in amphibians and fish, and differential responses among species can alter aquatic community composition and nutrient flows. Changes in rainfall patterns and drought regimes can facilitate other types of ecosystem disturbances, including fire (Smith et al., 2000) and biological invasion (Zavaleta and Hulvey, 2004). [WGII 14.4.2] Landward replacement of grassy freshwater marshes by more salt-tolerant mangroves, e.g., in the south-eastern Florida Everglades since the 1940s, has been attributed to the combined effects of sea-level rise and water management, resulting in lowered water tables (Ross et al., 2000). [WGII 1.3.3.2] Changes in freshwater runoff to the coast can alter salinity, turbidity and other aspects of water quality that determine the productivity and distribution of plant and animal communities. [WGII 6.4]

At high latitudes, several models simulate increased net primary productivity of North American ecosystems as a result of expansion of forests into the tundra, plus longer growing seasons (Berthelot et al., 2002), depending largely on whether there is sufficient enhancement of precipitation to offset increased evapotranspiration in a warmer climate. Forest growth appears to be slowly accelerating in regions where tree growth has historically been limited by low temperatures and short growing seasons. Growth is slowing, however, in areas subject to drought. Radial growth of white spruce on dry south-facing slopes in Alaska has decreased over the last 90 years, due to increased drought stress (Barber et al., 2000). Modelling experiments by Bachelet et al. (2001) project the areal extent of drought-limited ecosystems to increase 11% per 1ºC warming in the continental USA. [WGII 14.4] In North America's Prairie Pothole region, models have projected an increase in drought with a 3°C regional temperature increase and varying changes in precipitation, leading to large losses of wetlands and to declines in the populations of waterfowl breeding there (Johnson et al., 2005). [WGII 4.4.10]

Ecological sustainability of fish and fisheries productivity are closely tied to water supply and water temperature. It is *likely* that cold-water fisheries will be negatively affected by climate change; warm-water fisheries will generally gain; and the results for cool-water fisheries will be mixed, with gains in the northern and losses in the southern portions of their ranges. Salmonids, which prefer cold, clear water, are *likely* to experience the most negative impacts (Gallagher and Wood, 2003). Arctic freshwater fisheries are *likely* to be most affected, as they will experience the greatest warming (Wrona et al., 2005). In Lake Erie, larval recruitment of river-spawning walleye will depend on temperature and flow changes, but lake-spawning stocks will be *likely* to decline due to the effects of warming and lower lake levels (Jones et al., 2006). The ranges of warm-water species will tend to shift northwards or to higher altitudes (Clark et al., 2001; Mohseni et al., 2003) in response to changes in water temperature. [WGII 14.4]

5.6.2.6 Case studies of climate change impacts in large watersheds in North America

Boxes 5.7 and 5.8 describe two cases that illustrate the potential impacts and management challenges posed by climate change in 'water-scarce' and 'water-rich' environments in western North America: the Colorado and the Columbia River Basins, respectively.

5.6.3 Adaptation

Although North America has considerable capacity to adapt to the water-related aspects of climate change, actual practice has not always protected people and property from the adverse impacts of floods, droughts, storms and other extreme weather events. Especially vulnerable groups include indigenous peoples and those who are socially or economically disadvantaged. Traditions and institutions in North America have encouraged a decentralised response framework where adaptation tends to be reactive, unevenly distributed, and focused on coping with rather than preventing problems. Examples of adaptive behaviour influenced exclusively or predominantly by projections of climate change and its effects on water resources are largely absent from the literature. [WGII 14.5.2] A key prerequisite for sustainability in North America is 'mainstreaming' climate issues into decision making. [WGII 14.7]

The vulnerability of North America depends on the effectiveness of adaptation and the distribution of coping capacity; both of which are currently uneven and have not always protected vulnerable groups from the adverse impacts of climate variability and extreme weather events. [WGII 14.7] The USA and Canada are developed economies with extensive infrastructure and mature institutions, with important regional and socio-economic variation (NAST, 2000; Lemmen and Warren, 2004). These capabilities have led to adaptation and coping strategies across a wide range of historical conditions, with both successes and failures. Most studies on adaptive strategies consider implementation based on past experiences (Paavola and Adger, 2002). [WGII 14.5]

Box 5.7: Drought and climatic changes in the Colorado River Basin.

The Colorado River supplies much of the water needs of seven US states, two Mexican states, and thirty-four Native American tribes (Pulwarty et al., 2005). These represent a population of 25 million inhabitants with a projection of 38 million by the year 2020. Over the past 100 years the total area affected by severe or extreme climatological drought in the USA has averaged around 14% each year with this percentage having been as high as 65% in 1934.

The westward expansion of population and economic activities, and concurrent responses to drought events, have resulted in significant structural adaptations, including hundreds of reservoirs, irrigation projects and groundwater withdrawals, being developed in semi-arid environments. As widely documented, the allocation of Colorado River water to basin states occurred during the wettest period in over 400 years (i.e., 1905–1925). Recently, the western USA has experienced sustained drought, with 30–40% of the region under severe drought since 1999, and with the lowest 5-year period of Colorado River flow on record occurring from 2000 to 2004. At the same time, the states of the south-west USA are experiencing some of the most rapid growth in the country, with attendant social, economic and environmental demands on water resources, accompanied by associated legal conflicts (Pulwarty et al., 2005).

Only a small portion of the full Colorado Basin area (about 15%) supplies most (85%) of its flow. Estimates show that, with increased climatic warming and evaporation, concurrent runoff decreases would reach 30% during the 21st century (Milly et al., 2005). Under such conditions, together with projected withdrawals, the requirements of the Colorado River Compact may only be met 60–75% of the time by 2025 (Christensen et al., 2004). Some studies estimate that, by 2050, the *average* moisture conditions in the south-western USA could equal the conditions observed in the 1950s. These changes could occur as a consequence of increased temperatures (through increased sublimation, evaporation and soil moisture reduction), even if precipitation levels remain fairly constant. Some researchers argue that these assessments, because of model choice, may actually underestimate future declines.

Most scenarios of Colorado River flow at Lees Ferry (which separates the upper from the lower basin) indicate that, within 20 years, discharge may be insufficient to meet current consumptive water resource demands. The recent experience illustrates that ‘critical’ conditions already exist in the basin (Pulwarty et al., 2005). Climate variability and change, together with increasing development pressures, will result in drought impacts that are beyond the institutional experience in the region and will exacerbate conflicts among water users.

North American agriculture has been exposed to many severe weather events during the past decade. More variable weather, coupled with out-migration from rural areas and economic stresses, has increased the vulnerability of the agricultural sector overall, raising concerns about its future capacity to cope with a more variable climate (Senate of Canada, 2003; Wheaton et al., 2005). North American agriculture is, however, dynamic. Adaptation to multiple stresses and opportunities, including changes in markets and weather, is a normal process for the sector. Crop and enterprise diversification, as well as soil and water conservation, are often used to reduce weather-related risks (Wall and Smit, 2005). [WGII 14.2.4]

Many cities in North America have initiated ‘no regrets’ actions based on historical experience (MWD, 2005). [WGII Box 14.3] Businesses in Canada and the USA are also investing in adaptations relevant to changes in water resources, though few of these appear to be based on future climate change projections. [WGII 14.5.1] Examples of these types of adaptations include the following.

- Insurance companies are investing in research to prevent future hazard damage to insured property, and to adjust pricing models (Munich Re, 2004; Mills and Lecompte, 2006). [WGII 14.2.4]
- Ski resort operators are investing in lifts to reach higher altitudes and in equipment to compensate for declining snow cover (Elsasser et al., 2003; Census Bureau, 2004; Scott, 2005; Jones and Scott, 2006; Scott and Jones, 2006). [WGII 14.2.4]
- New York has reduced total water consumption by 27% and per capita consumption by 34% since the early 1980s (City of New York, 2005). [WGII 14.2.4]
- In the Los Angeles area, incentive and information programmes of local water districts encourage water conservation (MWD, 2005). [WGII Box 14.3]
- With highly detailed information on weather conditions, farmers are adjusting crop and variety selection, irrigation strategies and pesticide applications (Smit and Wall, 2003). [WGII 14.2.4]
- The City of Peterborough, Canada, experienced two 100-year flood events within 3 years; it responded by flushing the drainage systems and replacing the trunk sewer systems to meet more extreme 5-year flood criteria (Hunt, 2005). [WGII 14.5.1]
- Recent droughts in six major US cities, including New York and Los Angeles, led to adaptive measures involving investments in water conservation systems and new water supply/distribution facilities (Changnon and Changnon, 2000). [WGII 14.5.1]
- To cope with a 15% increase in heavy precipitation,

Box 5.8: Climate change adds challenges to managing the Columbia River Basin. [WGII Box 14.2]

Current management of water in the Columbia River basin involves balancing complex, often competing, demands for hydropower, navigation, flood control, irrigation, municipal uses, and maintenance of several populations of threatened and endangered species (e.g., salmon). Current and projected needs for these uses over-commit existing supplies. Water management in the basin operates in a complex institutional setting, involving two sovereign nations (Columbia River Treaty, ratified in 1964), aboriginal populations with defined treaty rights ('Boldt decision' in U.S. *vs.* Washington in 1974), and numerous federal, state, provincial and local government agencies (Miles et al., 2000; Hamlet, 2003). Pollution (mainly non-point source) is an important issue in many tributaries. The first-in-time first-in-right provisions of western water law in the U.S. portion of the basin complicate management and reduce water available to junior water users (Gray, 1999; Scott et al., 2004). Complexities extend to different jurisdictional responsibilities when flows are high and when they are low, or when protected species are in tributaries, the main stem or ocean (Miles et al., 2000; Mote et al., 2003).

With climate change, projected annual Columbia River flow changes relatively little, but seasonal flows shift markedly toward larger winter and spring flows and smaller summer and autumn flows (Hamlet and Lettenmaier, 1999; Mote et al., 1999). These changes in flows will be *likely* to coincide with increased water demand, principally from regional growth but also induced by climate change. Loss of water availability in summer would exacerbate conflicts, already apparent in low-flow years, over water (Miles et al. 2000). Climate change is also projected to impact urban water supplies within the basin. For example, a 2°C warming projected for the 2040s would increase demand for water in Portland, Oregon, by 5.7 million m^3/yr with an additional demand of 20.8 million m^3/yr due to population growth, while decreasing supply by 4.9 million m^3/yr (Mote et al., 2003). Long-lead climate forecasts are increasingly considered in the management of the river but in a limited way (Hamlet et al., 2002; Lettenmaier and Hamlet, 2003; Gamble et al., 2004; Payne et al., 2004). Each of 43 sub-basins of the system has its own sub-basin management plan for fish and wildlife, none of which comprehensively addresses reduced summertime flows under climate change (ISRP/ISAB, 2004).

The challenges of managing water in the Columbia River basin are *likely* to expand with climate change due to changes in snowpack and seasonal flows (Miles et al., 2000; Parson et al., 2001; Cohen et al., 2003). The ability of managers to meet operating goals (reliability) is *likely* to drop substantially under climate change (as projected by the HadCM2 and ECHAM4/OPYC3 AOGCMs under the IPCC IS92a emissions scenario for the 2020s and 2090s) (Hamlet and Lettenmaier, 1999). Reliability losses are projected to reach 25% by the end of the 21st century (Mote et al., 1999) and interact with operational rule requirements. For example, 'fishfirst' rules would reduce firm power reliability by 10% under the present climate and by 17% in years during the warm phase of the Pacific Decadal Oscillation (PDO). Adaptive measures have the potential to moderate the impact of the decrease in April snowpack but could lead to 10 to 20% losses of firm hydropower and lower than current summer flows for fish (Payne et al., 2004). Integration of climate change adaptation into regional planning processes is in the early stages of development (Cohen et al., 2006).

Burlington and Ottawa, Ontario, employed both structural and non-structural measures, including directing downspouts to lawns in order to encourage infiltration, and increasing depression and street detention storage (Waters et al., 2003). [WGII 14.5.1]

- A population increase of over 35% (nearly one million people) since 1970 has increased water use in Los Angeles by only 7% (California Regional Assessment Group, 2002), due largely to conservation practices. [WGII Box 14.3]
- The Regional District of Central Okanagan in British Columbia produced a water management plan in 2004 for a planning area known as the Trepanier Landscape Unit, which explicitly addresses climate scenarios, projected changes in water supply and demand, and adaptation options (Cohen et al., 2004; Summit Environmental Consultants, 2004). [WGII Box 3.1, 20.8.2]

5.7 Polar regions

5.7.1 Context

The polar regions are the areas of the globe expected to experience some of the earliest and most profound climate-induced changes, largely because of their large cryospheric components that also dominate their hydrological processes and water resources. Most concern about the effect of changing climate on water resources of the polar regions has been expressed for the Arctic. For the Antarctic, the focus has been on the mass balance of the major ice sheets and their influence on sea level, and to a lesser degree, induced changes in some aquatic systems. The Arctic contains a huge diversity of water resources, including many of the world's largest rivers

(Lena, Ob, Mackenzie and Yenisey), megadeltas (Lena and Mackenzie), large lakes (e.g., Great Bear), extensive glaciers and ice caps, and expanses of wetlands. Owing to a relatively small population (4 million: Bogoyavlenskiy and Siggner, 2004) and severe climate, water-resource-dependent industries such as agriculture and forestry are quite small-scale, whereas there are numerous commercial and subsistence fisheries. Although some nomadic peoples are still significant in some Arctic countries, populations are becoming increasingly concentrated in larger communities (two-thirds of the population now live in settlements with more than 5,000 inhabitants) although most of these are located near, and dependent on, transportation on major water routes. Relocation to larger communities has led to increased access to, for example, treated water supplies and modern sewage disposal (Hild and Stordhal, 2004). [WGI 10.6.4; WGII 15.2.1]

A significant proportion of the Arctic's water resources originate in the headwater basins of the large rivers that carry flow through the northern regions to the Arctic Ocean. The flows of these rivers have been the focus of significant hydro-electric development and remain some of the world's largest untapped hydropower potential (e.g., Shiklomanov et al., 2000; Prowse et al., 2004). Given the role of these rivers in transporting heat, sediment, nutrients, contaminants and biota into the north, climate-induced changes at lower latitudes exert a strong effect on the Arctic. Moreover, it is changes in the combined flow of all Arctic catchments that have been identified as being so important to the freshwater budget of the Arctic Ocean, sea-ice production and, ultimately, potential effects on thermohaline circulation and global climate. [WGI 10.3.4; WGII 15.4.1]

5.7.2 Observed changes

The most significant observed change to Arctic water resources has been the increase since the 1930s in the combined flow from the six largest Eurasian Rivers (approximately 7%: Peterson et al., 2002). Increased runoff to the Arctic Ocean from circumpolar glaciers, ice caps and the Greenland ice sheet has also been noted to have occurred in the late 20th century and to be comparable to the increase in combined river inflow from the largest pan-Arctic rivers (Dyurgerov and Carter, 2004). Changes in mass balance of ice masses is related to a complex response to changes in precipitation and temperature, resulting in opposing regional trends such as are found between the margins and some interior portions of the Greenland ice sheet (Abdalati and Steffen, 2001; Johannessen et al., 2005; Walsh et al., 2005). In the case of flow increases on the Eurasian rivers, potential controlling factors, such as ice melt from permafrost, forest-fire effects and dam storage variations, have been eliminated as being responsible (McClelland et al., 2004), and one modelling study suggests that anthropogenic climate forcing factors have played a role. Evaluating the effects of climate and other factors on the largest Arctic-flowing river in North America, the Mackenzie River, has proven particularly difficult because of the large dampening effects on flow created by natural storage-release effects of major lakes and reservoirs (e.g., Gibson et al., 2006; Peters et al., 2006). [WGI 9.5.4; WGII 15.4.1.1]

The effects of precipitation on runoff are difficult to ascertain, largely because of the deficiencies and sparseness of the Arctic precipitation network, but it is believed to have risen slowly by approximately 1% per decade (McBean et al., 2005; Walsh et al., 2005). Changes in the magnitude of winter discharge on major Arctic rivers have also been observed and linked to increased warming and winter precipitation in the case of the Lena River (Yang et al., 2002; Berezovskaya et al., 2005) but, although also previously thought to be climate-induced, simply to hydro-electric regulation on the Ob and Yenisei Rivers (Yang et al., 2004a, b). Changes have also occurred in the timing of the spring freshet, the dominant flow event on Arctic rivers, but these have not been spatially consistent over the last 60 years, with adjacent Siberian rivers showing both advancing (Lena: Yang et al., 2002) and delaying (Yenisei: Yang et al., 2004b) trends. Floating freshwater ice also controls the seasonal dynamics of Arctic rivers and lakes, particularly flooding regimes, and although there has been no reported change in ice-induced flood frequency or magnitude, ice-cover duration has decreased in much of the sub-Arctic (Walsh et al., 2005). [WGII 15.2.1, 15.4.1.1]

Significant changes to permafrost have occurred in the Arctic in the last half-century (Walsh et al., 2005) and, given the role of frozen ground in controlling flow pathways, thawing permafrost could be influencing seasonal precipitation-runoff responses (Serreze et al., 2003; Berezovskaya et al., 2005; Zhang et al., 2005). Permafrost thaw, and the related increase in substrate permeability, has also been suspected of producing changes in lake abundance in some regions of Siberia during a three-decade period at the end of the 20th century (Smith et al., 2005; see Figure 5.12). At higher latitudes, initial thaw is thought to have increased surface ponding and lake abundance whereas, at lower latitudes, lake abundance has declined as more extensive and deeper thaw has permitted ponded water to drain away to the sub-surface flow systems. In broader areas of the Arctic, the biological composition of lake and pond aquatic communities has been shown to respond to shifts in increasing mean annual and summer air temperatures and related changes in thermal stratification/stability and ice-cover duration (Korhola et al. 2002; Ruhland et al., 2003; Pienitz et al., 2004; Smol et al., 2005; Prowse et al., 2006). [WGI Chapter 4; WGII 15.4.1.1]

Freshwater aquatic ecosystems of the Antarctic have also been shown to be highly responsive to variations in climate, particularly to air temperature, although trends in such have varied across the continent. Productivity of lakes in the Dry Valleys, for example, has been observed to decline with decreasing air temperature (e.g., Doran et al., 2002). By contrast, rising air temperatures on the maritime sub-Antarctic Signy Island have produced some of the fastest and most amplified responses in lake temperature yet documented in the Southern Hemisphere (Quayle et al., 2002). Moreover, warming effects on snow and ice cover have produced a diverse array of ecosystem disruptions (Quayle et al., 2003). [WGII 15.2.2.2]

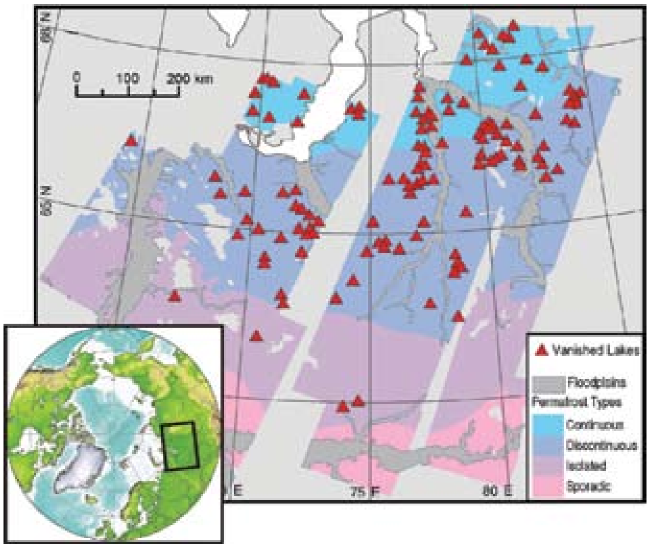


Figure 5.12: Locations of Siberian lakes that have disappeared after a three-decade period of rising soil and air temperatures (changes registered from satellite imagery from the early 1970s to 1997–2004), overlaid on various permafrost types. The spatial pattern of lake disappearance suggests that permafrost thawing has driven the observed losses. From Smith et al. (2005). Reprinted with permissions from AAAS. [WGII Figure 15.4]

5.7.3 Projected changes

Projecting changes in the hydrology, and thus water resources, of the Arctic are problematic because of strong variability in the seasonality and spatial patterns of the precipitation among GCM models. Although most predict an increase, prediction of runoff from precipitation inputs is confounded by problems in apportioning rain and snow as the region warms, or as additional moisture sources become available with the retreat of sea ice. In general, however, the latest projections for runoff from the major Arctic catchments indicate an overall increase in the range of 10–30%. One factor not included in such projections, however, is the rise in evapotranspiration that will occur as the dominating terrestrial vegetation shifts from non-transpiring tundra lichens to various woody species (e.g., Callaghan et al., 2005), although this might be offset by CO_2-induced reductions in transpiration (e.g., Gedney et al., 2006). Similarly not factored into current runoff projections are the effects of future permafrost thaw and deepening of active layers (Anisimov and Belolutskaia, 2004; Instanes et al., 2005), which will increasingly link surface and groundwater flow regimes, resulting in major changes in seasonal hydrographs. Associated wetting or drying of tundra, coupled with warming and increased active-layer depth, will determine its source/sink status for carbon and methane fluxes. Permafrost thaw and rising discharge is also expected to cause an increase in river sediment loads (Syvitski, 2002) and potential major transformations to channel networks (Bogaart and van Balen, 2000; Vandenberghe, 2002). [WGI Chapter 10; WGII 15.4.2.3, 15.4.1.2]

Runoff in both polar regions will be augmented by the wastage of glaciers, ice caps and the ice sheets of Greenland and Antarctica, although some ice caps and the ice sheets contribute most of their melt water directly to their surrounding oceans. More important to the terrestrial water resources are the various glaciers scattered throughout the Arctic, which are projected to largely retreat with time. While initially increasing streamflow, a gradual disappearance or a new glacier balance at smaller extents will eventually result in lower flow conditions, particularly during the drier late-summer periods, critical periods for aquatic Arctic biota. [WGI Chapter 10; WGII 15.4.1.3]

Projected warming also implies a continuation of recent trends toward later freeze-up and earlier break-up of river and lake ice (Walsh et al., 2005) and reductions in ice thickness, which will lead to changes in lake thermal structures, quality/quantity of under-ice habitat, and effects on river-ice jamming and related flooding (Beltaos et al., 2006; Prowse et al., 2006). The latter is important as a hazard to many river-based northern settlements but is also critical to sustaining the ecological health of riparian ecosystems that rely on the spring inundation of water, sediment and nutrients (Prowse et al., 2006). [WGII 15.4.1.2, 15.6.2]

The above major alterations to the cold-region hydrology of the Arctic will alter aquatic biodiversity, productivity, seasonal habitat availability and geographical distribution of species, including major fisheries populations (Prowse et al., 2006; Reist et al. 2006a, b, c; Wrona et al., 2006). Arctic peoples, functioning in subsistence and commercial economies, obtain many services from freshwater ecosystems (e.g., harvestable biota), and changes in the abundance, replenishment, availability and accessibility of such resources will alter local resource use and traditional lifestyles (Nuttall et al., 2005; Reist et al., 2006a). [WGII 15.4.1.3]

Given that the Arctic is projected to be generally 'wetter', a number of hydrological processes will affect the pathways and increase the loading of pollutants (e.g., persistent organic pollutants and mercury) to Arctic aquatic systems (MacDonald et al., 2003). Changes in aquatic trophic structure and food webs (Wrona et al., 2006) have the further potential to alter the accumulation of bio-magnifying chemicals. This has special health concerns for northern residents who rely on traditional sources of local food. Changes to the seasonal timing and magnitude of flows and available surface water will also be of concern for many northern communities that rely on surface and/or groundwater, often untreated, for drinking water (United States Environmental Protection Agency, 1997; Martin et al., 2005). Risks of contamination may also increase with the northward movement of species and related diseases, and via sea-water contamination of groundwater reserves resulting from sea-level rise in coastal communities (Warren et al., 2005). [WGII 15.4.1]

The large amount of development and infrastructure that tends to be concentrated near Arctic freshwater systems will be strongly affected by changes in northern hydrological regimes. Important examples include the decline of ice-road access to transport equipment and to northern communities; alterations in surface and groundwater availability to communities and industry; loss of containment security of mine wastes in northern lakes underlain by permafrost; and increased flow and ice hazards to instream drilling platforms and hydro-electric reservoirs (World Commission on Dams, 2000; Prowse et al, 2004; Instanes et al., 2005). Although the future electricity production of the entire Arctic has not been assessed, it has been estimated for an IS92a emissions scenario that the hydropower potential for plants existing at the end of the 20th century will increase by 15–30% in Scandinavia and northern Russia. [WGI 3.5.1; WGII 15.4.1.4]

5.7.4 Adaptation and vulnerability

A large amount of the overall vulnerability of Arctic freshwater resources to climate change relates to the abrupt changes associated with solid-to-liquid water-phase changes that will occur in many of the cryospheric hydrological systems. Arctic freshwater ecosystems have historically been able to adapt to large variations in climate, but over protracted periods (e.g., Ruhland et al., 2003). The rapid rates of change over the coming century, however, are projected to exceed the ability of some biota to adapt (Wrona et al., 2006), and to result in more negative than positive impacts on freshwater ecosystems (Wrona et al., 2005). [WGII 15.2.2.2]

From a human-use perspective, potential adaptation measures are extremely diverse, ranging from measures to facilitate use of water resources (e.g., changes in ice-road construction practices, increased open-water transportation, flow regulation for hydro-electric production, harvesting strategies, and methods of drinking-water access) to adaptation strategies to deal with increased/decreased freshwater hazards (e.g., protective structures to reduce flood risks or increase flows for aquatic systems; Prowse and Beltaos, 2002). Strong cultural and/or social ties to traditional uses of water resources by some northern peoples, however, could complicate the adoption of some adaptation strategies (McBean et al., 2005; Nuttall et al., 2005). [WGII 15.2.2.2]

5.8 Small islands

5.8.1 Context

The TAR (Chapter 17; IPCC, 2001b) noted that Small Island States share many similarities (e.g., physical size, proneness to natural disasters and climate extremes, extreme openness of economies, low risk-spreading and adaptive capacity) that enhance their vulnerability and reduce their resilience to climate variability and change. In spite of differences in emphasis and sectoral priorities on different islands, three common themes emerge.

1. All Small Island States National Communications[25] emphasise the urgency for adaptation action and the financial resources to support such action.
2. Freshwater is seen as a critical issue in all Small Island States, both in terms of water quality and quantity.
3. Many Small Island States, including all of the Small Island Developing States (SIDS), see the need for greater integrated watershed planning and management.

[WGII TAR Chapter 17]

Water is a multi-sectoral resource that links to all facets of life and livelihood, including security. Reliability of water supply is viewed as a critical problem on many islands at present and one whose urgency will increase in the future. There is strong evidence that, under most climate change scenarios, water resources in small islands are *likely* to be seriously compromised (*very high confidence*). Most small islands have a limited water supply, and water resources in these islands are especially vulnerable to future changes and distribution of rainfall. The range of adaptive measures considered, and the priorities assigned, are closely linked to each country's key socio-economic sectors, its key environmental concerns, and areas most at risk of climate change impacts such as sea-level rise. [WGII 16.ES, 16.5.2]

5.8.2 Observed climatic trends and projections in island regions

Hydrological conditions, water supply and water usage on small islands pose quite different research and adaptation problems compared with those in continental situations. These need to be investigated and modelled over a range of island types, covering different geology, topography and land cover, and in light of the most recent climate change scenarios and projections. [WGII 16.7.1] New observations and re-analyses of temperatures averaged over land and ocean surfaces since the TAR show consistent warming trends in all small-island regions over the 1901 to 2004 period. However, the trends are not linear and a lack of historical record keeping severely hinders trend analysis. [WGII 16.2.2.2]

Recent studies show that the annual and seasonal ocean surface and island air temperatures have increased by 0.6–1.0°C since 1910 throughout a large part of the South Pacific, south-west of the South Pacific Convergence Zone (SPCZ),[26] whereas decadal increases of 0.3–0.5°C in annual temperatures are only widely seen since the 1970s, preceded by some cooling after the 1940s, which is the beginning of the record, to the north-east of the SPCZ (Salinger, 2001; Folland et al., 2003*)*. For the Caribbean, Indian Ocean and Mediterranean regions, analyses shows that warming ranged from 0.24°C to 0.5°C per decade for the 1971 to 2004 period. Some high-latitude regions, including the western Canadian Arctic Archipelago, have experienced warming at a

[25] Under the UN Framework Convention for Climate Change (UNFCCC), countries are required to provide periodic national communications on their progress in reducing net GHG emissions, policies and measures enacted, and needs assessments.

[26] The SPCZ is part of the ITCZ and is a band of low-level convergence, cloudiness and precipitation extending from the west Pacific warm pool south-eastwards towards French Polynesia.

more rapid pace than the global mean (McBean et al., 2005). [WGII 16.2.2.2]

Trends in extreme daily rainfall and temperature across the South Pacific for the period 1961–2003 show increases in the annual number of hot days and warm nights, with decreases in the annual number of cool days and cold nights, particularly in years after the onset of El Niño, with extreme rainfall trends generally less spatially coherent than those of extreme temperature (Manton et al., 2001; Griffiths et al., 2003). In the Caribbean, the percentage of days with very warm temperature minima or maxima increased strongly since the 1950s, while the percentage of days with cold temperatures decreased (Petersen et al., 2002). [WGII 16.2.2.2]

For the Caribbean, a 1.5–2°C increase in global air temperature is projected to affect the region through [WGII TAR Chapter 17]:

- increases in evaporation losses,
- decreased precipitation (continuation of a trend of rainfall decline observed in some parts of the region),
- reduced length of the rainy season – down 7–8% by 2050,
- increased length of the dry season – up 6–8% by 2050,
- increased frequency of heavy rains – up 20% by 2050,
- increased erosion and contamination of coastal areas.

Variations in tropical and extra-tropical cyclones, hurricanes and typhoons in many small-island regions are dominated by ENSO and decadal variability. These result in a redistribution of tropical storms and their tracks such that increases in one basin are often compensated by decreases in other basins. For example, during an El Niño event, the incidence of hurricanes typically decreases in the Atlantic and far-western Pacific and Australasian regions, while it increases in the central, north and south Pacific, and especially in the western North Pacific typhoon region. There is observational evidence for an increase in intense tropical cyclone activity in the North Atlantic since about 1970, correlated with increases in tropical SSTs. There are also suggestions of increases in intense tropical cyclone activity in other regions where concerns over data quality are greater. Multi-decadal variability and the quality of records prior to about 1970 complicate the detection of long-term trends. Estimates of the potential destructiveness of tropical cyclones suggest a substantial upward trend since the mid-1970s. [WGI TS, 3.8.3; WGII 16.2.2.2]

Analyses of sea-level records having at least 25 years of hourly data from stations installed around the Pacific Basin show an overall average mean relative sea-level rise of 0.7 mm/yr (Mitchell et al., 2001). Focusing only on the island stations with more than 50 years of data (only four locations), the average rate of sea-level rise (relative to the Earth's crust) is 1.6 mm/yr. [WGI 5.5.2]

5.8.2.1 Water

Table 5.8, based on seven GCMs and for a range of SRES emissions scenarios, compares projected precipitation changes over small islands by region. In the Caribbean, many islands are expected to experience increased water stress as a result of climate change, with all SRES scenarios projecting reduced rainfall in summer across the region. It is unlikely that demand would be met during low rainfall periods. Increased rainfall in the Northern Hemisphere winter is unlikely to compensate, due to a combination of lack of storage and high runoff during storms. [WGII 16.3.1]

***Table 5.8:** Projected change in precipitation over small islands, by region (%). Ranges are derived from seven AOGCMs run under the SRES B1, B2, A2 and A1FI scenarios. [WGII Table 16.2]*

Regions	2010–2039	2040–2069	2070–2099
Mediterranean	-35.6 to +55.1	-52.6 to +38.3	-61.0 to +6.2
Caribbean	-14.2 to +13.7	-36.3 to +34.2	-49.3 to +28.9
Indian Ocean	-5.4 to +6.0	-6.9 to +12.4	-9.8 to +14.7
Northern Pacific	-6.3 to +9.1	-19.2 to +21.3	-2.7 to +25.8
Southern Pacific	-3. 9 to + 3.4	-8.23 to +6.7	-14.0 to +14.6

In the Pacific, a 10% reduction in average rainfall (by 2050) would lead to a 20% reduction in the size of the freshwater lens on Tarawa Atoll, Kiribati. Reduced rainfall coupled with sea-level rise would compound the risks to water supply reliability. [WGII 16.4.1]

Many small islands have begun to invest in the implementation of adaptation strategies, including desalination, to offset current and projected water shortages. However, the impacts of desalination plants themselves on environmental amenities and the need to fully address environmental water requirements have not been fully considered. [WGII 16.4.1]

Given the high visibility and impacts of hurricanes, droughts have received less attention by researchers and planners, although these may lead to increased withdrawals and potential for saltwater intrusion into near-shore aquifers. In the Bahamas, for instance, freshwater lenses are the only exploitable groundwater resources. These lenses are affected periodically by saline intrusions caused by over-pumping and excess evapotranspiration. Groundwater in most cases is slow-moving and, as a result, serious reductions in groundwater reserves are slow to recover and may not be reversible; variability in annual volumes of available water is generally not as extreme as for surface water resources; and water quality degradation and pollution have long-term effects and cannot quickly be remedied. [WGII 16.4.1]

Some Island States such as Malta (MRAE, 2004) emphasise potential economic sectors that will require adaptation, including power generation, transport and waste management; whereas agriculture and human health figure prominently in communications from the Comoros (GDE, 2002), Vanuatu (Republic of Vanuatu, 1999) and St. Vincent and the Grenadines (NEAB, 2000). In these cases, sea-level rise is not seen as the most critical issue, although it is in the low-lying atoll states such as Kiribati, Tuvalu, Marshall Islands and the Maldives. [WGII 16.4.2]

5.8.2.2 Energy

Access to reliable and affordable energy is a vital element in most small islands, where the high cost of energy is regarded as a barrier to the goal of attaining sustainable development. Some islands, such as Dominica in the Caribbean, rely on hydropower for a significant part of their energy supply. Research and development into energy efficiency and options appropriate to small islands, such as solar and wind, could help in both adaptation and mitigation strategies, while enhancing the prospect of achieving sustainable growth. [WGII 16.4.6, 16.4.7]

5.8.2.3 Health

Many small islands lie in tropical or sub-tropical zones with weather conducive to the transmission of diseases such as malaria, dengue, *filariasis*, *schistosomiasis* and food- and water-borne diseases. The rates of occurrence of many of these diseases are increasing in small islands for a number of reasons, including poor public health practices, inadequate infrastructure, poor waste-management practices, increasing global travel, and changing climatic conditions (WHO, 2003). In the Caribbean, the incidence of dengue fever increases during warm years of ENSO cycles (Rawlins et al., 2005). Because the greatest risk of dengue transmission is during annual wet seasons, vector control programmes should target these periods in order to reduce disease burdens. The incidence of diarrhoeal diseases is associated with annual average temperature (Singh et al., 2001) [WGII 8.2, 8.4], and negatively associated with water availability in the Pacific (Singh et al., 2001). Therefore, increasing temperatures and decreasing water availability due to climate change may increase burdens of diarrhoeal and other infectious diseases in some Small Island States. [WGII 16.4.5]

5.8.2.4 Agriculture

Projected impacts of climate change include extended periods of drought and, on the other hand, loss of soil fertility and degradation as a result of increased precipitation, both of which will negatively impact on agriculture and food security. In its study on the economic and social implications of climate change and variability for selected Pacific islands, the World Bank (2000) found that, in the absence of adaptation, a high island such as Viti Levu, Fiji, could experience damages of US$23–52 million per year by 2050, (equivalent to 2–3% of Fiji's GDP in 2002), while a group of low islands such as Tarawa, Kiribati, could face damages of more than US$8–16 million a year (equivalent to 17–18% of Kiribati's GDP in 2002) under SRES A2 and B2. On many Caribbean islands, reliance on agricultural imports, which themselves include water used for production in the countries of origin, constitute up to 50% of food supply. [WGII 16.4.3]

5.8.2.5 Biodiversity

Burke et al. (2002) and Burke and Maidens (2004) indicate that about 50% of the reefs in south-east Asia and 45% in the Caribbean are classed in the high to very high risk category (see also Graham et al, 2006). There are, however, significant local and regional differences in the scale and type of threats to coral reefs in both continental and small island situations. [WGII 16.4.4]

Both the terrestrial ecosystems of larger islands and coastal ecosystems of most islands have been subjected to increasing degradation and destruction in recent decades. For instance, analysis of coral reef surveys over three decades has revealed that coral cover across reefs in the Caribbean has declined by 80% in just 30 years, largely as a result of pollution, sedimentation, marine diseases and over-fishing (Gardner et al., 2003). Runoff from land areas, together with direct input of freshwater through heavy rain events, can have significant impacts on reef quality and susceptibility to disease. [WGII 16.4.4]

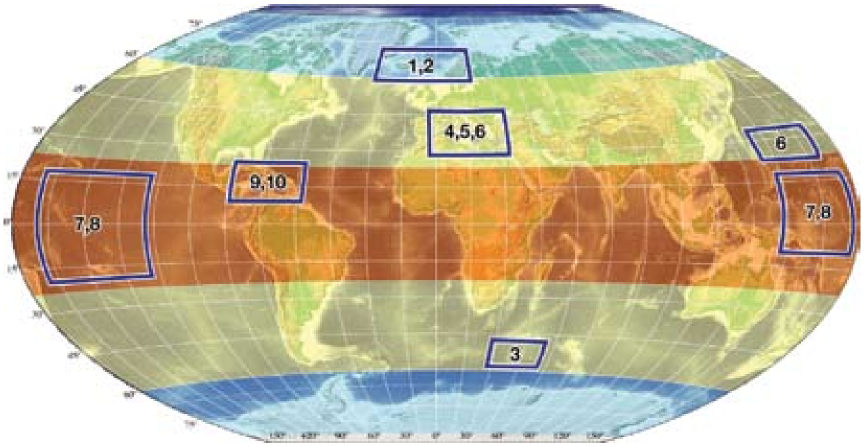
5.8.3 Adaptation, vulnerability and sustainability

Sustainable development is often stated as an objective of management strategies for small islands. Relatively little work has explicitly considered what sustainable development means for islands in the context of climate change (Kerr, 2005). It has long been known that the problems of small scale and isolation, of specialised economies, and of the opposing forces of globalisation and localisation, may mean that current development in small islands becomes unsustainable in the long term. [WGII 16.6]

Danger is associated with the narrowing of adaptation options to expected impacts of climate change, under the uncertainty of potential climate-driven physical impacts. Table 5.9 summarises the results of several scenario-based impact studies for island environments from the present through to 2100, i.e., some impacts are already occurring. It provides the context for other potential climate impacts that might exacerbate water-related stresses. Thresholds may originate from social as well as environmental processes. Furthermore, the challenge is to understand the adaptation strategies that have been adopted in the past and the benefits and limits of these for future planning and implementation. [WGII 16.5]

While there has been considerable progress in regional projections of sea level since the TAR, such projections have not been fully utilised in small islands because of the greater uncertainty attached to their local manifestations, as opposed to global projections. Reliable and credible projections based on outputs at finer resolution, together with local data, are needed to inform the development of reliable climate change scenarios for small islands. These approaches could lead to improved vulnerability assessments and the identification of more appropriate adaptation options at the scale of islands and across time-scales of climatic impacts. [WGII 16.7.1]

Vulnerability studies conducted for selected small islands (Nurse et al., 2001) show that the costs of infrastructure and settlement protection represent a significant proportion of GDP, often well beyond the financial means of most Small Island States; a problem not always shared by the islands of continental countries. More recent studies have identified major areas of adaptation, including water resources and watershed management, reef conservation, agricultural and forest management, conservation of biodiversity, energy security, increased development of renewable energy and optimised



* Numbers in bold relate to the regions defined on the map.

Table 5.9: *Range of future impacts and vulnerabilities in small islands. [WGII Box 16.1]*

Region* and System at risk	Scenario and Reference	Changed parameters	Impacts and vulnerability
1. Iceland and isolated Arctic islands of Svalbard and the Faroe Islands: Marine ecosystem and plant species	SRES A1 and B2 ACIA (2005)	Projected rise in temperature	• The imbalance of species loss and replacement leads to an initial loss in diversity. Northward expansion of dwarf-shrub and tree-dominated vegetation into areas rich in rare endemic species results in their loss. • Large reduction in, or even a complete collapse of, the Icelandic capelin stock leads to considerable negative impacts on most commercial fish stocks, whales and seabirds.
2. High-latitude islands (Faroe Islands): Plant species	Scenario I/II: temperature increase/ decrease by 2°C Fosaa et al. (2004)	Changes in soil temperature, snow cover and growing degree days	• Scenario I: Species most affected by warming are restricted to the uppermost parts of mountains. For other species, the effect will mainly be upward migration. • Scenario II: Species affected by cooling are those at lower altitudes.
3. Sub-Antarctic Marion Islands: Ecosystem	Own scenarios Smith (2002)	Projected changes in temperature and precipitation	• Changes will directly affect the indigenous biota. An even greater threat is that a warmer climate will increase the ease with which the islands can be invaded by alien species.
4. Mediterranean Basin five islands: Ecosystems	SRES A1FI and B1 Gritti et al. (2006)	Alien plant invasion under climatic and disturbance scenarios	• Climate change impacts are negligible in many simulated marine ecosystems. • Invasion into island ecosystems becomes an increasing problem. In the longer term, ecosystems will be dominated by exotic plants irrespective of disturbance rates.
5. Mediterranean: Migratory birds (pied flycatchers – *Ficedula hypoleuca*)	None (GLM/STATISTICA model) Sanz et al. (2003)	Temperature increase, changes in water levels and vegetation index	• Some fitness components of pied flycatchers suffer from climate change in two of the southernmost European breeding populations, with adverse effects on the reproductive output of pied flycatchers.
6. Pacific and Mediterranean: Siam weed (*Chromolaena odorata*)	None (CLIMEX model) Kriticos et al. (2005)	Increase in moisture, cold, heat and dry stress	• Pacific islands at risk of invasion by Siam weed. • Mediterranean semi-arid and temperate climates predicted to be unsuitable for invasion.
7. Pacific small islands: Coastal erosion, water resources and human settlement	SRES A2 and B2 World Bank (2000)	Changes in temperature and rainfall, and sea-level rise	• Accelerated coastal erosion, saline intrusion into freshwater lenses and increased flooding from the sea cause large effects on human settlements. • Less rainfall coupled with accelerated sea-level rise compound the threat to water resources; a 10% reduction in average rainfall by 2050 is *likely* to correspond to a 20% reduction in the size of the freshwater lens on Tarawa Atoll, Kiribati.
8. American Samoa; 15 other Pacific islands: Mangroves	Sea-level rise 0.88 m to 2100 Gilman et al. (2006)	Projected rise in sea level	• 50% loss of mangrove area in American Samoa; 12% reduction in mangrove area in 15 other Pacific islands.
9. Caribbean (Bonaire, Netherlands Antilles): Beach erosion and sea turtle nesting habitats	SRES A1, A1FI, B1, A2, B2 Fish et al. (2005)	Projected rise in sea level	• On average, up to 38% (±24% SD) of the total current beach could be lost with a 0.5 m rise in sea level, with lower narrower beaches being the most vulnerable, reducing turtle nesting habitat by one-third.
10. Caribbean (Bonaire, Barbados): Tourism	None Uyarra et al. (2005)	Changes to marine wildlife, health, terrestrial features and sea conditions	• The beach-based tourism industry in Barbados and the marine-diving-based ecotourism industry in Bonaire are both negatively affected by climate change through beach erosion in Barbados and coral bleaching in Bonaire.

energy consumption. A framework which considers current and future community vulnerability and involves methodologies integrating climate science, social science and communication, provides the basis for building adaptive capacity. [WGII Box 16.7] This approach requires community members to identify climate conditions relevant to them, and to assess present and potential adaptive strategies. One such methodology was tested in Samoa, and results from one village (Saoluafata: see Sutherland et al., 2005). In this case, local residents identified several adaptive measures including building a seawall, a water-drainage system, water tanks, a ban on tree clearing, some relocation, and renovation to existing infrastructure. [WGII 16.5]

The IPCC AR4 has identified several key areas and gaps that are under-represented in contemporary research on the impacts of climate change on small islands. [WGII 16.7] These include:

- the role of coastal ecosystems such as mangroves, coral reefs and beaches in providing natural defences against sea-level rise and storms;
- establishing the response of terrestrial upland and inland ecosystems to changes in mean temperature and rainfall and in temperature and rainfall extremes;
- considering how commercial agriculture, forestry and fisheries, as well as subsistence agriculture, artisanal fishing and food security, will be impacted by the combination of climate change and non-climate-related forces;
- expanding knowledge of climate-sensitive diseases in small islands through national and regional research – not only for vector-borne diseases but for skin, respiratory and water-borne diseases;
- given the diversity of 'island types' and locations, identifying the most vulnerable systems and sectors, according to island types.

In contrast to the other regions in this assessment, there is also an absence of reliable demographic and socio-economic scenarios and projections for small islands. The result is that future changes in socio-economic conditions on small islands have not been well presented in the existing assessments. For example, without either adaptation or mitigation, the impacts of sea-level rise, more intense storms and other climate change [WGII 6.3.2] will be substantial, suggesting that some islands and low-lying areas may become unliveable by 2100. [WGII 16.5]

6

Climate change mitigation measures and water

6.1 Introduction

The relationship between climate change mitigation measures and water is a reciprocal one. Mitigation measures can influence water resources and their management, and it is important to realise this when developing and evaluating mitigation options. On the other hand, water management policies and measures can have an influence on greenhouse gas (GHG) emissions and, thus, on the respective sectoral mitigation measures; interventions in the water system might be counter-productive when evaluated in terms of climate change mitigation.

The issue of mitigation is addressed in the IPCC WGIII AR4 (Mitigation), where the following seven sectors were discussed: energy supply, transportation and its infrastructure, residential and commercial buildings, industry, agriculture, forestry, and waste management. Since water issues were not the focus of that volume, only general interrelations with climate change mitigation were mentioned, most of them being qualitative. However, other IPCC reports, such as the TAR, also contain information on this issue.

Sector-specific mitigation measures can have various effects on water, which are explained in the sections below (see also Table 6.1). Numbers in parentheses in the titles of the sub-sections correspond to the practices or sector-specific mitigation options described in Table 6.1.

6.2 Sector-specific mitigation

6.2.1 Carbon dioxide capture and storage (CCS) (refer to (1) in Table 6.1)

Carbon dioxide (CO_2) capture and storage (CCS) is a process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere. The injection of CO_2 into the pore space and fractures of a permeable formation can displace *in situ* fluid, or the CO_2 may dissolve in or mix with the fluid or react with the mineral grains, or there may be some combination of these processes. As CO_2 migrates through the formation, some of it will dissolve into the formation water. Once CO_2 is dissolved in the formation fluid, it is transported by the regional groundwater flow. Leakage of CO_2 from leaking injection wells, abandoned wells, and leakage across faults and ineffective confining layers could potentially degrade the quality of groundwater; and the release of CO_2 back into the atmosphere could also create local health and safety concerns. [CCS SPM, 5.ES]

It is important to note that, at this point, there is no complete insight into the practicality, consequences or unintended consequences of this carbon sequestration concept. Avoiding or mitigating the impacts will require careful site selection, effective regulatory oversight, an appropriate monitoring programme, and implementation of remediation methods to stop or control CO_2 releases. [CCS 5.ES, 5.2].

6.2.2 Bio-energy crops (2)

Bio-energy produces mitigation benefits by displacing fossil-fuel use. [LULUCF 4.5.1] However, large-scale bio-fuel production raises questions on several issues including fertiliser and pesticide requirements, nutrient cycling, energy balances, biodiversity impacts, hydrology and erosion, conflicts with food production, and the level of financial subsidies required. [LULUCF 4.5.1] The energy production and GHG mitigation potentials of dedicated energy crops depends on the availability of land, which must also meet demands for food as well as for nature protection, sustainable management of soils and water reserves, and other sustainability criteria. Various studies have arrived at differing figures for the potential contribution of biomass to future global energy supplies, ranging from below 100 EJ/yr to above 400 EJ/yr in 2050 (Hoogwijk, 2004; Hoogwijk et al., 2005; Sims et al., 2006). Smeets et al. (2007) indicate that the ultimate technical potential for energy cropping on current agricultural land, with projected technological progress in agriculture and livestock, could deliver over 800 EJ/yr without jeopardising the world's food supply. Differences between studies are largely attributable to uncertainty in land availability, energy crop yields, and assumptions about changes in agricultural efficiency. Those with the largest projected potential assume that not only degraded/surplus lands are used, but also land currently used for food production, including pasture land (as did Smeets et al., 2007). [WGIII 8.4.4.2]

Agricultural practices for mitigation of GHGs could, in some cases, intensify water use, thereby reducing streamflow or groundwater reserves (Unkovich, 2003; Dias de Oliveira et al., 2005). For instance, high-productivity, evergreen, deep-rooted bio-energy plantations generally have a higher water use than the land cover they replace (Berndes and Börjesson, 2002; Jackson et al., 2005). Some practices may affect water quality through enhanced leaching of pesticides and nutrients (Machado and Silva, 2001; Freibauer et al., 2004). [WGIII 8.8]

Agricultural mitigation practices that divert products to alternative uses (e.g., bio-energy crops) may induce the conversion of forests to cropland elsewhere. Conversely, increasing productivity on existing croplands may 'spare' some forest or grasslands (West and Marland, 2003; Balmford et al., 2005; Mooney et al., 2005). The net effect of such trade-offs on biodiversity and other ecosystem services has not yet been fully quantified (Huston and Marland, 2003; Green et al., 2005). [WGIII 8.8]

If bio-energy plantations are appropriately located, designed and managed, they may reduce nutrient leaching and soil erosion and generate additional environmental services such as soil carbon accumulation, improved soil fertility, and the removal of cadmium and other heavy metals from soils or wastes. They may also increase nutrient recirculation, aid in the

***Table 6.1:** Influence of sector-specific mitigation options (or their consequences) on water quality, quantity and level. Positive effects on water are indicated with [+]; negative effects with [−]; and uncertain effects with [?]. Numbers in round brackets refer to the Notes, and also to the sub-section numbers in Section 6.2.*

Water aspect	Energy	Buildings	Industry	Agriculture	Forests	Waste
Quality						
Chemical/ biological	CCS(1) [?] Bio-fuels(2) [+/-] Geothermal energy(5) [-] Unconventional oil(13) [-]		CCS(1) [?] Wastewater treatment(12) [-] Biomass electricity(3) [-/?]	Land-use change and management (7) [+/-] Cropland management (water)(8) [+/-]	Afforestation (sinks)(10) [+]	Solid waste management; Wastewater treatment(12) [+/-]
Temperature	Biomass electricity(3) [+]			Cropland management (reduced tillage) (9) [+/-]		
Quantity						
Availability/ demand	Hydropower(4) [+/-] Unconventional oil(13) [-] Geothermal energy(5) [-]	Energy use in buildings(6) [+/-]		Land-use change and management (7) [+/-] Cropland management (water)(8) [-]	Afforestation (10) [+/-] Avoided/ reduced deforestation (11) [+]	Wastewater treatment(12) [+]
Flow/runoff/ recharge	Bio-fuels(2) [+/-] Hydropower (4) [+/-]			Cropland management (reduced tillage) (9) [+]		
Water level						
Surface water	Hydropower (4) [+/-]			Land-use change and management (7) [+/-]		
Groundwater	Geothermal energy(5) [-]			Land-use change and management (7) [+/-]	Afforestation(10) [-]	

Notes:
(1) Carbon capture and storage (CCS) underground poses potential risks to groundwater quality; deep-sea storage (below 3,000 m water depth and a few hundred metres of sediment) seems to be the safest option.
(2) Expanding bio-energy crops and forests may cause negative impacts such as increased water demand, contamination of underground water and promotion of land-use changes, leading to indirect effects on water resources; and/or positive impacts through reduced nutrient leaching, soil erosion, runoff and downstream siltation.
(3) Biomass electricity: in general, a higher contribution of renewable energy (as compared to fossil-fuel power plants) means a reduction of the discharge of cooling water to the surface water.
(4) Environmental impact and multiple benefits of hydropower need to be taken into account for any given development; they could be either positive or negative.
(5) Geothermal energy use might result in pollution, subsidence and, in some cases, a claim on available water resources.
(6) Energy use in the building sector can be reduced by different approaches and measures, with positive and negative impacts.
(7) Land-use change and management can influence surface water and groundwater quality (e.g., through enhanced or reduced leaching of nutrients and pesticides) and the (local) hydrological cycle (e.g., a higher water use).
(8) Agricultural practices for mitigation can have both positive and negative effects on conservation of water and on its quality.
(9) Reduced tillage promotes increased water-use efficiency.
(10) Afforestation generally improves groundwater quality and reduces soil erosion. It influences both catchment and regional hydrological cycles (a smoothed hydrograph, thus reducing runoff and flooding). It generally gives better watershed protection, but at the expense of surface water yield and aquifer recharge, which may be critical in semi-arid and arid regions.
(11) Stopping/slowing deforestation and forest degradation conserve water resources and prevent flooding, reduce run-off, control erosion and reduce siltation of rivers.
(12) The various waste management and wastewater control and treatment technologies can both reduce GHG emissions and have positive effects on the environment, but they may cause water pollution in case of improperly designed or managed facilities.
(13) As conventional oil supplies become scarce and extraction costs increase, unconventional liquid fuels will become more economically attractive, but this is offset by greater environmental costs (a high water demand; sanitation costs).

treatment of nutrient-rich wastewater and sludge, and provide habitats for biodiversity in the agricultural landscape (Berndes and Börjesson, 2002; Berndes et al., 2004; Börjesson and Berndes, 2006). [WGIII 8.8] In the case of forest plantations for obtaining bio-fuels, negative environmental impacts are avoidable through good project design. Environmental benefits include, among others, reduced soil degradation, water runoff, and downstream siltation and capture of polluting agricultural runoff. [LULUCF Fact Sheet 4.21]

6.2.3 Biomass electricity (3)

Non-hydro renewable energy supply technologies, particularly solar, wind, geothermal and biomass, are currently small overall contributors to global heat and electricity supply, but are increasing most rapidly, albeit from a low base. Growth of biomass electricity is restricted due to cost, as well as social and environmental barriers. [WGIII 4.ES] For the particular case of biomass electricity, any volumes of biomass needed above those available from agricultural and forest residues [WGIII Chapters 8 and 9] will need to be purpose-grown, so could be constrained by land and water availability. There is considerable uncertainty, but there should be sufficient production possible in all regions to meet the additional generation from bio-energy of 432 TWh/yr by 2030, as projected in this analysis. [WGIII 4.4.4] In general, the substitution of fossil fuels by biomass in electricity generation will reduce the amount of cooling water discharged to surface water streams.

6.2.4 Hydropower (4)

Renewable energy systems such as hydro-electricity can contribute to the security of energy supply and protection of the environment . However, construction of hydro-electric power plants may also cause ecological impacts on existing river ecosystems and fisheries, induced by changes in flow regime (the hydrograph) and evaporative water losses (in the case of dam-based power-houses). Also social disruption may be an impact. Finally, water availability for shipping (water depth) may cause problems. Positive effects are flow regulation, flood control, and availability of water for irrigation during dry seasons. Furthermore, hydropower does not require water for cooling (as in the case of thermal power plants) or, as in the case of bio-fuels, for growth. About 75% of water reservoirs in the world were built for irrigation, flood control and urban water supply schemes, and many could have small hydropower generation retrofits added without additional environmental impacts. [WGIII 4.3.3]

Large (>10 MW) hydro-electricity systems accounted for over 2,800 TWh of consumer energy in 2004 and provided 16% of global electricity (90% of renewable electricity). Hydro projects under construction could increase the share of hydro-electricity by about 4.5% on completion and new projects could be deployed to provide a further 6,000 TWh/yr or more of electricity economically, mainly in developing countries. Repowering existing plants with more powerful and efficient turbine designs can be cost-effective whatever the plant scale. [WGIII 4.3.3.1]

Small (<10 MW) and micro (<1 MW) hydropower systems, usually run-of-river schemes, have provided electricity to many rural communities in developing countries such as Nepal. Their present generation output is uncertain, with predictions ranging from 4 TWh/yr to 9% of total hydropower output at 250 TWh/yr. The global technical potential of small and micro-hydro is around 150–200 GW, with many unexploited resource sites available. [WGIII 4.3.3.1]

The many benefits of hydro-electricity, including irrigation and water supply resource creation, rapid response to grid demand fluctuations due to peaks or intermittent renewables, recreational lakes, and flood control, as well as the negative aspects, need to be evaluated for any given development. [WGIII 4.3.3.1]

6.2.5 Geothermal energy (5)

Geothermal resources have long been used for direct heat extraction for district urban heating, industrial processing, domestic water and space heating, leisure and balneotherapy applications. [WGIII 4.3.3.4]

Geothermal fields of natural steam are rare, most being a mixture of steam and hot water requiring single or double flash systems to separate out the hot water, which can then be used in binary plants or for direct heating. Re-injection of the fluids maintains a constant pressure in the reservoir, hence increasing the field's life and reducing concerns about environmental impacts. [WGIII 4.3.3.4]

Sustainability concerns relating to land subsidence, heat extraction rates exceeding natural replenishment (Bromley and Currie, 2003), chemical pollution of waterways (e.g., with arsenic), and associated CO_2 emissions have resulted in some geothermal power plant permits being declined. This could be partly overcome by re-injection techniques. Deeper drilling technology could help to develop widely abundant hot dry rocks where water is injected into artificially fractured rocks and heat extracted as steam. However, at the same time, this means a claim on available water resources. [WGIII 4.3.3.4]

6.2.6 Energy use in buildings (6)

Evaporative cooling, as a mitigation measure, means substantial savings in annual cooling energy use for residences. However, this type of cooling places an extra pressure on available water resources. Cooling energy use in buildings can be reduced by different measures, for example reducing the cooling load by building shape and orientation. Reducing this energy means, in the case of using water for cooling, a lower water demand. [WGIII 6.4.4]

6.2.7 Land-use change and management (7)

According to IPCC Good Practice Guidance for LULUCF, there are six possible broad land-use categories: forest land, cropland, grassland, wetlands, settlements, and other. Changes in land use (e.g., conversion of cropland to grassland) may result in net changes in carbon stocks and in different impacts on water resources. For land-use changes other than land converted to forest (as discussed in Section 6.2.10), previous IPCC documents contain very few references to their impacts on water resources. Wetland restoration, one of the main mitigation practices in agriculture [WGIII 8.4.1.3], results in the improvement of water quality and decreased flooding. [LULUCF Table 4.10] Set-aside, another mitigation practice identified by WGIII, may have positive impacts on both water conservation and water quality. [WGIII Table 8.12]

Land management practices implemented for climate change mitigation may also have different impacts on water resources. Many of the practices advocated for soil carbon conservation – reduced tillage, more vegetative cover, greater use of perennial crops – also prevent erosion, yielding possible benefits for improved water and air quality (Cole et al., 1993). These practices may also have other potential adverse effects, at least in some regions or conditions. Possible effects include enhanced contamination of groundwater with nutrients or pesticides via leaching under reduced tillage (Cole et al., 1993; Isensee and Sadeghi, 1996). These possible negative effects, however, have not been widely confirmed or quantified, and the extent to which they may offset the environmental benefits of carbon sequestration is uncertain. [WGIII TAR 4.4.2]

The group of practices known as agriculture intensification (Lal et al., 1999; Bationo et al., 2000; Resck et al., 2000; Swarup et al., 2000), including those that enhance production and the input of plant-derived residues to soil (crop rotations, reduced bare fallow, cover crops, high-yielding varieties, integrated pest management, adequate fertilisation, organic amendments, irrigation, water-table management, site-specific management, and others), has numerous ancillary benefits, the most important of which is the increase and maintenance of food production. Environmental benefits can include erosion control, water conservation, improved water quality, and reduced siltation of reservoirs and waterways. Soil and water quality is adversely affected by the indiscriminate use of agriculture inputs and irrigation water. [LULUCF Fact Sheet 4.1]

Nutrient management to achieve efficient use of fertilisers has positive impacts on water quality. [WGIII Table 8.12] In addition, practices that reduce N_2O emission often improve the efficiency of nitrogen use from these and other sources (e.g., manures), thereby also reducing GHG emissions from fertiliser manufacture and avoiding deleterious effects on water and air quality from nitrogen pollutants (Dalal et al., 2003; Paustian et al., 2004; Oenema et al., 2005; Olesen et al., 2006). [WGIII 8.8]

Agro-forestry systems (plantation of trees in cropland) can provide multiple benefits including energy to rural communities with synergies between sustainable development and GHG mitigation. [LULUCF 4.5.1] However, agro-forestry may have negative impacts on water conservation. [WGIII Table 8.12]

6.2.8 Cropland management (water) (8)

Agricultural practices which promote the mitigation of greenhouse gases can have both negative and positive effects on the conservation of water, and on its quality. Where the measures promote water-use efficiency (e.g., reduced tillage), they provide potential benefits. But in some cases, the practices could intensify water use, thereby reducing streamflow or groundwater reserves (Unkovich, 2003; Dias de Oliveira et al., 2005). Rice management has generally positive impacts on water quality through a reduction in the amount of chemical pollutants in drainage water. [WGIII Table 8.12]

6.2.9 Cropland management (reduced tillage) (9)

Conservation tillage is a generic term that includes a wide range of tillage practices, including chisel plough, ridge till, strip till, mulch till and no till (CTIC, 1998). Adoption of conservation tillage has numerous ancillary benefits. Important among these benefits are the control of water and wind erosion, water conservation, increased water-holding capacity, reduced compaction, increased soil resilience to chemical inputs, increased soil and air quality, enhanced soil biodiversity, reduced energy use, improved water quality, reduced siltation of reservoirs and waterways, and possible double-cropping. In some areas (e.g., Australia), increased leaching from greater water retention with conservation tillage can cause downslope salinisation. [LULUCF Fact Sheet 4.3] Important secondary benefits of conservation tillage adoption include soil erosion reduction, improvements in water quality, increased fuel efficiency, and increases in crop productivity. [LULUCF 4.4.2.4] Tillage/residue management has positive impacts on water conservation. [WGIII Table 8.12]

6.2.10 Afforestation or reforestation (10)

Forests, generally, are expected to use more water (the sum of transpiration and evaporation of water intercepted by tree canopies) than crops, grass, or natural short vegetation. This effect, occurring in lands that are subjected to afforestation or reforestation, may be related to increased interception loss, especially where the canopy is wet for a large proportion of the year (Calder, 1990) or, in drier regions, to the development of more massive root systems, which allow water extraction and use during prolonged dry seasons. [LULUCF 2.5.1.1.4]

Interception losses are greatest from forests that have large leaf areas throughout the year. Thus, such losses tend to be greater for evergreen forests than for deciduous forests (Hibbert, 1967; Schulze, 1982) and may be expected to be larger for fast-growing forests with high rates of carbon storage than for slow-growing forests. Consequently, afforestation with fast-growing conifers on non-forest land commonly decreases the flow of water from catchments and can cause water shortages during droughts (Hibbert, 1967; Swank and Douglass, 1974). Vincent (1995), for example, found that establishing high-water-demanding species of pines to restore degraded Thai watersheds markedly reduced dry season streamflows relative to the original deciduous forests. Although forests lower average flows, they may reduce peak flows and increase flows during dry seasons because forested lands tend to have better infiltration capacity and a high capacity to retain water (Jones and Grant, 1996). Forests also play an important role in improving water quality. [LULUCF 2.5.1.1.4]

In many regions of the world where forests grow above shallow saline water tables, decreased water use following deforestation can cause water tables to rise, bringing salt to the surface (Morris and Thomson, 1983). In such situations, high water use by trees (e.g., through afforestation or reforestation) can be of benefit (Schofield, 1992). [LULUCF 2.5.1.1.4]

In the dry tropics, forest plantations often use more water than short vegetation because trees can access water at greater depth and evaporate more intercepted water. Newly planted forests can use more water (by transpiration and interception) than the annual rainfall, by mining stored water (Greenwood et al., 1985). Extensive afforestation or reforestation in the dry tropics can therefore have a serious impact on supplies of groundwater and river flows. It is less clear, however, whether replacing natural forests with plantations, even with exotic species, increases water use in the tropics when there is no change in rooting depth or stomatal behaviour of the tree species. In the dry zone of India, water use by *Eucalyptus* plantations is similar to that of indigenous dry deciduous forest: both forest types essentially utilise all the annual rainfall (Calder, 1992). [LULUCF 2.5.1.1.4]

Afforestation and reforestation, like forest protection, may also have beneficial hydrological effects. After afforestation in wet areas, the amount of direct runoff initially decreases rapidly, then gradually becomes constant, and baseflow increases slowly as stand age increases towards maturity (Fukushima, 1987; Kobayashi, 1987), suggesting that reforestation and afforestation help to reduce flooding and enhance water conservation. In water-limited areas, afforestation, especially plantations of species with high water demand, can cause a significant reduction in streamflow, affecting the inhabitants of the basin (Le Maitre and Versfeld, 1997), and reducing water flow to other ecosystems and rivers, thus affecting aquifers and recharge (Jackson et al., 2005). In addition, some possible changes in soil properties are largely driven by changes in hydrology. The hydrological benefits of afforestation may need to be evaluated individually for each site. [WGIII TAR 4.4.1]

Positive socio-economic benefits, such as wealth or job creation, must be balanced by the loss of welfare resulting from reductions in available water, grazing, natural resources, and agricultural land. Afforestation of previously eroded or otherwise degraded land may have a net positive environmental impact; in catchments where the water yield is large or is not heavily used, streamflow reduction may not be critical. [LULUCF 4.7.2.4]

6.2.11 Avoided/reduced deforestation (11)

Stopping or slowing deforestation and forest degradation (loss of carbon density) and sustainable management of forests may significantly contribute to avoided emissions, may conserve water resources and prevent flooding, reduce runoff, control erosion, reduce siltation of rivers, and protect fisheries and investments in hydro-electric power facilities; and at the same time preserve biodiversity (Parrotta, 2002). [WGIII 9.7.2]

Preserving forests conserves water resources and prevents flooding. For example, the flood damage in Central America following Hurricane Mitch was apparently enhanced by the loss of forest cover. By reducing runoff, forests control erosion and salinity. Consequently, maintaining forest cover can reduce siltation of rivers, protecting fisheries and investment in hydro-electric power facilities (Chomitz and Kumari, 1996). [WGIII TAR 4.4.1]

Deforestation and degradation of upland catchments can disrupt hydrological systems, replacing year-round water flows in downstream areas with flood and drought regimes (Myers, 1997). Although there are often synergies between increased carbon storage through afforestation, reforestation and deforestation (ARD) activities and other desirable associated impacts, no general rules can be applied; impacts must be assessed individually for each specific case. Associated impacts can often be significant, and the overall desirability of specific ARD activities can be greatly affected by their associated impacts. [LULUCF 3.6.2]

6.2.12 Solid waste management; wastewater treatment (12)

Controlled landfill (with or without gas recovery and utilisation) controls and reduces GHG emissions but may have negative impacts on water quality in the case of improperly managed sites. This also holds for aerobic biological treatment (composting) and anaerobic biological treatment (anaerobic digestion). Recycling, reuse and waste minimisation can be negative for waste scavenging from open dump sites, with water pollution as a potential consequence. [WGIII Table 10.7]

When efficiently applied, wastewater transport and treatment technologies reduce or eliminate GHG generation and emissions. In addition, wastewater management promotes water conservation by preventing pollution from untreated discharges to surface water, groundwater, soils, and coastal zones, thus reducing the volume of pollutants, and requiring a smaller volume of water to be treated. [WGIII 10.4.6]

Treated wastewater can either be reused or discharged, but reuse is the most desirable option for agricultural and horticultural irrigation, fish aquaculture, artificial recharge of aquifers, or industrial applications. [WGIII 10.4.6]

6.2.13 Unconventional oil (13)

As conventional oil supplies become scarce and extraction costs increase, unconventional liquid fuels will become more economically attractive, although this is offset by greater environmental costs (Williams et al., 2006). Mining and upgrading of oil shale and oil sands requires the availability of abundant water. Technologies for recovering tar sands include open cast (surface) mining, where the deposits are shallow enough, or injection of steam into wells *in situ* to reduce the viscosity of the oil prior to extraction. The mining process uses about four litres of water to produce one litre of oil but produces a refinable product. The *in situ* process uses about two litres of water to one litre of oil, but the very heavy product needs cleaning and diluting (usually with naphtha) at the refinery or needs to be sent to an upgrader to yield syncrude at an energy efficiency of around 75% (NEB, 2006). The energy efficiency of oil sand upgrading is around 75%. Mining of oil sands leaves behind large quantities of pollutants and areas of disturbed land. [WGIII 4.3.1.4]

6.3 Effects of water management policies and measures on GHG emissions and mitigation

As shown in the previous section, climate change mitigation practices in various sectors may have an impact on water resources. Conversely, water management policies and measures can have an influence on GHG emissions associated with different sectors, and thus on their respective mitigation measures (Table 6.2).

6.3.1 Hydro dams (1)

About 75% of water reservoirs in the world were built for irrigation, flood control and urban water supply schemes. Greenhouse gas emissions vary with reservoir location, power density (power capacity per area flooded), flow rate, and whether the plant is dam-based or run-of-river type. Recently, the greenhouse gas footprint of hydropower reservoirs has been questioned. Some reservoirs have been shown to absorb carbon dioxide at their surface, but most emit small amounts of GHGs as water conveys carbon in the natural carbon cycle. High emissions of methane have been recorded at shallow, plateau-type tropical reservoirs where the natural carbon cycle is most productive, while deep-water reservoirs exhibit lower emissions. Methane from natural floodplains and wetlands may be suppressed if they are inundated by a new reservoir, since methane is oxidised as it rises through the water column. Methane formation in freshwater involves by-product carbon compounds (phenolic and humic acids) that effectively sequester the carbon involved. For shallow tropical reservoirs, further research is needed to establish the extent to which these may increase methane emissions. [WGIII 4.3.3.1]

The emission of greenhouse gases from reservoirs due to rotting vegetation and carbon inflows from the catchment is a recently identified ecosystem impact of dams. This challenges the conventional wisdom that hydropower produces only positive atmospheric effects (e.g., reductions in emissions of CO_2 and nitrous oxides), when compared with conventional power generation sources (World Commission on Dams, 2000).

Lifecycle assessments of hydropower projects available at the time of the AR4 showed low overall net greenhouse gas emissions. Given that measuring the incremental anthropogenic-related emissions from freshwater reservoirs remains uncertain, the UNFCCC Executive Board has excluded large hydro projects with significant water storage from its Clean Development Mechanism (CDM). [WGIII 4.3.3.1]

6.3.2 Irrigation (2)

About 18% of the world's croplands now receive supplementary water through irrigation (Millennium Ecosystem Assessment, 2005a, b). Expanding this area (where water reserves allow), or using more effective irrigation measures, can enhance carbon storage in soils through enhanced yields and residue returns (Follett, 2001; Lal, 2004). However, some of these gains may be offset by carbon dioxide from energy used to deliver the water (Schlesinger, 1999; Mosier et al., 2005) or from N_2O emissions from higher moisture and fertiliser nitrogen inputs (Liebig et al., 2005), though the latter effect has not been widely measured [WGIII 8.4.1.1.d]. The expansion of wetland rice area may also cause increased methane emissions from soils (Yan et al., 2003). [WGIII 8.4.1.1.e]

6.3.3 Residue return (3)

Weed competition for water is an important cause of crop failure or decreases in crop yields worldwide. Advances in weed control methods and farm machinery now allow many crops to be grown with minimal tillage (reduced tillage) or without tillage (no-till). These practices, which result in the maintenance of crop residues on the soil surface, thus avoiding water losses by evaporation, are now being used increasingly throughout the world (e.g., Cerri et al., 2004). Since soil disturbance tends to stimulate soil carbon losses through enhanced decomposition and erosion (Madari et al., 2005), reduced- or no-till agriculture often results in soil carbon gain, though not always (West and Post, 2002; Alvarez, 2005; Gregorich et al., 2005; Ogle et al., 2005). Adopting reduced- or no-till may also affect emissions of N_2O, but the net effects are inconsistent and not well quantified globally (Cassman et al., 2003; Smith and Conen, 2004; Helgason et al., 2005; Li et al., 2005). The effect of reduced tillage on N_2O emissions may depend on soil and climatic conditions: in some areas reduced tillage promotes N_2O emissions; elsewhere it may reduce emissions or have no measurable influence (Marland et al., 2001). Furthermore, no-tillage systems can reduce carbon dioxide emissions from

Table 6.2: *Influence of water management on sectoral GHG emissions. Increased GHG emissions are indicated with [−], (because this implies a negative impact) and reduced GHG emissions with [+]. Numbers in round brackets refer to the Notes, and also to the sub-section numbers in Section 6.3.*

Sector	Quality		Quantity		Water level	
	Chemical/ biological	Temperature	Average demand	Soil moisture	Surface water	Ground water
Energy		Geothermal energy(7) [+]	Hydro dams(1) [+/-] Irrigation(2) [-] Geothermal energy(7) [+] Desalinisation(6) [-]		Hydro dams (1) [+/-]	
Agriculture			Hydro dams(1) [-]	Irrigation(2) [+/-] Residue return(3) [+]		Drainage of cropland(4) [+/-]
Waste	Wastewater treatment(5) [+/-]					

Notes:
(1) Hydropower does not require fossil fuel and is an important source of renewable energy. However, recently the GHG footprint of hydropower reservoirs has been questioned. In particular, methane is a problem.
(2) Applying more effective irrigation measures can enhance carbon storage in soils through enhanced yields and residue returns, but some of these gains may be offset by CO_2 emissions from the energy used to deliver the water. Irrigation may also induce additional CH_4 and N_2O emissions, depending on case-specific circumstances.
(3) Residue returned to the field, to improve water-holding capacity, will sequester carbon through both increased crop productivity and reduced soil respiration.
(4) Drainage of agricultural lands in humid regions can promote productivity (and hence soil carbon) and perhaps also suppress N_2O emissions by improving aeration. Any nitrogen lost through drainage, however, may be susceptible to loss as N_2O.
(5) Depending on the design and management of facilities (wastewater treatment and treatment purification technologies), more or less CH_4 and N_2O emissions – the major GHG emissions from wastewater – can be emitted during all stages from source to disposal; however, in practice, most emissions occur upstream of treatment.
(6) Desalinisation requires the use of energy, and thus generates GHG emissions.
(7) Using geothermal energy for heating purposes does not generate GHG emissions, as is the case with other methods of energy production.

energy use (Marland et al., 2003; Koga et al., 2006). Systems that retain crop residues also tend to increase soil carbon because these residues are the precursors for soil organic matter, the main store of carbon in soil. Avoiding the burning of residues (e.g., mechanising the harvest of sugarcane, eliminating the need for pre-harvest burning; Cerri et al., 2004), also avoids emissions of aerosols and GHGs generated from fire, although carbon dioxide emissions from fuel use may increase. [WGIII 8.4.1.1.c]

6.3.4 Drainage of cropland (4)

Drainage of croplands in humid regions can promote productivity (and hence soil carbon) and perhaps also suppress N_2O emissions by improving aeration (Monteny et al., 2006). Any nitrogen lost through drainage, however, may be susceptible to loss as N_2O (Reay et al., 2003). [WGIII 8.4.1.1.d]

6.3.5 Wastewater treatment (5)

For landfill CH_4, the largest GHG emission source from the waste sector, emissions continue several decades after waste disposal, and thus estimation of emission trends requires models which include temporal trends. CH_4 is also emitted during wastewater transport, sewage treatment processes, and leakage from anaerobic digestion of waste or wastewater sludges. The major sources of N_2O are human sewage and wastewater treatment. [WGIII 10.3.1]

The methane emissions from wastewater alone are expected to increase by almost 50% between 1990 and 2020, especially in the rapidly developing countries of eastern and southern Asia. Estimates of global N_2O emissions from wastewater are incomplete and based only on human sewage treatment, but these indicate an increase of 25% between 1990 and 2020. It is important to emphasise, however, that these are business-as-usual scenarios, and actual emissions could be much lower if additional measures were put in place. Future reductions in emissions from the waste sector will partially depend on the post-2012 availability of Kyoto mechanisms such as the CDM. [WGIII 10.3.1]

In developing countries, due to rapid population growth and urbanisation without concurrent development of wastewater infrastructure, CH_4 and N_2O emissions from wastewater are generally higher than in developed countries. This can be seen by examining the 1990 estimated methane and N_2O emissions and projected trends to 2020 from wastewater and human sewage. [WGIII 10.3.3]

Although current GHG emissions from wastewater are lower than emissions from waste, it is recognised that there are substantial emissions that are not quantified by current estimates, especially from septic tanks, latrines, and uncontrolled discharges in developing countries. Decentralised 'natural' treatment processes and septic tanks in developing countries may result in relatively large emissions of methane and N_2O, particularly in China, India and Indonesia. Open sewers or informally ponded wastewaters in developing countries often result in uncontrolled discharges to rivers and lakes, causing rapidly increasing wastewater volumes going along with economic development. On the other hand, low-water-use toilets (3–5 litres) and ecological sanitation approaches (including ecological toilets) where nutrients are safely recycled into productive agriculture and the environment, are being used in Mexico, Zimbabwe, China and Sweden. These could also be applied in many developing and developed countries, especially where there are water shortages, irregular water supplies, or where additional measures for the conservation of water resources are needed. All of these measures also encourage smaller wastewater treatment plants with reduced nutrient loads and proportionally lower GHG emissions. [WGIII 10.6.2] All in all, the quantity of wastewater collected and treated is increasing in many countries in order to maintain and improve potable water quality, as well for other public health and environmental protection benefits. Concurrently, GHG emissions from wastewater will decrease relative to future increases in wastewater collection and treatment. [WGIII 10.6.2]

6.3.6 Desalinisation (6)

In water-scarce regions, water supply may take place (partly) by desalinisation of saline water. Such a process requires energy and this implies the generation of GHG emissions in the case of fossil-fuel utilisation. [WGII 3.3.2]

6.3.7 Geothermal energy (7)

Using geothermal energy for heating purposes does not generate GHG emissions, as is the case with other methods of energy generation (see also Section 6.2.5).

6.4 Potential water resource conflicts between adaptation and mitigation

Possible conflicts between adaptation and mitigation might arise over water resources. The few studies that exist (e.g., Dang et al., 2003) indicate that the repercussions from mitigation for adaptation and *vice versa* are mostly marginal at the global level, although they may be significant at the regional scale. In regions where climate change will trigger significant shifts in the hydrological regime, but where hydropower potentials are still available, this would increase the competition for water, especially if climate change adaptation efforts in various sectors are implemented (such as competition for surface water resources between irrigation, to cope with climate change impacts in agriculture, increased demand for drinking water, and increased demand for cooling water for the power sector). This confirms the importance of integrated land and water management strategies for river basins, to ensure the optimal allocation of scarce natural resources (land, water). Also, both mitigation and adaptation have to be evaluated at the same time, with explicit trade-offs, in order to optimise economic investments while fostering sustainable development.[WGII 18.8, 18.4.3]

Several studies confirm potential clashes between water supply, flood control, hydropower and minimum streamflow (required for ecological and water quality purposes) under changing climatic and hydrological conditions (Christensen et al., 2004; Van Rheenen et al., 2004). [WGII 18.4.3]

Adaptation to changing hydrological regimes and water availability will also require continuous additional energy input. In water-scarce regions, the increasing reuse of wastewater and the associated treatment, deep-well pumping, and especially large-scale desalination, would increase energy use in the water sector (Boutkan and Stikker, 2004), thus generating GHG emissions, unless 'clean energy' options are used to generate the necessary energy input. [WGII 18.4.3]

7

Implications for policy and sustainable development

Climate change poses a major conceptual challenge to water managers, water resource users (e.g., in agriculture) as well as to policymakers in general, as it is no longer appropriate to assume that past climatic and hydrological conditions will continue into the future. Water resources management clearly impacts on many other policy areas (e.g., energy, health, food security, nature conservation). Thus, the appraisal of adaptation and mitigation options needs to be conducted across multiple water-dependent sectors.

Substantial changes have been observed over recent decades in many water-related variables, but clear formal attribution of the observed changes to natural or anthropogenic causes is not generally possible at present. Projections of future precipitation, soil moisture and runoff at regional scales are subject to substantial uncertainty. In many regions, models do not agree on the sign of projected change. However, some robust patterns are found across climate model projections. Increases in precipitation (and river flow) are *very likely* at high latitudes and in some wet tropics (including populous areas in east and south-east Asia), and decreases are *very likely* over much of the mid-latitudes and dry tropics [WGII Figure 3.4]. Interpretation and quantification of uncertainties has recently improved, and new methods (e.g., ensemble-based approaches) are being developed for their characterisation [WGII 3.4, 3.5]. Nevertheless, quantitative projections of changes in precipitation, river flows and water levels at the river-basin scale remain uncertain, so that planning decisions involving climate change must be made in the context of this uncertainty. [WGII TS, 3.3.1, 3.4]

Effective adaptation to climate change occurs across temporal and spatial scales, including incorporation of lessons from responses to climate variability into longer-term vulnerability reduction efforts and within governance mechanisms from communities and watersheds to international agreements. Continued investment in adaptation in response to historical experience alone, rather than projected future conditions that will include both variability and change, is *likely* to increase the vulnerability of many sectors to climate change. [WGII TS, 14.5]

7.1 Implications for policy by sector

Water resource management

- Catchments that are dominated by seasonal snow cover already experience earlier peak flows in spring, and this shift is expected to continue under a warmer climate. At lower altitudes, winter precipitation will increasingly be in the form of rainfall instead of snowfall. In many mountain areas, e.g., in the tropical Andes and many Asian mountains, where glaciers provide the main runoff during pronounced dry seasons, water volumes stored in glaciers and snow cover are projected to decline. Runoff during warm and dry seasons is enhanced while glaciers are shrinking, but will dramatically drop after they have disappeared. [WGII 3.4.1]
- Drought-affected areas are *likely* to increase; and extreme precipitation events, which are *very likely* to increase in frequency and intensity, will augment flood risk. Up to 20% of the world's population live in river basins that are *likely* to be affected by increased flood hazard by the 2080s in the course of climate change. [WGII 3.4.3]
- Semi-arid and arid areas are particularly exposed to the impacts of climate change on freshwater. Many of these areas (e.g., the Mediterranean Basin, western USA, southern Africa, north-eastern Brazil, southern and eastern Australia) will suffer a decrease in water resources due to climate change. [WGII Box TS.5, 3.4, 3.7] Efforts to offset declining surface water availability due to increasing precipitation variability will be hampered by the fact that groundwater recharge is projected to decrease considerably in some water-stressed regions [WGII 3.4.2], exacerbated by the increased water demand. [WGII 3.5.1]
- Higher water temperatures, increased precipitation intensity and longer periods of low flows exacerbate many forms of water pollution, with impacts on ecosystems, human health, and water system reliability and operating costs. [WGII 3.2, 3.4.4, 3.4.5]
- Areas in which runoff is projected to decline will face a reduction in the value of services provided by water resources. The beneficial impacts of increased annual runoff in some other areas will be tempered by the negative effects of increased precipitation variability and seasonal runoff shifts on water supply, water quality and flood risks. [WGII 3.4, 3.5]
- At the global level, the negative impacts of climate change on freshwater systems outweigh the benefits. [WGII 3.4, 3.5]
- Adverse effects of climate on freshwater systems aggravate the impacts of other stresses, such as population growth, land-use change and urbanisation. [WGII 3.3.2, 3.5] Globally, water demand will grow in the coming decades, primarily due to population growth and increased affluence. [WGII 3.5.1]
- Climate change affects the function and operation of existing water infrastructure as well as water management practices. Current water management practices are *very likely* to be inadequate to reduce the negative impacts of climate change on water-supply reliability, flood risk, health, energy and aquatic ecosystems. [WGII TS, 3.4, 3.5, 3.6]
- Adaptation procedures and risk management practices for the water sector are being developed in some countries and regions (e.g., the Caribbean, Canada, Australia, the Netherlands, the UK, the USA and Germany) that recognise the uncertainty of projected hydrological changes, but evaluation criteria on effectiveness need to be developed. [WGII 3.6]

Ecosystems

- The resilience of many ecosystems and their ability to adapt naturally is *likely* to be exceeded by 2100 by an unprecedented combination of change in climate, associated disturbances (e.g., flooding, drought, wildfire) and other global change drivers (e.g., land-use change, pollution, over-exploitation of resources). [WGII TS]

- Greater rainfall variability is *likely* to compromise wetlands through shifts in the timing, duration and depth of water levels. [WGII 4.4.8]
- Of all ecosystems, freshwater ecosystems will have the highest proportion of species threatened with extinction due to climate change. [WGII 4.4.8]
- Current conservation practices are generally poorly prepared to adapt to the projected changes in water resources during the coming decades. [WGII 4.ES]
- Effective adaptation responses that will conserve biodiversity and other ecosystem services are *likely* to be costly to implement, but unless conservation water needs are factored into adaptation strategies, many natural ecosystems and the species they support will decline. [WGII 4.ES, 4.4.11, Table 4.1, 4.6.1, 4.6.2]

Agriculture, forests

- An increased frequency of droughts and floods negatively affects crop yields and livestock, with impacts that are both larger and earlier than predicted by using changes in mean variables alone. [WGII 5.4.1, 5.4.2] Increases in the frequency of droughts and floods will have a negative effect on local production, especially in subsistence sectors at low latitudes. [WGII SPM]
- Impacts of climate change on irrigation water requirements may be large. [WGII 5.4] New water storages, both surface and underground, can alleviate water shortages but are not always feasible. [WGII 5.5.2]
- Farmers may be able to partially adjust by changing cultivars and/or planting dates for annual crops and by adopting other strategies. The potential for higher water needs should be considered in the design of new irrigation supply systems and in the rehabilitation of old systems. [WGII 5.5.1]
- Measures to combat water scarcity, such as the reuse of wastewater for agriculture, need to be carefully managed to avoid negative impacts on occupational health and food safety. [WGII 8.6.4]
- Unilateral measures to address water shortages due to climate change can lead to competition for water resources. International and regional approaches are required in order to develop joint solutions. [WGII 5.7]

Coastal systems and low-lying areas

- Sea-level rise will extend areas of salinisation of groundwater and estuaries, resulting in a decrease in freshwater availability. [WGII 3.2, 3.4.2]
- Settlements in low-lying coastal areas that have low adaptive capacity and/or high exposure are at increased risk from floods and sea-level rise. Such areas include river deltas, especially Asian megadeltas (e.g., the Ganges-Brahmaputra in Bangladesh and west Bengal), and low-lying coastal urban areas, especially areas prone to natural or human-induced subsidence and tropical storm landfall (e.g., New Orleans, Shanghai). [WGII 6.3, 6.4]

Industry, settlement and society

- Infrastructure, such as urban water supply systems, are vulnerable, especially in coastal areas, to sea-level rise and reduced regional precipitation. [WGII 7.4.3, 7.5]
- Projected increases in extreme precipitation events have important implications for infrastructure: design of storm drainage, road culverts and bridges, levees and flood control works, including sizing of flood control detention reservoirs. [WGII 7.4.3.2]
- Planning regulations can be used to prevent development in high-flood-risk zones (e.g., on floodplains), including housing, industrial development and siting of landfill sites etc. [WGII 7.6]
- Infrastructure development, with its long lead times and large investments, would benefit from incorporating climate-change information. [WGII 14.5.3, Figure 14.3]

Sanitation and human health

- Climate-change-induced effects on water pose a threat to human health through changes in water quality and availability. Although access to water supplies and sanitation is determined primarily by non-climate factors, in some populations climate change is expected to exacerbate problems of access at the household level. [WGII 8.2.5]
- Appropriate disaster planning and preparedness need to be developed in order to address the increased risk of flooding due to climate change and to reduce impacts on health and health systems. [WGII 8.2.2]

Climate information needs

Progress in understanding the climate impact on the water cycle depends on improved data availability. Relatively short hydrometric records can underestimate the full extent of natural variability. Comprehensive monitoring of water-related variables, in terms of both quantity and quality, supports decision making and is a prerequisite for the adaptive management required under conditions of climate change. [WGII 3.8]

7.2 The main water-related projected impacts by regions

Africa

- The impacts of climate change in Africa are *likely* to be greatest where they co-occur with a range of other stresses (population growth; unequal access to resources; inadequate access to water and sanitation [WGII 9.4.1]; food insecurity [WGII 9.6]; poor health systems [WGII 9.2.2, 9.4.3]). These stresses and climate change will increase the vulnerabilities of many people in Africa. [WGII 9.4]
- An increase of 5–8% (60–90 million ha) of arid and semi-arid land in Africa is projected by the 2080s under a range of climate change scenarios. [WGII 9.4.4]
- Declining agricultural yields are *likely* due to drought and land degradation, especially in marginal areas. Mixed rain-fed systems in the Sahel will be greatly affected by climate

change. Mixed rain-fed and highland perennial systems in the Great Lakes region and in other parts of East Africa will also be severely affected. [WGII 9.4.4, Box TS.6]

- Current water stress in Africa is *likely* to be increased by climate change, but water governance and water-basin management must also be considered in future assessments of water stress in Africa. Increases in runoff in East Africa (and increased risk of flood events) and decreases in runoff (and increased risk of drought) in other areas (e.g., southern Africa) are projected by the 2050s. [WGII 9.4.1, 9.4.2, 9.4.8]
- Any changes in the primary production of large lakes will have important impacts on local food supplies. Lake Tanganyika currently provides 25–40% of animal protein intake for the surrounding populations, and climate change is *likely* to reduce primary production and possible fish yields by roughly 30% [WGII 9.4.5, 3.4.7, 5.4.5]. The interaction of poor human management decisions, including over-fishing, is *likely* to further reduce fish yields from lakes. [WGII 9.2.2, Box TS.6]

Asia

- The per capita availability of freshwater in India is expected to drop from around 1,820 m^3 currently to below 1,000 m^3 by 2025 in response to the combined effects of population growth and climate change. [WGII 10.4.2.3]
- More intense rain and more frequent flash floods during the monsoon would result in a higher proportion of runoff and a reduction in the proportion reaching the groundwater. [WGII 10.4.2]
- Agricultural irrigation demand in arid and semi-arid regions of east Asia is expected to increase by 10% for an increase in temperature of 1°C. [WGII 10.4.1]
- Coastal areas, especially heavily populated Asian megadelta regions, will be at greatest risk due to increased flooding from the sea and, in some megadeltas, flooding from rivers. [WGII 6.4, 10.4.3]
- Changes in snow and glacier melt, as well as rising snowlines in the Himalayas, will affect seasonal variation in runoff, causing water shortages during dry summer months. One-quarter of China's population and hundreds of millions in India will be affected (Stern, 2007). [WGII 3.4.1, 10.4.2.1]

Australia and New Zealand

- Ongoing water security problems are *very likely* to increase in southern and eastern Australia (e.g., a 0–45% decline in runoff in Victoria by 2030 and a 10–25% reduction in river flow in Australia's Murray-Darling Basin by 2050) and, in New Zealand, in Northland and some eastern regions. [WGII 11.4.1]
- Risks to major infrastructure are *likely* to increase due to climate change. Design criteria for extreme events are *very likely* to be exceeded more frequently by 2030. Risks include failure of floodplain levees and urban drainage systems, and flooding of coastal towns near rivers. [WGII 11.ES, 11.4.5, 11.4.7]
- Production from agriculture and forestry by 2030 is projected to decline over much of southern and eastern Australia, and over parts of eastern New Zealand, due to, among other things, increased drought. However, in New Zealand, initial benefits are projected in western and southern areas and close to major rivers, with increased rainfall. [WGII 11.4]

Europe

- The probability of an extreme winter precipitation exceeding two standard deviations above normal is expected to increase by up to a factor of five in parts of the UK and northern Europe by the 2080s with a doubling of CO_2. [WGII 12.3.1]
- By the 2070s, annual runoff is projected to increase in northern Europe, and decrease by up to 36% in southern Europe, with summer low flows reduced by up to 80% under the IS92a scenario. [WGII 12.4.1, T12.2]
- The percentage of river-basin area in the severe water stress category (withdrawal:availability ratio greater than 0.4) is expected to increase from 19% today to 34–36% by the 2070s. [WGII 12.4.1]
- The number of additional people living in water-stressed watersheds in 17 countries in western Europe is *likely* to increase by 16–44 million (HadCM3 climate model results) by the 2080s. [WGII 12.4.1]
- By the 2070s, hydropower potential for the whole of Europe is expected to decline by 6%, with strong regional variations from a 20–50% decrease in the Mediterranean region to a 15–30% increase in northern and eastern Europe. [WGII 12.4.8]
- Small mountain glaciers in different regions will disappear, while larger glaciers will suffer a volume reduction between 30% and 70% by 2050 under a range of emissions scenarios, with concomitant reductions in discharge in spring and summer. [WGII 12.4.3]

Latin America

- Any future reductions in rainfall in arid and semi-arid regions of Argentina, Chile and Brazil are *likely* to lead to severe water shortages. [WGII 13.4.3]
- Due to climate change and population growth, the number of people living in water-stressed watersheds is projected to reach 37–66 million by the 2020s (compared to an estimate of 56 million without climate change) for the SRES A2 scenario. [WGII 13.4.3]
- Areas in Latin America with severe water stress include eastern Central America, the plains, Motagua Valley and Pacific slopes of Guatemala, eastern and western regions of El Salvador, the central valley and Pacific region of Costa Rica, the northern, central and western intermontane regions of Honduras, and the peninsula of Azuero in Panama). In these areas, water supply and hydro-electricity generation could be seriously affected by climate change. [WGII 13.4.3]
- Glacier shrinkage is expected to increase dry-season water shortages under a warming climate, with adverse

consequences for water availability and hydropower generation in Bolivia, Peru, Colombia and Ecuador. Flood risk is expected to grow during the wet season. [WGII 13.2.4, 13.4.3]

North America

- Projected warming in the western mountains by the mid-21st century is *very likely* to cause large decreases in snowpack, earlier snowmelt, more winter rain events, increased peak winter flows and flooding, and reduced summer flows. [WGII 14.4.1]
- Reduced water supplies coupled with increases in demand are *likely* to exacerbate competition for over-allocated water resources. [WGII 14.2.1, Box 14.2]
- Moderate climate change in the early decades of the century is projected to increase aggregate yields of rain-fed agriculture by 5–20%, but with important variability among regions. Major challenges are projected for crops that are near the warm end of their suitable range or which depend on highly utilised water resources. [WGII 14.4.4]
- Vulnerability to climate change is *likely* to be concentrated in specific groups and regions, including indigenous peoples and others dependent on narrow resource bases, and the poor and elderly in cities. [WGII 14.2.6, 14.4.6]

Polar regions

- Northern Hemisphere permafrost extent is *likely* to decrease by 20–35% by 2050. The depth of seasonal thawing is projected to increase by 15–25% in most areas by 2050, and by 50% or more in northernmost locations under the full range of SRES scenarios. [WGII 15.3.4] In the Arctic, disruption of ecosystems is projected as a result. [WGII 15.4.1]
- Further reductions in lake and river ice cover are expected, affecting thermal structures, the quality/quantity of under-ice habitats and, in the Arctic, the timing and severity of ice jamming and related flooding. Freshwater warming is expected to influence the productivity and distribution of aquatic species, especially fish, leading to changes in fish stock, and reductions in those species that prefer colder waters. [WGII 15.4.1]
- Increases in the frequency and severity of flooding, erosion and destruction of permafrost threaten Arctic communities, industrial infrastructure and water supply. [WGII 15.4.6]

Small islands

- There is strong evidence that, under most climate change scenarios, water resources in small islands are *likely* to be seriously compromised [WGII 16.ES]. Most small islands have a limited water supply, and water resources in these islands are especially vulnerable to future changes and distribution of rainfall. Many islands in the Caribbean are *likely* to experience increased water stress as a result of climate change. Under all SRES scenarios, reduced rainfall in summer is projected for this region, so that it is *unlikely* that demand would be met during low rainfall periods. Increased rainfall in winter is *unlikely* to compensate, due to the lack of storage and high runoff during storm events. [WGII 16.4.1]
- A reduction in average rainfall would lead to a reduction in the size of the freshwater lens. In the Pacific, a 10% reduction in average rainfall (by 2050) would lead to a 20% reduction in the size of the freshwater lens on Tarawa Atoll, Kiribati. Reduced rainfall, coupled with increased withdrawals, sea-level rise and attendant salt-water intrusion, would compound this threat. [WGII 16.4.1]
- Several small-island countries (e.g., Barbados, Maldives, Seychelles and Tuvalu) have begun to invest in the implementation of adaptation strategies, including desalination, to offset current and projected water shortages. [WGII 16.4.1]

7.3 Implications for climate mitigation policy

Implementing important mitigation options such as afforestation, hydropower and bio-fuels may have positive and negative impacts on freshwater resources, depending on site-specific situations. Therefore, site-specific joint evaluation and optimisation of (the effectiveness of) mitigation measures and water-related impacts are needed.

Expansion of irrigated areas and dam-based hydro-electric power generation can lead to reduced effectiveness of associated mitigation potential. In the case of irrigation, CO_2 emissions due to energy consumption for pumping water and to methane emissions in rice fields may partly offset any mitigation effects. Freshwater reservoirs for hydropower generation may produce some greenhouse gas emissions, so that an overall case-specific evaluation of the ultimate greenhouse gas budget is needed. [WGIII 4.3.3.1, 8.4.1.1]

7.4 Implications for sustainable development

Low-income countries and regions are expected to remain vulnerable over the medium term, with fewer options than high-income countries for adapting to climate change. Therefore, adaptation strategies should be designed in the context of development, environment and health policies. Many of the options that can be used to reduce future vulnerability are of value in adapting to current climate and can be used to achieve other environmental and social objectives.

In many regions of the globe, climate change impacts on freshwater resources may affect sustainable development and put at risk the reduction of poverty and child mortality (Table 7.1). It is *very likely* that negative impacts of increased frequency and severity of floods and droughts on sustainable development cannot be avoided [WGII 3.7]. However, aside from major extreme events, climate change is seldom the main factor exerting stress on sustainability. The significance of climate change lies in its interactions with other sources of change and stress, and its impacts should be considered in such a multi-cause context. [WGII 7.1.3, 7.2, 7.4]

Table 7.1: Potential contribution of the water sector to attain the Millennium Development Goals. [WGII Table 3.6]

Goals	Direct relation to water	Indirect relation to water
Goal 1: Eradicate extreme poverty and hunger	Water is a factor in many production activities (e.g., agriculture, animal husbandry, cottage industries) Sustainable production of fish, tree crops and other food brought together in common property resources	Reduced ecosystem degradation improves local-level sustainable development Reduced urban hunger by means of cheaper food from more reliable water supplies
Goal 2: Achieve universal education		Improved school attendance through improved health and reduced water-carrying burdens, especially for girls
Goal 3: Promote gender equity and empower women	Development of gender-sensitive water management programmes	Reduce time wasted and health burdens through improved water service, leading to more time for income-earning and more balanced gender roles
Goal 4: Reduce child mortality	Improved access to drinking water of more adequate quantity and better quality, and improved sanitation, to reduce the main factors of morbidity and mortality in young children	
Goal 6: Combat HIV/AIDS, malaria and other diseases	Improved access to water and sanitation supports HIV/AIDS-affected households and may improve the impact of health care programmes Better water management reduces mosquito habitats and the risk of malaria transmission	
Goal 7: Ensure environmental sustainability	Improved water management reduces water consumption and recycles nutrients and organics Actions to ensure access to improved and, possibly, productive eco-sanitation for poor households Actions to improve water supply and sanitation services for poor communities Actions to reduce wastewater discharge and improve environmental health in slum areas	Develop operation, maintenance, and cost recovery system to ensure sustainability of service delivery

8

Gaps in knowledge and suggestions for further work

There is abundant evidence from observational records and climate projections that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change. However, the ability to quantify future changes in hydrological variables, and their impacts on systems and sectors, is limited by uncertainty at all stages of the assessment process. Uncertainty comes from the range of socio-economic development scenarios, the range of climate model projections for a given scenario, the downscaling of climate effects to local/regional scales, impacts assessments, and feedbacks from adaptation and mitigation activities. Limitations in observations and understanding restrict our current ability to reduce these uncertainties. Decision making needs to operate in the context of this uncertainty. Robust methods to assess risks based on these uncertainties are at an early stage of development.

Capacity for mitigation of climate change and adaptation to its impacts is limited by the availability and economic viability of appropriate technologies and robust collaborative processes for decision making among multiple stakeholders and management criteria. Knowledge of the costs and benefits (including avoided damages) of specific options is scarce. Management strategies that adapt as the climate changes require an adequate observational network to inform them. There is limited understanding of the legal and institutional frameworks and demand-side statistics necessary for mainstreaming adaptation into development plans to reduce water-related vulnerabilities, and of appropriate channels for financial flows into the water sector for adaptation investment.

This section notes a number of key gaps in knowledge related to these needs.

8.1 Observational needs

Better observational data and data access are necessary to improve understanding of ongoing changes, to better constrain model projections, and are a prerequisite for adaptive management required under conditions of climate change. Progress in knowledge depends on improved data availability. Shrinkage of some observational networks is occurring. Relatively short records may not reveal the full extent of natural variability and confound detection studies, while long-term reconstruction can place recent trends and extremes in a broader context. Major gaps in observations of climate change related to freshwater and hydrological cycles were identified as follows [WGI TS.6; WGII 3.8]:

- Difficulties in the measurement of precipitation remain an area of concern in quantifying global and regional trends. Precipitation measurements over oceans (from satellites) are still in the development phase. There is a need to ensure ongoing satellite monitoring, and the development of reliable statistics for inferred precipitation. [WGI 3.3.2.5]
- Many hydrometeorological variables e.g., streamflow, soil moisture and actual evapotranspiration, are inadequately measured. Potential evapotranspiration is generally calculated from parameters such as solar radiation, relative humidity and wind speed. Records are often very short, and available for only a few regions, which impedes complete analysis of changes in droughts. [WGI 3.3.3, 3.3.4]
- There may be opportunities for river flow data rescue in some regions. Where no observations are available, the construction of new observing networks should be considered. [WGI 3.3.4]
- Groundwater is not well monitored, and the processes of groundwater depletion and recharge are not well modelled in many regions. [WGI 3.3.4]
- Monitoring data are needed on water quality, water use and sediment transport.
- Snow, ice and frozen ground inventories are incomplete. Monitoring of changes is unevenly distributed in both space and time. There is a general lack of data from the Southern Hemisphere. [WGI TS 6.2, 4.2.2, 4.3]
- More information is needed on plant evapotranspiration responses to the combined effects of rising atmospheric CO_2, rising temperature and rising atmospheric water vapour concentration, in order to better understand the relationship between the direct effects of atmospheric CO_2 enrichment and changes in the hydrological cycle. [WGI 7.2]
- Quality assurance, homogenisation of data sets, and inter-calibration of methods and procedures could be important whenever different agencies, countries etc., maintain monitoring within one region or catchment.

8.2 Understanding climate projections and their impacts

8.2.1 Understanding and projecting climate change

Major uncertainties in understanding and modelling changes in climate relating to the hydrological cycle include the following [SYR; WGI TS.6]:

- Changes in a number of radiative drivers of climate are not fully quantified and understood (e.g., aerosols and their effects on cloud properties, methane, ozone, stratospheric water vapour, land-use change, past solar variations).
- Confidence in attributing some observed climate change phenomena to anthropogenic or natural processes is limited by uncertainties in radiative forcing, as well as by uncertainty in processes and observations. Attribution becomes more difficult at smaller spatial and temporal scales, and there is less confidence in understanding precipitation changes than there is for temperature. There are very few attribution studies for changes in extreme events.
- Uncertainty in modelling some modes of climate variability, and of the distribution of precipitation between heavy and light events, remains large. In many regions, projections of changes in mean precipitation also vary widely between models, even in the sign of the change. It is necessary to improve understanding of the sources of uncertainty.
- In many regions where fine spatial scales in climate are

generated by topography, there is insufficient information on how climate change will be expressed at these scales.

- Climate models remain limited by the spatial resolution and ensemble size that can be achieved with present computer resources, by the need to include some additional processes, and by large uncertainties in the modelling of certain feedbacks (e.g., from clouds and the carbon cycle).
- Limited knowledge of ice sheet and ice shelf processes leads to unquantified uncertainties in projections of future ice sheet mass balance, leading in turn to uncertainty in sea-level rise projections.

8.2.2 Water-related impacts [WGII 3.5.1, 3.8]

- Because of the uncertainties involved, probabilistic approaches are required to enable water managers to undertake analyses of risk under climate change. Techniques are being developed to construct probability distributions of specified outcomes. Further development of this research, and of techniques to communicate the results, as well as their application to the user community, are required.
- Further work on detection and attribution of present-day hydrological changes is required; in particular, changes in water resources and in the occurrence of extreme events. As part of this effort, the development of indicators of climate change impacts on freshwater, and operational systems to monitor them, are required.
- There remains a scale mismatch between the large-scale climatic models and the catchment scale – the most important scale for water management. Higher-resolution climate models, with better land-surface properties and interactions, are therefore required to obtain information of more relevance to water management. Statistical and physical downscaling can contribute.
- Most of the impact studies of climate change on water stress in countries assess demand and supply on an annual basis. Analysis at the monthly or higher temporal resolution scale is desirable, since changes in seasonal patterns and the probability of extreme events may offset the positive effect of increased availability of water resources.
- The impact of climate change on snow, ice and frozen ground as sensitive storage variables in the water cycle is highly non-linear and more physically- and process-oriented modelling, as well as specific atmospheric downscaling, is required. There is a lack of detailed knowledge of runoff changes as caused by changing glaciers, snow cover, rain–snow transition, and frozen ground in different climate regions.
- Methods need to be improved that allow the assessment of the impacts of changing climate variability on freshwater resources. In particular, there is a need to develop local-scale data sets and simple climate-linked computerised watershed models that would allow water managers to assess impacts and to evaluate the functioning and resilience of their systems, given the range of uncertainty surrounding future climate projections.
- Feedbacks between land use and climate change (including vegetation change and anthropogenic activity such as irrigation and reservoir construction) should be analysed more extensively; e.g., by coupled climate and land-use modelling.
- Improved assessment of the water-related consequences of different climate policies and development pathways is needed.
- Climate change impacts on water quality are poorly understood for both developing and developed countries, particularly with respect to the impact of extreme events.
- Relatively few results are available on the socio-economic aspects of climate change impacts related to water resources, including climate change impacts on water demand.
- Impacts of climate change on aquatic ecosystems (not only temperatures, but also altered flow regimes, water levels and ice cover) are not understood adequately.
- Despite its significance, groundwater has received little attention in climate change impact assessment compared to surface water resources.

8.3 Adaptation and mitigation

- Water resources management clearly impacts on many other policy areas (e.g., energy projections, land use, food security and nature conservation). Adequate tools are not available to facilitate the appraisal of adaptation and mitigation options across multiple water-dependent sectors, including the adoption of water-efficient technologies and practices.
- In the absence of reliable projections of future changes in hydrological variables, adaptation processes and methods which can be usefully implemented in the absence of accurate projections, such as improved water-use efficiency and water-demand management, offer no-regrets options to cope with climate change. [WGII 3.8]
- *Biodiversity.* Identification of water resources needs for maintaining environmental values and services, especially related to deltaic ecosystems, wetlands and adequate instream flows.
- *Carbon capture and storage:* Better understanding is needed of leakage processes, because of potential degradation of groundwater quality. This requires an enhanced ability to monitor and verify the behaviour of geologically stored CO_2. [CCS, TS, Chapter 10]
- *Hydropower/dam construction:* An integrated approach is needed, given the diversity of interests (flood control, hydropower, irrigation, urban water supply, ecosystems, fisheries and navigation), to arrive at sustainable solutions. Methane emissions have to be estimated. Also, the net effect on the carbon-budget in the affected region has to be evaluated.
- *Bio-energy:* Insight is required into the water demand, and its consequences, of large-scale plantations of commercial bio-energy crops. [WGIII 4.3.3.3]
- *Agriculture:* Net effects of more effective irrigation on the GHG budget need to be better understood (higher carbon

storage in soils through enhanced yields and residue returns and its offset by CO_2 emissions from energy systems to deliver the water, or by N_2O emissions from higher moisture and fertiliser inputs). [WGIII 8.4.1.1]

- *Forestry:* Better understanding of the effects of massive afforestation on the processes forming the hydrological cycle, such as rainfall, evapotranspiration, runoff, infiltration and groundwater recharge is needed. [WGIII 9.7.3]
- *Wastewater and water reuse:* Greater insight is needed into emissions from decentralised treatment processes and uncontrolled wastewater discharges in developing countries. The impact of properly reusing water on mitigation and adaptation strategies needs to be understood and quantified.

References

Abdalati, W. and K. Steffen, 2001: Greenland ice sheet melt extent: 1979–1999. *J. Geophys. Res.*, **106**(D24), 33983–33988.

Abeku, T.A., G.J. van Oortmarssen, G. Borsboom, S.J. de Vlas and J.D.F. Habbema, 2003: Spatial and temporal variations of malaria epidemic risk in Ethiopia: factors involved and implications. *Acta Trop.*, **87**, 331-340.

Abou-Hadid, A.F., 2006: *Assessment of Impacts: Adaptation and Vulnerability to Climate Change in North Africa: Food Production and Water Resources*. Washington, DC, 127 pp. http://www.aiaccproject.org/Final%20Reports/Final%20Reports/FinalRept_AIACC_AF90.pdf.

Abou-Hadid, A.F., R. Mougou, A. Mokssit and A. Iglesias, 2003: *Assessment of Impacts, Adaptation, and Vulnerability to Climate Change in North Africa: Food Production and Water Resources*. AIACC AF90 Semi-Annual Progress Report, 37 pp.

Abu-Taleb, M.F., 2000: Impacts of global climate change scenarios on water supply and demand in Jordan. *Water International*, **25**(3), 457–463.

ACIA (Arctic Climate Impact Assessment), 2004: *Impacts of a Warming Arctic: Synthesis Report of the Arctic Climate Impact Assessment*, Policy Document prepared by the Arctic Council and presented at the Fourth Arctic Council Ministerial Meeting, Reykjavik, 24 November 2004, 140 pp.

ACIA (Arctic Climate Impact Assessment), 2005: *Arctic Climate Impact Assessment*. Cambridge University Press, Cambridge, 1042 pp.

ADB (Asia Development Bank), 1994: *Climate Change in Asia: Vietnam Country Report*. Asia Development Bank, Manila, 103 pp.

Adler, R.F. and Co-authors, 2003: The version 2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979–present). *J. Hydrometeorol.*, **4**, 1147–1167.

AEMA**,** 2002: *Uso sostenible del agua en Europa. Gestión de la demanda*. Ministerio de Medio Ambiente, Madrid, 94 pp.

Agarwal, P.K., S.K. Bandyopadhyay, H. Pathak, N. Kalra, S. Chander and S. Kumar, 2000: Analysis of yield trends of the rice–wheat system in north-western India. *Outlook on Agriculture*, **29**(4), 259–268.

Agoumi, A., 2003: *Vulnerability of North African Countries to Climatic Changes: Adaptation and Implementation Strategies for Climatic Change,* IISD. http://www.cckn.net//pdf/north_africa.pdf.

Aguilar, E., T.C. Peterson, P. Ramírez Obando, R. Frutos, J.A. Retana, M. Solera, J. Soley, I. González García and co-authors, 2005: Changes in precipitation and temperature extremes in Central America and northern South America, 1961–2003. *J. Geophys. Res.*, **110**, D23107, doi:10.1029/2005JD006119.

Alcamo, J. and T. Henrichs, 2002: Critical regions: a model-based estimation of world water resources sensitive to global changes. *Aquat. Sci.*, **64**, 352-362.

Alcamo, J., P. Döll, T. Henrichs, F. Kaspar, B. Lehner, T. Rösch and S. Siebert, 2003a: Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrol. Sci. J.*, **48**, 317–338.

Alcamo, J., P. Döll, T. Henrichs, F. Kaspar, B. Lehner, T. Rösch and S. Siebert, 2003b: Global estimates of water withdrawals and availability under current and future "business-as-usual" conditions. *Hydrol. Sci. J.*, **48**, 339–348.

Alcamo, J. and Co-authors, 2004: A new perspective on the impacts of climate change on Russian agriculture and water resources. *Proc. World Climate Change Conference*, 29 September–3 October, 2003, Moscow, 324–335.

Alcamo, J., M. Flörke and M. Marker, 2007: Future long-term changes in global water resources driven by socio-economic and climatic change. *Hydrol. Sci. J.*, **52**, 247–275.

Aldhous, P., 2004: Borneo is burning. *Nature*, **432**, 144–146.

Alexander, L.V., X. Zhang, T.C. Peterson, J. Caesar, B. Gleason, A.M.G. Klein Tank, M. Haylock, D. Collins, B. Trewin, F. Rahimzadeh, A. Tagipour, K. Rupa Kumar, J. Revadekar, G. Griffiths, L. Vincent, D.B. Stephenson, J. Burn, E. Aguilar, M. Brunet, M. Taylor, M. New, P. Zhai, M. Rusticucci and J.L. Vazquez-Aguirre, 2006: Global observed changes in daily climate extremes of temperature and precipitation. *J. Geophys. Res.*, **111**, D05109, doi:10.1029/2005JD006290.

Allen Consulting Group, 2005: *Climate Change Risk and Vulnerability: Promoting an Efficient Adaptation Response in Australia*. Report to the Australian Greenhouse Office by the Allen Consulting Group, 159 pp. http://www.greenhouse.gov.au/impacts/publications/risk-vulnerability.html.

Alvarez, R., 2005: A review of nitrogen fertilizer and conservative tillage effects on soil organic storage. *Soil Use Manage.*, **21,** 38-52.

Álvarez Cobelas, M., J. Catalán and D. García de Jalón, 2005: Impactos sobre los ecosistemas acuáticos continentales. *Evaluación Preliminar de los Impactos en España por Efecto del Cambio Climático,* J.M. Moreno, Ed., Ministerio de Medio Ambiente, Madrid, 113–146.

Ames, A., 1998: A documentation of glacier tongue variations and lake development in the Cordillera Blanca, Peru. *Z. Glet. Glazialgeol.*, **34**(1), 1–26.

Andréasson, J., S. Bergström, B. Carlsson, L.P. Graham and G. Lindström, 2004: Hydrological change: climate impact simulations for Sweden. *Ambio*, **33**(4–5), 228–234.

Andreone, F., J.E. Cadle, N. Cox, F. Glaw, R.A. Nussbaum, C.J. Raxworthy, S.N. Stuart amd D. Vallan, 2005: Species review of amphibian extinction risks in Madagascar: conclusions from the Global Amphibian Assessment. *Conserv. Biol.*, **19**, 1790–1802.

Anisimov, O.A. and M.A. Belolutskaia, 2004: Predictive modelling of climate change impacts on permafrost: effects of vegetation. *Meteorol. Hydrol.*, **11**, 73–81.

Antle, J.M., S.M. Capalbo, E.T. Elliott and K.H. Paustian, 2004: Adaptation, spatial heterogeneity, and the vulnerability of agricultural systems to climate change and CO_2 fertilization: an integrated assessment approach. *Climatic Change*, **64**, 289-315.

Aparicio, M., 2000: *Vulnerabilidad y Adaptación a la Salud Humana ante los Efectos del Cambio Climático en Bolivia*. Ministerio de Desarrollo Sostenible y Planificación. Viceministerio de Medio Ambiente, Recursos Naturales y Desarrollo Forestal. Programa Nacional de Cambios Climáticos. PNUD/GEF.

Arkell, B.P. and Darch, G.J.C., 2006: Impact of climate change on London's transport network. *Proc. Institution of Civil Engineers-Municipal Engineer*, **159**(4), 231–237.

Arnell, N.W., 2003: Relative effects of multi-decadal climatic variability and changes in the mean and variability of climate due to global warming: future streamflows in Britain. *J. Hydrol.*, **270**, 195-213.

Arnell, N.W., 2004: Climate change and global water resources: SRES emissions and socio economic scenarios. *Global Environmen. Chang.*, **14**, 31–52.

Arnell, N.W., 2006a: Global impacts of abrupt climate change: an initial assessment. Working Paper 99, Tyndall Centre for Climate Change Research, University of East Anglia, Norwich, 37 pp.

Arnell, N.W., 2006b: Climate change and water resources: a global perspective. *Avoiding Dangerous Climate Change*, H.J. Schellnhuber, W. Cramer, N. Nakićenović, T. Wigley and G. Yohe, Eds., Cambridge University Press, Cambridge, 167-175.

Arnell, N.W. and E.K. Delaney, 2006: Adapting to climate change: public water supply in England and Wales, *Climatic Change*, **78**, 227-255.

Arnell, N.W., M.J.L. Livermore, S. Kovats, P.E. Levy, R. Nicholls, M.L. Parry and S.R. Gaffin, 2004: Climate and socio-economic scenarios for global-scale climate change impacts assessments: characterising the SRES storylines. *Global Environ. Chang.*, **14**, 3–20.

Ashton, P.J., 2002: Avoiding conflicts over Africa's water resources, *Ambio*, **31**(3), 236–242.

Attaher, S., M.A. Medany, A.A. Abdel Aziz and A. El-Gindy, 2006: Irrigation-water demands under current and future climate conditions in Egypt. *Misr. Journal of Agricultural Engineering*, **23**, 1077-1089.

Auer, I. and Co-authors, 2007: Histalp - historical instrumental climatological surface time series of the Greater Alpine Region 1760-2003. *Int. J. Climatol.*, **27**, 17-46.

Bachelet, D., R.P. Neilson, J.M. Lenihan and R.J. Drapek, 2001: Climate change effects on vegetation distribution and carbon budget in the United States. *Ecosystems*, **4**, 164-185.

Baker, T.R., O.L. Phillips, Y. Malhi, S. Almeida, L. Arroyo, A. Di Fiore, T. Erwin, N. Higuchi, and Co-authors, 2004: Increasing biomass in Amazonian forest plots. *Philos. T. Roy. Soc. Lond. B*, **359**, 353–365.

Balmford, A., P. Crane, A. Dobson, R.E. Green and G.M. Mace, 2005: The 2010 challenge: data availability, information needs and extraterrestrial insights. *Philos. T. Roy. Soc. Lond. B*, **360**, 221-228.

Barber, V.A., G.P. Juday and B.P. Finney, 2000: Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. *Nature*, **405**, 668-673.

Barnett, T.P., R. Malone, W. Pennell, D. Stammer, B. Semtner and W. Washington, 2004: The effects of climate change on water resources in the West: introduction and overview. *Climatic Change*, **62**, 1–11.

Barnett, T.P., J.C. Adam and D.P. Lettenmaier, 2005: Potential impacts of warming climate on water availability in snow-dominated regions. *Nature*, **438**, 303–309.

Barras, J., S. Beville, D. Britsch, S. Hartley, S. Hawes, J. Johnston, P. Kemp, Q. Kinler, A. Martucci, J. Porthouse, D. Reed, K. Roy, S. Sapkota and J. Suhayda, 2003: *Historical and Projected Coastal Louisiana Land Changes: 1978–2050*. Open File Report 03-334. U.S. Geological Survey. 39 pp.

Barreira, A., 2004: *Dams in Europe. The Water Framework Directive and the World Commission on Dam Recommendations: A Legal and Policy Analysis*. http://assets.panda.org/downloads/wfddamsineurope.pdf

Basán Nickisch, M., 2002: Sistemas de captación y manejo de agua. Estación Experimental Santiago del Estero. Instituto Nacional de Tecnología Agropecuaria. http://www.inta.gov.ar/santiago/info/documentos/agua/0001res_sistemas.htm.

Batima, P., 2003: Climate change: pasture–livestock. Synthesis Report. *Potential Impacts of Climate Change, Vulnerability and Adaptation Assessment for Grassland Ecosystem and Livestock Sector in Mongolia*. Admon Publishing, Ulaanbaatar, 36–47.

Batima, P., Batnasan N. and Lehner B., 2004: *The Freshwater Systems of Western Mongolia's Great Lakes Basin: Opportunities and Challenges in the Face of Climate Change*. Admon Publishing, Ulaanbaatar, 95 pp.

Batima, P., T. Ganbaatar, D. Tumerbaatar, B. Erdenetsetseg, B. Bolortsetseg, B. Gantsetseg, G. Sanjid and S. Khudulmur, 2005: Climate change impacts on environment. *Climate Change Impacts*, P. Batima and B. Bayasgalan, Eds., Admon Publishing, Ulaanbaatar, 59–115.

Bationo, A., S.P. Wani, C.L. Bielders, P.L.G. Velk and A.U. Mokwunye, 2000: Crop residues and fertilizer management to improve soil organic carbon content, soil quality and productivity in the desert margins of West Africa. *Global Climate Change and Tropical Ecosystems*, R. Lal, J.M. Kimble and B.A. Stewart, Eds., CRC-Lweis Publishers, Boca Raton, FL, 117-146.

Bauder, E.T., 2005: The effects of an unpredictable precipitation regime on vernal pool hydrology. *Freshw. Biol.*, **50**, 2129–2135.

Beare, S. and A. Heaney, 2002: *Climate change and water resources in the Murray Darling Basin, Australia; impacts and adaptation*. Conference Paper 02.11, Australian Bureau of Agricultural and Resource Economics, 33 pp. http://www.abarepublications.com/product.asp?prodid=12389.

Beaulieu, N. and M. Allard, 2003: The impact of climate change on an emerging coastline affected by discontinuous permafrost: Manitounuk Strait, northern Quebec. *Can. J. Earth Sci.*, **40**, 1393-1404.

Beck, C., J. Grieser and B. Rudolph, 2005: A New Monthly Precipitation Climatology for the Global Land Areas for the Period 1951 to 2000. DWD, *Klimastatusbericht 2004*, 181–190.

Beltaos, S. and Co-authors, 2006: Climatic effects on ice-jam flooding of the Peace-Athabasca Delta. *Hydrol. Process.,* **20**(19), 4031–4050.

Benhin, J.K.A., 2006: *Climate change and South African agriculture: impacts and adaptation options*. CEEPA Discussion Paper No.21. Special Series on Climate Change and Agriculture in Africa. The Centre for Environmental Economics and Policy in Africa, University of Pretoria, Pretoria, 78 pp.

Beniston, M. and H.F. Díaz, 2004: The 2003 heatwave as an example of summers in a greenhouse climate? Observations and climate model simulations for Basel, Switzerland. *Global Planet. Change*, **44**, 73–81.

Beniston, M., D.B. Stephenson, O.B. Christensen, C.A.T. Ferro, C. Frei, S. Goyette, K. Halsnaes, T. Holt, K. Jylhä, B. Koffi, J. Palutikof, R. Schöll, T. Semmler and K. Woth, 2007: Future extreme events in European climate: an exploration of regional climate model projections. *Climatic Change,* **81**(Suppl. 1), 71-95.

Berezovskaya, S., D.Q. Yang and L. Hinzman, 2005: Long-term annual water balance analysis of the Lena River. *Global Planet. Change*, **48**(1–3), 84–95.

Berger, T., J. Mendoza, B. Francou, F. Rojas, R. Fuertes, M. Flores, L. Noriega, C. Ramallo, E. Ramírez and H. Baldivieso, 2005: Glaciares Zongo – Chacaltaya – Charquini Sur – Bolivia 16°S. Mediciones Glaciológicas, Hidrológicas y Meteorológicas, Año Hidrológico 2004-2005. *Informe Great Ice Bolivia, IRD-IHH-SENMAHI-COBEE*, 171.

Berndes, G. and P. Börjesson, 2002: Multi-functional biomass production systems. http://www.brdisolutions.com/pdfs/bcota/abstracts/6/70.pdf.

Berndes, G., F. Fredrikson, and P. Borjesson, 2004: Cadmium accumulation and Salix-based phytoextraction on arable land in

Sweden. *Agriculture, Ecosystems & Environment*, **103**, 207-223.

Berthelot, M., P. Friedlingstein, P. Ciais, P. Monfray, J.L. Dufresen, H.L. Treut and L. Fairhead, 2002: Global response of the terrestrial biosphere and CO_2 and climate change using a coupled climate-carbon cycle model. *Global Biogeochem. Cy.*, **16**, doi:10.1029/2001GB001827.

Betts, R.A., P.M. Cox, S.E. Lee and F.I. Woodward, 1997: Contrasting physiological and structural vegetation feedbacks in climate change simulations. *Nature*, **387**, 796–799.

Betts, R.A., O. Boucher, M. Collins, P.M. Cox, P.D. Falloon, N. Gedney, D.L. Hemming, C. Huntingford, C.D. Jones, D. Sexton and M. Webb, 2007: Projected increase in continental runoff due to plant responses to increasing carbon dioxide. *Nature,* **448**, 1037-1041.

Beuhler, M., 2003: Potential impacts of global warming on water resources in southern California. *Water Sci. Technol.*, **47**(7–8), 165–168.

Bhadra, B., 2002: Regional cooperation for sustainable development of Hindu Kush Himalaya region: opportunities and challenges. Keynote paper presented at T*he Alpine Experience – An Approach for other Mountain Regions*, Berchtesgaden, Germany, June 26–29.

Bidegain, M., R.M. Caffera, F. Blixen, V.P. Shennikov, L.L. Lagomarsino, E.A. Forbes and G.J. Nagy, 2005: Tendencias climáticas, hidrológicas y oceanográficas en el Río de la Plata y costa Uruguaya. *El Cambio Climático en el Río de la Plata,* V. Barros A. Menéndez and G.J. Nagy, Eds., Proyectos AIACC, 137-143.

Bigio, A., 2003: Cities and climate change. *Building Safer Cities: The Future of Disaster Risk*, A. Kreimer, M. Arnold and A. Carlin, Eds., World Bank, Washington, DC, 91-100.

Bindoff, N., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C.L. Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L. Talley and A. Unnikrishnan, 2007: Observations: oceanic climate change and sea level. *Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, Eds., Cambridge University Press, Cambridge, 385-432.

Blais, J.M., D.W. Schindler, D.C.G. Muir, M. Sharp, D. Donald, M. Lafreniere, E. Braekevelt and W. M.J. Strachan, 2001: Melting glaciers: a major source of persistent organochlorines to subalpine Bow Lake in Banff National Park, Canada. *Ambio*, **30**, 410-415.

Blythe, E.M., A.J. Dolman and J. Noilhan, 1994: The effect of forest on mesoscale rainfall: an example from HAPEX-MOBILHY. *J. Appl. Meteorol.,* **33**, 445-454.

Bobba, A., V. Singh, R. Berndtsson and L. Bengtsson, 2000: Numerical simulation of saltwater intrusion into Laccadive Island aquifers due to climate change. *J. Geol. Soc. India*, **55**, 589–612.

Bodaly, R.A., J.W.M. Rudd, R.J.P. Fudge and C.A. Kelly, 1993: Mercury concentrations in fish related to size of remote Canadian shield lakes. *Can. J. Fish. Aquat. Sci.*, **50**, 980-987.

Bogaart, P.W. and R.T. van Balen, 2000: Numerical modeling of the response of alluvial rivers to Quaternary climatic change. *Global Planet. Change*, **27**, 124–141.

Bogoyavlenskiy, D. and A. Siggner, 2004: Arctic demography. *Arctic Human Development Report (AHDR),* N. Einarsson, J.N. Larsen, A. Nilsson and O.R. Young, Eds., Steffanson Arctic Institute, Akureyri, 27–41.

Börjesson, P. and G. Berndes, 2006: The prospects for willow plantations for wastewater treatment in Sweden. *Biomass and Bioenergy*, **30**, 428-438.

Bouma, M.J., 2003: Methodological problems and amendments to demonstrate effects of temperature on the epidemiology of malaria: a new perspective on the highland epidemics in Madagascar, 1972–1989. *Trans. Roy. Soc. Trop. Med. Hyg.*, **97**, 133-139.

Bouraoui, F., B. Grizzetti, K. Granlund, S. Rekolainen and G. Bidoglio, 2004: Impact of climate change on the water cycle and nutrient losses in a Finnish catchment. *Climatic Change*, **66**, 109–126.

Boutkan, E. and A. Stikker, 2004: Enhanced water resource base for sustainable integrated water resource management. *Nat. Resour. Forum*, **28**, 150-154.

Bou-Zeid, E. and El-Fadel, M., 2002: Climate change and water resources in Lebanon and the Middle East. *J. Water Res. Pl.-ASCE*, **128**(5), 343–355.

Box, J.E. and Co-authors, 2006: Greenland ice-sheet surface mass balance variability (1988-2004) from calibrated polar MM5 output. *J. Clim.*, **19**(12), 2783–2800.

Bradley, R.S., F.T. Keimig and H.F. Diaz, 2004: Projected temperature changes along the American cordillera and the planned GCOS network. *Geophys. Res. Lett.*, **31**, L16210, doi:10.1029/2004GL020229.

Bradley, R.S., M. Vuille, H. Diaz and W. Vergara, 2006: Threats to water supplies in the tropical Andes. *Science*, **312**, 1755-1756.

Braun, O., M. Lohmann, O. Maksimovic, M. Meyer, A. Merkovic, E. Messerschmidt, A. Reidel and M. Turner, 1999: Potential impact of climate change effects on preferences for tourism destinations: a psychological pilot study, *Clim. Res.*, **11**, 2477–2504.

Briers, R.A., J.H.R. Gee and R. Geoghegan, 2004: Effects of North Atlantic oscillation on growth and phenology of stream insects. *Ecography*, **27**, 811–817.

Brklacich, M., C. Bryant, B. Veenhof and A. Beauchesne, 1997: Implications of global climatic change for Canadian agriculture: a review and appraisal of research from 1984–1997. *Canada Country Study: Climate Impacts and Adaptation*, Environment Canada, Toronto, ON, 220–256.

Bromley, C.J. and S. Currie, 2003: Analysis of subsidence at Crown Road, Taupo: a consequence of declining groundwater. *Proc. 25th New Zealand Geothermal Workshop*, Auckland University, 113-120.

Brouyere, S., G. Carabin and A. Dassargues, 2004: Climate change impacts on groundwater resources: modelled deficits in a chalky aquifer, Geer basin, Belgium. *Hydrogeol. J.*, **12**(2), 123–134.

Brown, R.A., N.J. Rosenberg, C.J. Hays, W.E. Easterling and L.O. Mearns, 2000: Potential production and environmental effects of switchgrass and traditional crops under current and greenhouse-altered climate in the central United States: a simulation study. *Agric. Ecosyst. Environ.*, **78**, 31-47.

Brown, R.D. and R.O. Braaten, 1998: Spatial and temporal variability of Canadian monthly snow depths. *Atmos.-Ocean*, **36**, 37–54.

Bruinsma, J., 2003: *World Agriculture: Towards 2015/2030. An FAO Perspective*. Earthscan, London, 444 pp.

Brutsaert, W. and M.B. Parlange, 1998: Hydrologic cycle explains the evaporation paradox. *Nature*, **396**, 30.

Bunn, S.E. and Arthington, A.H., 2002: Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environ. Manage.*, **30**, 492–507.

Burger, R.L., 1992: *Chavin and the Origins of Andean Civilization*. Thames and Hudson, London, 240 pp.

Burke, E.J., S.J. Brown, and N. Christidis, 2006: Modelling the recent evolution of global drought and projections for the 21 st century with the Hadley Centre climate model. *J. Hydrometeorol.*, **7**, 1113–1125.

Burke, L. and J. Maidens, 2004: *Reefs at Risk in the Caribbean*. World Resources Institute, Washington, DC, 81 pp. http://archive.wri.org/publication_detail.cfm?pubid=3944.

Burke, L., E. Selig and M. Spalding, 2002: *Reefs at Risk in Southeast Asia*. World Resources Institute, Washington DC, 37 pp. http://www.wri.org/biodiv/pubs_description.cfm?PubID=3144.

Burkett, V.R. and J. Kusler, 2000: Climate change: potential impacts and interactions in wetlands of the United States. *J. Am. Water Resour. Assoc.*, **36**, 313–320.

Burkett, V.R., D.A. Wilcox, R. Stottlemeyer, W. Barrow, D. Fagre, J. Baron, J. Price, J. Nielsen, C.D. Allen, D.L. Peterson, G. Ruggerone amd T. Doyle, 2005: Nonlinear dynamics in ecosystem response to climate change: case studies and policy implications. *Ecological Complexity*, **2**, 357–394.

Buttle, J., J.T. Muir and J. Frain, 2004: Economic impacts of climate change on the Canadian Great Lakes hydro-electric power producers: a supply analysis. *Can. Water Resour. J.*, **29**, 89–109.

Calder, I.R., 1990: *Evaporation in the Uplands*. John Wiley and Sons, Chichester, 148 pp.

Calder, I.R., 1992: Water use of eucalyptus – a review. *Growth and Water Use of Forest Plantations,* I.R. Calder, R.L. Hall and P.G. Adlard, Eds., John Wiley and Sons, Chichester, 167-179.

Caldwell, C.R., S.J. Britz and R.M. Mirecki, 2005: Effect of temperature, elevated carbon dioxide, and drought during seed development on the isoflavone content of dwarf soybean [*Glycine max* (L.) Merrill] grown in controlled environments. *J. Agr. Food Chem.*, **53**(4), 1125–1129.

California Regional Assessment Group, 2002: *The Potential Consequences of Climate Variability and Change for California: The California Regional Assessment*. National Center for Ecological Analysis and Synthesis, University of California Santa Barbara, Santa Barbara, California, 432 pp. http://www.ncgia.ucsb.edu/pubs/CA_Report.pdf.

Callaghan, T.V., L.O. Björn, F.S. Chapin III, Y. Chernov, T.R. Christensen, B. Huntley, R. Ims, M. Johansson, D.J. Riedlinger, S. Jonasson, N. Matveyeva, W. Oechel, N. Panikov and G. Shaver, 2005: Arctic tundra and polar desert ecosystems. *Arctic Climate Impact Assessment (ACIA): Scientific Report*, C. Symon, L. Arris and B. Heal, Eds., Cambridge University Press, Cambridge, 243-352.

Camilloni, I., 2005: Tendencias climáticas. *El Cambio Climático en el Río de la Plata*, V. Barros, A. Menéndez and G.J. Nagy, Eds., CIMA/CONICET-UBA, Buenos Aires, 13-19.

Canziani, O.F. and L.J. Mata, 2004: The fate of indigenous communities under climate change. UNFCCC Workshop on impacts of, and vulnerability and adaptation to, climate change. *Tenth Session of the Conference of Parties (COP-10)*, Buenos Aires, 3 pp.

Caran, S.C. and J.A. Nelly, 2006: Hydraulic engineering in prehistoric Mexico. *Sci. Am. Mag.*, **October**, 8 pp.

Carey, M., 2005: Living and dying with glaciers: people's historical vulnerability to avalanches and outburst floods in Peru. *Global Planet. Change*, **47**, 122-134.

Cassman, K.G., A. Dobermann, D.T. Walters and H. Yang, 2003: Meeting cereal demand while protecting natural resources and improving environmental quality. *Annu. Rev. Environ. Resour.*, **28**, 315-358.

CCME, 2003: *Climate, Nature, People: Indicators of Canada's Changing Climate*. Climate Change Indicators Task Group of the Canadian Council of Ministers of the Environment, Canadian Council of Ministers of the Environment Inc., Winnipeg, Canada, 51 pp.

CDC (Centers for Disease Control), 2005: Vibrio illnesses after Hurricane Katrina: multiple states, August–September 2005. *MMWR–Morb. Mortal. Wkly. Rep.*, **54**, 928-931.

Census Bureau, 2004: *(U. S. Census Bureau), NP-T1. Annual Projections of the Total Resident Population as of July 1: Middle, Lowest, Highest, and Zero International Migration Series, 1999 to 2100*. Population Division, U.S. Census Bureau, Washington, D.C. 20233, Washington DC. http://www.census.gov/population/projections/nation/summary/np-t1.txt.

Cerri, C.C., M. Bernoux, C.E.P. Cerri and C. Feller, 2004: Carbon cycling and sequestration opportunities in South America: the case of Brazil. *Soil Use Manage.*, **20,** 248-254.

Chan, N.W., 1986: Drought trends in northwestern peninsular Malaysia: is less rain falling? *Wallaceana*, **4**, 8-9.

Chang, H., C.G. Knight, M.P. Staneva and D. Kostov, 2002: Water resource impacts of climate change in southwestern Bulgaria. *GeoJournal*, **57**, 159–168.

Changnon, S.A., 2005: Economic impacts of climate conditions in the United States: past, present, and future – an editorial essay. *Climatic Change*, **68**, 1–9.

Changnon, S.A. and D. Changnon, 2000: Long-term fluctuations in hail incidences in the United States. *J. Climate*, **13**, 658–664.

Chappell, A. and C.T. Agnew 2004: Modelling climate change in West African Sahel rainfall (1931–90) as an artifact of changing station locations. *Int. J. Clim.*, **24**(5), 547–554.

Chattopadhyay, N. and M. Hulme, 1997: Evaporation and potential evapotranspiration in India under conditions of recent and future climate change. *Agric. For. Meteorol.*, **87**, 55–73.

Chauhan, M. and B. Gopal, 2001: Biodiversity and management of Keoladeo National Park (India): a wetland of international importance. *Biodiversity in Wetlands: Assessment, Function and Conservation*. Volume 2. Backhuys Publishers, Leiden, 217–256.

Checkley, W., L.D. Epstein, R.H. Gilman, D. Figueroa, R.I. Cama, J.A. Patz and R.E. Black, 2000: Effects of El Niño and ambient temperature on hospital admissions for diarrhoeal diseases in Peruvian children. *Lancet*, **355**, 442–450.

Cheikh, N., P.W. Miller and G. Kishore, 2000: Role of biotechnology in crop productivity in a changing environment. *Global Change and Crop Productivity*, K.R. Reddy and H.F. Hodges, Eds., CAP International, New York, 425-436.

Chen, C., D. Gillig and B.A. McCarl, 2001: Effects of climatic change on a water dependent regional economy: a study of the Texas Edwards Aquifer. *Climatic Change*, **49**, 397–409.

Chen, M., P. Xie, and J.E. Janowiak, 2002: Global land precipitation: a 50-yr monthly analysis based on gauge observations. *J. Hydrometeorol.*, **3**, 249–266.

Chen, Z., S. Grasby and K. Osadetz, 2004: Relation between climate variability and groundwater levels in the upper carbonate aquifer, southern Manitoba, Canada. *J. Hydrol.*, **290**(1–2), 43–62.

Chiew, F.H.S., T.I. Harrold, L. Siriwardenena, R.N. Jones and R. Srikanthan, 2003: Simulation of climate change impact on runoff using rainfall scenarios that consider daily patterns of change from GCMs. *MODSIM 2003: Proc. International Congress on Modelling and Simulation*, D.A. Post, Ed., Modelling and Simulation Society of Australia and New Zealand, Canberra ACT, Townsville, 154–159.

Choi, O. and A. Fisher, 2003: The impacts of socioeconomic development and climate change on severe weather catastrophe losses: Mid-Atlantic Region MAR and the U.S. *Climatic Change*, **58**(1–2), 149–170.

Chomitz, K.M. and K. Kumari, 1996: *The domestic benefits of tropical forests: a critical review emphasizing hydrological functions*. Policy Research Working Paper, World-Bank, No. WPS1601, 41 pp.

Christensen, J.H. and O.B. Christensen, 2003: Severe summertime flooding in Europe. *Nature*, **421**, 805.

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

Christensen, N.S., A.W. Wood, N. Voisin, D.P. Lettenmaier and R.N. Palmer, 2004: The effects of climate change on the hydrology and water resources of the Colorado River basin. *Climatic Change*, **62**(1–3), 337–363.

Ciais, P., M. Reichstein, N. Viovy, A. Granier, J. Ogee, V. Allard, M. Aubinet, N. Buchmann, et al., 2005: Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*, **437**, 529–533.

City of New York, 2005: New York City's Water Supply System. The City of New York Department of Environmental Protection, New York, New York. http://www.ci.nyc.ny.us/html/dep/html/watersup.html.

Clark, M.E., K.A. Rose, D.A. Levine and W.W. Hargrove, 2001: Predicting climate change effects on Appalachian trout: combining GIS and individual-based modeling. *Ecol. Appl.*, **11**, 161-178.

Clarke, R. and J. King, 2004: *The Atlas of Water*. Earthscan, London, 128 pp.

Cohen, S., D. Neilsen and R. Welbourn, Eds., 2004: *Expanding the dialogue on climate change and water management in the Okanagan Basin, British Columbia*. Final Report 1 January 2002 to 30 June 2004. http://www.ires.ubc.ca/aird/documents/Okanagan2004-final.pdf.

Cohen, S.J., R. de Loë, A. Hamlet, R. Herrington, L.D. Mortsch and D. Shrubsole, 2003: *Integrated and cumulative threats to water availability. Threats to Water Availability in Canada*. National Water Research Institute, Burlington, Ontario, 117-127. http://www.nwri.ca/threats2full/ThreatsEN_03web.pdf.

COHIFE, 2003: Principios rectores de Política Hídrica de la República Argentina. *Acuerdo Federal del Agua, Consejo Hídrico Federal*, COHIFE 8, August 2003, Argentina.

Cole, C.V., K. Flach, J. Lee, D. Sauerbeck and B. Stewart, 1993: Agricultural sources and sinks of carbon. *Water Air Soil Poll.,* **70**, 111-122.

Coleman, J.M. and O.K. Huh, 2004: *Major World Deltas: A Perspective fromSpace*. Coastal Studies Institute, Louisiana State University, Baton Rouge, Louisiana. http://www.geol.lsu.edu/WDD/PUBLICATIONS/introduction.htm

Compton, K., T. Ermolieva, and J.C. Linnerooth-Bayer, 2002: Integrated Disaster Risk Management: Megacity Vulnerability and Resilience, *Proc. Second Annual IIASA-DPRI Meeting*, IIASA Laxenburg, 20 pp.

Conde, C., D. Liverman, M. Flores, R. Ferrer, R. Araujo, E. Betancourt, G. Villareal and C. Gay, 1997: Vulnerability of rainfed maize crops in Mexico to climate change. *Clim. Res.*, **9**, 17–23.

Conway, D., 2005: From headwater tributaries to international river: observing and adapting to climate variability and change in the Nile basin. *Global Environ. Chang.*, **15**, 99–114.

Cook, E.R., R.D. D'Arrigo and M.E. Mann, 2002: A well-verified, multiproxy reconstruction of the winter North Atlantic Oscillation index since A.D. 1400. *J. Clim.*, **15**, 1754–1764.

Cortazar, P.F., 1968: Documental del Perú, Departamento del Cusco, S.A. Ioppe. Ed., February 1968.

Cosgrove, W., R. Connor and J. Kuylenstierna, 2004: Workshop 3 (synthesis): climate variability, water systems and management options. *Water Sci. Techn.*, **7**, 129–132.

Coudrain, A., B. Francou and Z.W. Kundzewicz, 2005: Glacier shrinkage in the Andes and consequences for water resources: Editorial. *Hydrol. Sci. J.*, **50**(6), 925–932.

Crabbe, P. and M. Robin, 2006: Institutional adaptation of water resource infrastructures to climate change in Eastern Ontario. *Climatic Change*, **78**(1), 103–133.

Craig, M.H., I. Kleinschmidt, D. Le Sueur and B.L. Sharp, 2004: Exploring thirty years of malaria case data in KwaZulu-Natal, South Africa. Part II. The impact of non-climatic factors. *Trop. Med. Int. Health*, **9**, 1258-1266.

Cross, J., 2001: Megacities and small towns: different perspectives on hazard vulnerability. *Environmental Hazards*, **3**, 63–80.

CTIC, 1998: *17th Annual Crop Residue Management Survey Report*. Conservation Technology Information Center, West Lafayette, IN. http://www.ctic.purdue.edu.

Cullen, P., 2002: Living with water: sustainability in a dry land. *Adelaide Festival of Arts, Getting it Right Symposium, 1–12 March, 2002*.

Curriero, F., J.A. Patz, J.B. Rose and S. Lele, 2001: The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948–1994. *Am. J. Public Health*, **91**, 1194–1199.

Cury, P. and L. Shannon, 2004: Regime shifts in upwelling ecosystems: observed changes and possible mechanisms in the northern and southern Benguela. *Prog. Oceanogr.*, **60**, 223–243.

CWC (Central Water Commission), 2001: *Water and related statistics*, Report of the Ministry of Water Resources, New Delhi.

DAFF, 2006a: *National Water Initiative*. Department of Agriculture, Forestry and Fisheries, Australia. http://www.pmc.gov.au/water_reform/nwi.cfm.

DAFF, 2006b: Contours. Department of Agriculture, Fisheries and Forestry, Australia, 24 pp. http://www.daff.gov.au/__data/assets/pdf_file/0020/98201/contours-dec-06.pdf.

Dai, A. and K.E. Trenberth, 2002: Estimates of freshwater discharge from continents: Latitudinal and seasonal variations. *J. Hydrometeorol.*, **3**, 660–687.

Dai, A., P.J. Lamb, K.E. Trenberth, M. Hulme, P.D. Jones and P. Xie, 2004a: The recent Sahel drought is real. *Int. J. Climatol.*, **24**, 1323—1331.

Dai, A., K.E. Trenberth and T. Qian, 2004b: A global data set of Palmer Drought Severity Index for 1870–2002: relationship with soil moisture and effects of surface warming. *J. Hydrometeorol.*, **5**, 1117–1130.

Dalal, R.C., W. Wang, G.P. Robertson and W.J. Parton, 2003: Nitrous oxide emission from Australian agricultural lands and mitigation options: a review. *Australian J. Soil Res.*, **41**, 165-195.

Dang, H.H., A. Michaelowa and D.D. Tuan, 2003: Synergy of adaptation and mitigation strategies in the context of sustainable development: the case of Vietnam. *Clim. Policy*, **3**, S81-S96.

DaSilva, J., B. Garanganga, V. Teveredzi, S. Marx, S. Mason and S. Connor, 2004: Improving epidemic malaria planning, preparedness and response in Southern Africa. *Malaria J.*, **3**, 37.

Davis, J.R., Ed., 1997: *Managing Algal Blooms. Outcomes from CSIRO's Multi-Divisional Blue-Green Algae Program*. CSIRO Land and Water, Canberra, 113 pp.

de Wit, M. and J. Stankiewicz, 2006: Changes in surface water supply across Africa with predicted climate change. *Science Express*, doi:10.1126/science.1119929. http://www.scienceexpress.org.

Declerck, S., J. Vandekerkhove, L.S. Johansson, K. Muylaert, J.M. Conde-Porcuna, K. van der Gucht, C. Pérez-Martínez, T.L. Lauridsen, K. Schwenk, G. Zwart, W. Rommens, J. López-Ramos, E. Jeppesen, W. Vyverman, L. Brendonck and L. de Meester, 2005: Multi-group biodiversity in shallow lakes along gradients of phosphorus and water plant cover. *Ecology*, **86**, 1905–1915.

Delworth, T.L. and M.E. Mann, 2000: Observed and simulated multidecadal variability in the Northern Hemisphere. *Clim. Dyn.*, **16**, 661–676.

Dessai, S., X. Lu and J.S. Risbey, 2005: On the role of climate scenarios for adaptation planning. *Global Environ. Chang.*, **15**, 87–97.

DEUS, 2006: *NSW Government Water Savings Fund*. Department of Energy, Utilities and Sustainability, 17 pp. http://www.deus.nsw.gov.au/Publications/WaterSavingsFundR3Guide.pdf.

Dias de Oliveira, M.E., B.E. Vaughan, and E.J. Rykiel, Jr., 2005: Ethanol as fuel: energy, carbon dioxide balances, and ecological footprint. *BioScience*, **55**, 593-602.

Diaz-Nieto, J. and R. Wilby, 2005: A comparison of statistical downscaling and climate change factor methods: impact on low flows in the river Thames, United Kingdom. *Climatic Change*, **69**, 245–268.

Dinesh Kumar, P.K., 2006: Potential vulnerability implications of sea level rise for the coastal zones of Cochin, southwest coast of India. *Environ. Monit. Assess.*, **123**, 333–344.

DNPC, 2005/2006: Informe de las lluvias caídas en Venezuela en los meses de Febrero y marzo de 2005 y Febrero 2006. Dirección Nacional de Protección Civil, República Bolivariana de Venezuela.

Döll, P., 2002: Impact of climate change and variability on irrigation requirements: a global perspective. *Climatic Change*, **54**, 269–293.

Döll, P. and M. Flörke, 2005: Global-scale estimation of diffuse groundwater recharge. *Frankfurt Hydrology Paper 03*, Institute of Physical Geography, Frankfurt University, Frankfurt.

Döll, P., M. Flörke, M. Mörker and S. Vassolo, 2003: Einfluss des Klimawandels auf Wasserressourcen und Bewässerungswasserbedarf: eine globale Analyse unter Berücksichtigung neuer Klimaszenarien (Impact of climate change on water resources and irrigation water requirements: a global analysis using new climate change scenarios). *Klima–Wasser–Flussgebietsmanagement – im Lichte der Flut*, H.-B. Kleeberg, Ed., *Proc. Tag der Hydrologie 2003 in Freiburg, Germany, Forum für Hydrologie und Wasserbewirtschaftung,* 11–14.

Donevska, K. and S. Dodeva, 2004: Adaptation measures for water resources management in case of drought periods. *Proc. XXIInd Conference of the Danubian Countries on the Hydrological Forecasting and Hydrological Bases of Water Management*. Brno, 30 August–2 September 2004, CD-edition.

Doran, P.T. and Co-authors, 2002: Antarctic climate cooling and terrestrial ecosystem response. *Nature*, **415**, 517–520.

Dore, M. and I. Burton, 2001: *The Costs of Adaptation to Climate Change in Canada: A Stratified Estimate by Sectors and Regions – Social Infrastructure*. Climate Change Laboratory, Brock University, St Catharines, ON, 117 pp.

Douglas, E.M., R.M. Vogel and C.N. Kroll, 2000: Trends in floods and low flows in the United States: impact of spatial correlation. *J. Hydrol*., **240**(1–2), 90–105.

Dourojeanni, A., 2000: *Procedimientos de Gestión para el Desarrollo Sustentable*. ECLAC, Santiago, 376 pp.

Douville, H., F. Chauvin, S. Planton, J.F. Royer, D. Salas-Melia and S. Tyteca, 2002: Sensitivity of the hydrological cycle to increasing amounts of greenhouse gases and aerosols. *Clim. Dyn*., **20**, 45–68.

Downing, T.E., R.E. Butterfield, B. Edmonds, J.W. Knox, S. Moss, B.S. Piper, E.K. Weatherhead and the CCDeW Project Team, 2003: *Climate change and the demand for water, Research Report*. Stockholm Environment Institute, Oxford Office, Oxford.

DPMC, 2004: *Water Reform*. Department of Prime Minister and Cabinet, Australia. http://www.dpmc.gov.au/nwi/index.cfm.

Drennen, P.M., M. Smith, D. Goldsworthy and J. van Staten, 1993: The occurrence of trahaolose in the leaves of the desiccation-tolerant angiosperm *Myronthamnus flabellifoliius* Welw. *J. Plant Physiol*., **142**, 493-496.

du Plessis, C., D.K. Irurah and R.J. Scholes, 2003: The built environment and climate change in South Africa. *Build. Res. Inf.*, **31**(3–4), 240–256.

Duguay, C.R. and Co-authors, 2003: Ice-cover variability on shallow lakes at high latitudes: model simulations and observations. *Hydrol. Process*., **17**, 3465–3483.

Duong, L.C., 2000: Lessons from severe tropical storm Linda, Workshop Report: "The Impact of El Niño and La Niña on Southeast Asia", 21–23 February, Hanoi.

Dwight, R.H., J.C. Semenza, D.B. Baker and B.H. Olson, 2002: Association of urban runoff with coastal water quality in Orange County, California. *Water Environ. Res*., **74**, 82-90.

Dyurgerov, M. and M.F. Meier, 2005: *Glaciers and Changing Earth System: A 2004 Snapshot*. 58, INSTAAR, Boulder, CO.

Dyurgerov, M.B. and C.L. Carter, 2004: Observational evidence of increases in freshwater inflow to the Arctic Ocean. *Arct. Antarct. Alp. Res*., **36**(1), 117–122.

Eakin, H. and M.C. Lemos, 2006: Adaptation and the state: Latin America and the challenge of capacity – building under globalization. *Global Environ. Chang*., **16**, 7–18.

Easterling, W.E., 2003: Observed impact of climate change in agriculture and forestry. *IPCC Workshop on the Detection and Attribution of the Effects of Climate Change*, GISS, New York, 54-55.

Ebi, K.L., D.M. Mills, J.B. Smith and A. Grambsch, 2006: Climate change and human health impacts in the United States: an update on the results of the US National Assessment. *Environ. Health Persp*., **114**(9), 1318–1324

ECF (European Climate Forum) and Potsdam Institute, 2004: *Report on the Beijing Symposium on Article 2*, September, 2004.

Eckhardt, K. and U. Ulbrich, 2003: Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range. *J. Hydrol*., **284**(1–4), 244–252.

EEA, 2004: *Impacts of Europe's changing climate: an indicator-based assessment*. EEA Report No 2/2004, European Environment Agency, Copenhagen, Denmark (or: Luxembourg, Office for Official Publications of the EC), 107 pp.

EEA, 2005: *Vulnerability and adaptation to climate change in Europe*. EEA Technical Report No. 7/2005, European Environment Agency, Copenhagen, Denmark (or: Luxembourg, Office for Official Publications of the EC).

Eheart, J.W. and D.W. Tornil, 1999: Low-flow frequency exacerbation by irrigation withdrawals in the agricultural Midwest under various climate change scenarios. *Water Resour. Res*., **35**, 2237–2246.

Eid, H.M., S.M. El-Marsafawy and S.A. Ouda, 2006: *Assessing the Impacts of Climate Change on Agriculture in Egypt: a Ricardian Approach*. Centre for Environmental Economics and Policy in Africa (CEEPA) Discussion Paper No. 16, Special Series on Climate Change and Agriculture in Africa, University of Pretoria, Pretoria, 1-33.

Eisenreich, S.J., Ed., 2005: *Climate* Change *and the European Water Dimension*. Report to the European Water Directors. European Commission-Joint Research Centre, Ispra, 253 pp.

Eitzinger, J., M. Stastna, Z. Zalud and M. Dubrovsky, 2003: A simulation study of the effect of soil water balance and water stress in winter wheat production under different climate change scenarios. *Agric. Water Manage.,* **61**, 195-217.

El-Gindy, A., A.A. Abdel Azziz and E.A. El-Sahaar, 2001: *Design of Irrigation and Drainage Networks*. Faculty of Agriculture lectures, Ain Shams University, 28 pp (in Arabic).

Ellis, J., 1995: Climate variability and complex ecosystem dynamics; implications for pastoral development. *Living with Uncertainty: New Directions in Pastoral Development in Africa*, I. Scoones, Ed., Intermediate Technology Publications, London, 37-46.

Elpiner**,** L.I., 2004: Scenarios of human health changes under global hydroclimatic transformations. *Proc. Climate Change and Public Health in Russia in the XXI Century.* April 5–6, 2004, Publishing Company "Adamant", Moscow, 195–199 (in Russian).

Elsasser, H. and R. Burki, 2002: Climate change as a threat to tourism in the Alps. *Clim. Res*., **20**, 253–257.

Elsasser, H., R. Bürki and B. Abegg, 2003: *Fifth World Conference on Sport and the Environment*, IOC/UNEP, Turin. http://www.unep.org/sport_env/Documents/torinobuerki.doc.

Enfield, D.B., A.M. Mestas-Nuñez and P.J Trimble, 2001: The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental US. *Geophys. Res. Lett*., **28**, 2077–2080.

Environment Canada, 2001: *Threats to sources of drinking water and aquatic ecosystems health in Canada. National Water Research Report No.1*. National Water Resources Research Institute, Burlington, Ontario, 72 pp.

EPIQ (Environmental Policy and Institutional Strengthening Indefinite

Quantity, Water Policy Reform Activity, Agricultural Policy Reform Programme and Market-Based Incentives Team), 2002: Economic Instruments for Improved Water Resources Management in Egypt, Prepared for the United States Agency for International Development/Egypt, No. PCE-I-00-96-00002-00, 173 pp.

Ericson, J.P., C.J. Vorosmarty, S.L. Dingman, L.G. Ward and M. Meybeck, 2006: Effective sea-level rise and deltas: causes of change and human dimension implications. *Global Planet. Change*, **50**, 63–82.

Etchevers, P., C. Golaz, F. Habets and J. Noilhan, 2002: Impact of a climate change on the Rhone river catchment hydrology. *J. Geophys. Res.*, **107**, 4293, doi:10.1029/2001JD000490.

Evans, E., R. Ashley, J. Hall, E. Penning-Rowsell, A. Saul, P. Sayers, C. Thorne and A. Watkinson, 2004: *Foresight. Future Flooding. Scientific Summary: Volume 1. Future Risks and their Drivers*. Office of Science and Technology, London.

Falconer, I.R., 1997: Blue-green algae in lakes and rivers: their harmful effects on human health. *Australian Biologist*, **10**(2), 107–110.

FAO (Food and Agriculture Organization), 2003: *World Agriculture Towards 2015/2030*. http://www.fao.org/documents/show_cdr.asp?url_file=/docrep/004/y3557e/y3557e00.htm.

FAO (Food and Agriculture Organization), 2004a: *Yearbook of Fishery Statistics 2002*. Capture Production, Vol. 94/1, Food and Agriculture Organization of the United Nations, Rome, 654 pp.

FAO (Food and Agriculture Organization), 2004b: *Yearbook of Fishery Statistics 2002*, Aquaculture production, Vol. 94/2, Food and Agriculture Organization of the United Nations, Rome, 206 pp.

FAO (Food and Agriculture Organization), 2004c: *Data Base*, Food and Agriculture Organization of the United Nations, Rome.

FAO (Food and Agriculture Organization), 2006: Third Session of the Sub-Committee on Aquaculture: Committee on Fisheries (COFI). Food and Agriculture Organization of the United Nations (FAO), New Delhi, India, 4-8 September.

Faruqui, N.I., A.K. Biswas and M.J. Bino, Eds., 2001: *Water Management in Islam*. United Nations University Press, Tokyo, 149 pp.

Fay, M., F. Ghesquiere and T. Solo, 2003b: Natural disasters and the urban poor. *IRDB En Breve,* **32**, The World Bank, 4 pp.

Fay, P.A., J.D. Carlisle, A.K. Knapp, J.M. Blair and S.L. Collins, 2003a: Productivity responses to altered rainfall patterns in a C-4-dominated grassland. *Oecologia*, **137**(2), 245–251.

Fedorov, A. and P. Konstantinov, 2003: Observations of surface dynamics with thermokarst initiation, Yukechi site, Central Yakutia. *Proc. VII International Permafrost Conference*, Switzerland, 21–25 July, 139–243.

Feng, S. and Q. Hu, 2004: Changes in agro-meteorological indicators in the contiguous United States: 1951-2000. *Theor. Appl. Climatol.*, **78**, 247-264.

Ferguson, G. and S.S. George, 2003: Historical and estimated ground water levels near Winnipeg, Canada and their sensitivity to climatic variability. *J. Am. Water Resour. As.*, **39**, 1249-1259.

Fink, A.H., T. Brücher, A. Krüger, G.C. Leckebusch, J.G. Pinto, and U. Ulbrich, 2004: The 2003 European summer heatwaves and drought: synoptic diagnosis and impacts. *Weather*, **59**, 209–216.

Fischer, G., M. Shah and H.V. Velthuizen, 2002a: *Climate Change and Agricultural Vulnerability*. International Institute for Applied Systems Analysis, Laxenburg, 152 pp.

Fischer, G., H. van Velthuizen, M. Shah and F.O. Nachtergaele, 2002b: *Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results*. Research Report RR-02-02. International Institute for Applied Systems Analysis, Laxenburg, 119 pp and CD-Rom.

Fischer, G., F.N. Tubiello, H. van Velthuizen and D. Wiberg, 2006: Climate change impacts on irrigation water requirements: global and regional effects of mitigation, 1990–2080. *Tech. Forecasting Soc. Ch.*, **74,** doi:10.1016/j.techfore.2006.05.021.

Fish, M.R., I.M. Cote, J.A. Gill, A.P. Jones, S. Renshoff and A. Watkinson, 2005: Predicting the impact of sea level rise on Caribbean sea turtle nesting habitat. *Conserv. Biol.*, **19**(2), 482–491.

Fleury, M.D., D. Charron, J. Holt, B. Allen and A. Maarouf, 2006: The role of ambient temperature in foodborne disease in Canada using time series methods *Int. J. Biometeorol.*, **50**, doi:10.1007/s00484-00006-00028-00489.

Folland, C. K., J.A. Renwick, M.J. Salinger, N. Jiang and N.A. Rayner, 2003: Trends and variations in South Pacific islands and ocean surface temperatures. *J. Climate*, **16**, 2859–2874.

Follett, R.F., 2001: Organic carbon pools in grazing land soils. *The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect*. R.F. Follett, J.M. Kimble and R. Lal, Eds., Lewis Publishers, Boca Raton, FL, 65-86.

Fosaa, A.M., M.T. Sykes, J.E. Lawesson and M. Gaard, 2004: Potential effects of climate change on plant species in the Faroe Islands, *Global Ecol. Biogeogr.*, **13**, 427–437.

Francou, B. and C. Vincent, 2006: Les glaciers à l'épreuve du climat. IRD/BELIN, Paris, 274 pp.

Francou, B., M. Vuille, P. Wagnon, J. Mendoza and J.-E. Sicart, 2003: Tropical climate change recorded by a glacier in the central Andes during the last decades of the twentieth century: Chacaltaya, Bolivia, 16°S. *J. Geophys. Res.*, **108**, doi:10.1029/2002JD002959.

Frauenfeld, O.W., T. Zhang, R.G. Barry and D. Gilichinsky, 2004: Interdecadal changes in seasonal freeze and thaw depths in Russia. *J. Geophys. Res.*, **109**, doi:10.1029/2003JD004245.

Freibauer, A., M. Rounsevell, P. Smith and A. Verhagen, 2004: Carbon sequestration in the agricultural soils of Europe. *Geoderma,* **122**, 1-23.

Frich, P., L.V. Alexander, P. Della-Marta, B. Gleason, M. Haylock, A.M.G.K. Tank and T. Peterson, 2002: Observed coherent changes in climatic extremes during the second half of the twentieth century. *Clim. Res.*, **19**, 193–212.

Frolov, I., G. Alekseev and A. Danilov, 2004: Climate change in polar areas. *Proc. World Climate Change Conference*, Moscow, 29 September–3 October 2003, 484–490.

Fukushima, Y., 1987: Influence of forestation on mountainside at granite highlands. *Water Sci.*, **177**, 17-34.

Gagnon, A.S., K.E. Smoyer-Tomic and A. Bush, 2002: The El Niño Southern Oscillation and malaria epidemics in South America. *Int. J. Biometeorol.*, **46**, 81-89.

Gallagher, P. and L. Wood, 2003: *Proc. World Summit on Salmon*, June 10-13, 2003, Vancouver, British Columbia. http://www.sfu.ca/cstudies/science/summit.htm.

Gardner, T.A., I. Cote, G. Gill, A. Grant and A. Watkinson, 2003: Long-term region-wide declines in Caribbean corals. *Science*, **301**, 958–960.

Gash, J.H.C. and W.J. Shuttleworth, 1991: Tropical deforestation: albedo and the surface energy balance. *Climatic Change*, **19**, 123-133.

Gavriliev, P.P. and P.V. Efremov, 2003: Effects of cryogenic processes on Yakutian landscapes under climate warming. *Proc. VII International Permafrost Conference*, Switzerland, 21–25 July, 277–282.

GDE (General Directorate of Environment, Comoros), 2002: *Initial National Communication on Climate Change*, Union des Comoros, Ministry of Development, Infrastructure, Post and Telecommunications.

Gedney, N., P.M. Cox, R.A. Betts, O. Boucher, C. Huntingford and P.A. Stott, 2006: Detection of a direct carbon dioxide effect in continental river runoff records. *Nature*, **439**(7078), 835–838.

Genovese, G., C. Lazar and F. Micale, 2005: Effects of observed climate fluctuation on wheat flowering as simulated by the European crop growth monitoring system (CGMS). *Proc. Workshop on Adaptation of Crops and Cropping Systems to Climate Change, 7-8 November 2005, Dalum Landbrugsskole, Odense, Denmark*. Nordic Association of Agricultural Scientists, 12 pp.

Genthon, C., G. Krinner and M. Sacchettini, 2003: Interannual Antarctic tropospheric circulation and precipitation variability. *Clim. Dyn.*, **21**, 289–307.

GEO-3, 2003: *Global Environmental Outlook*. United Nations Environmental Program, 279 pp. http://www.unep.org/geo/pdfs/GEO__lac2003English.pdf.

Georges, C., 2004: The 20th century glacier fluctuations in the Cordillera Blanca (Perú). *Arct. Antarct. Alp. Res.*, **36**(1), 100–107.

Geres, D., 2004: Analysis of the water demand management. *Proc. XXII Conference of the Danubian Countries on the Hydrological Forecasting and Hydrological Bases of Water Management*. Brno, 30 August–2 September 2004. CD-edition.

Gerolomo, M. and M.F. Penna, 1999: Os primeiros cinco anos da setima pandemia de cólera no Brasil. *Informe Epid. SUS*, **8**(3), 49–58.

Gerten, D., S. Schaphoff, U. Haberlandt, W. Lucht and S. Sitch, 2004: Terrestrial vegetation and water balance: hydrological evaluation of a dynamic global vegetation model. *J. Hydrol.*, **286**(1–4), 249–270.

Gibson, J.J., T.D. Prowse and D.L. Peters, 2006: Partitioning impacts of climate and regulation on water level variability in Great Slave Lake. *J. Hydrol.*, **329**, 196-206.

Gilman, E., H. Van Lavieren, J. Ellison, V. Jungblut, L. Wilson, F.Ereki, G. Brighouse, J. Bungitak, E. Dus, M. Henry, I. Sauni, M. Kilman, E. Matthews, N.Teariki-Ruatu, S. Tukia, K. Yuknavage, 2006: Pacific island mangroves in a changing climate and rising sea. *UNEP Regional Sea Reports and Studies,* **179**, United Nations Environment Programme, Regional Sea 44 Programme, Nairobi, 45 pp.

Giorgi, F., X. Bi and J. Pal, 2004: Mean, interannual variability and trend in a regional climate change experiment over Europe. II: Climate change scenarios 2071–2100. *Clim. Dyn.,* **23,** doi:10.1007/s00382-004-0467-0.

Gitay, H., S. Brown, W. Easterling and B. Jallow, 2001: Ecosystems and their goods and services. *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White, Eds., Cambridge University Press, Cambridge, 237-342.

Gitay, H., A. Suárez, R.T. Watson and D.J. Dokken, Eds., 2002: *Climate Change and Biodiversity*. IPCC Technical Paper V, IPCC, Geneva, 85 pp.

Githeko, A.K. and W. Ndegwa, 2001: Predicting malaria epidemics in Kenyan highlands using climate data: a tool for decision makers. *Global Change Human Health*, **2**, 54-63.

Glantz, M.H., Ed., 2001: *Once Burned, Twice Shy? Lessons Learned from the 1997–98 El Niño*, United Nations University, 294 pp.

Gnadlinger, J., 2003: *Captação e Manejo de Água de Chuva e Desenvolvimento Sustentável do Semi-Árido Brasileiro - Uma Visão Integrada,* 4º Simpósio Brasileiro de captação e Manejo de água de chuva. 9-12/07/2003. Juazeiro, BA, 2003.

Goldenberg, S.B. and Co-authors, 2001: The recent increase in Atlantic hurricane activity: causes and implications. *Science*, **293**, 474–479.

Golubev, V.S. and Co-authors, 2001: Evaporation changes over the contiguous United States and the former USSR: a reassessment. *Geophys. Res. Lett.*, **28**, 2665–2668.

Gonzalez, P., 2001. Desertification and a shift of forest species in the West African Sahel. *Clim. Res.*, **17**, 217–228

Good, P., L. Bärring, C. Giannakopoulos, T. Holt and J. Palutikof, 2006: Non-linear regional relationships between climate extremes and annual mean temperatures in model projections for 1961-2099 over Europe. *Clim. Res.*, **31**, 19–34.

Gordon, W. and J.S. Famiglietti, 2004: Response of the water balance to climate change in the United States over the 20th and 21st centuries: results from the VEMAP phase 2 model intercomparisons. *Global Biogeochem. Cy.*, **181**, GB1030.

Gorham, E., 1991: Northern peatlands: role in the carbon cycle and probable responses to climatic warming. *Ecol. Appl.*, **1**, 182–195.

Government of South Australia, 2005: *Water Proofing Adelaide: A Thirst for Change 2005–2025*. Government of SA, 64 pp. http://www.waterproofingadelaide.sa.gov.au/pdf/wpa_Strategy.pdf.

Government of Western Australia, 2003: *Securing our Water Future: A State Water Strategy for Western Australia*. Government of WA, 64 pp. http://dows.lincdigital.com.au/files/State_Water_Strategy_complete_001.pdf.

Government of Western Australia, 2006: *Draft State Water Plan*. Government of WA, 88 pp. http://dows.lincdigital.com.au/files/Draft%20State%20Water%20Plan.pdf.

Graham, N.A.J., S.K. Wilson, S. Jennings, N.V.C. Polunin, J.P. Bijoux and J. Robinson, 2006: Dynamic fragility of oceanic coral reef ecosystems. *P. Natl. Acad. Sci. USA*, **103**, 8425–8429.

Graves, H. M. and M. C. Phillipson, 2000: Potential implications of climate change in the built environment. *FBE Report* **2**. Building Research Establishment Press, London, 74 pp.

Green, R.E., S.J. Cornell, J.P.W. Scharlemann and A. Balmford, 2005: Farming and the fate of wild nature. *Science*, **307**, 550-555.

Greenwood, E.A.N., L.B. Klein, J.D. Beresford and G.D. Watson, 1985: Differences in annual evaporation between grazed pasture and eucalyptus species in plantation on a saline farm catchment. *J. Hydrol.*, **78**, 261-278.

Gregorich, E.G., P. Rochette, A.J. van den Bygaart and D.A. Angers, 2005: Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. *Soil and Tillage Res.*, **83**, 53-72.

Griffiths, G.M., M.J. Salinger and I. Leleu, 2003: Trends in extreme daily rainfall across the South Pacific and relationship to the South Pacific Convergence Zone. *J. Climatol.*, **23**, 847–869.

Gritti, E.S., B. Smith and M.T. Sykes., 2006: Vulnerability of Mediterranean Basin ecosystems to climate change and invasion by exotic plant species. *J. Biogeogr.*, **33**, 145–157.

Groisman, P.Y., R.W. Knight, T.R. Karl, D.R. Easterling, B. Sun and J.H. Lawrimore, 2004: Contemporary changes of the hydrological cycle over the contiguous United States: trends derived from *in situ* observations. *J. Hydrometeorol.*, **5**, 64–85.

Groisman, P.Y. and Co-authors, 2005: Trends in intense precipitation in the climate record. *J. Clim.*, 18, 1326–1350.

Gruza, G. and E. Rankova, 2004: Detection of changes in climate state, climate variability and climate extremity, in *Proc. World Climate Change Conference*, 29 September–3 October, 2003, Moscow, 90–93.

Gueye, L., M. Bzioul and O. Johnson, 2005: Water and sustainable development in the countries of Northern Africa: coping with challenges and scarcity. *Assessing Sustainable Development in Africa*, Africa's Sustainable Development Bulletin, Economic Commission for Africa, Addis Ababa, 24-28.

Guo, Q.X., J.L. Li, J.X. Liu and Y.M. Zhang, 2001: The scientific significance of the forest vegetation ecotone between Daxing'an and Xiaoxing'an Mountains to global climate change study. *J. Forestry, Northeast University*, **29**(5), 1–4.

Gupta, S.K. and R.D. Deshpande, 2004: Water for India in 2050: first-order assessment of available options. *Current Sci.*, **86**(9), 1216–1224.

Gutiérrez Teira, B., 2003: Variaciones de las comunidades y poblaciones de macroinvertebrados del tramo alto del río manzanares a causa de la temperatura. Posibles efectos del cambio climático. *Tesis*

Doctoral. Escuela Técnica Superior de Ingenieros de Montes. Universidad Politécnica de Madrid. Madrid.

GWP (Global Water Partnership), 2002: *Dialogue on Effective Water Governance*, GWP, 6 pp.

Haeberli, W. and C. Burn, 2002: Natural hazards in forests - glacier and permafrost effects as related to climate changes. *Environmental Change and Geomorphic Hazards in Forests,* R.C. Sidle, Ed., IUFRO Research Series, 9, 167-202.

Hales S., N. de Wett, J. Maindonald and A. Woodward, 2002: Potential effect of population and climates change models on global distribution of dengue fever: an empirical model. *Lancet*, **360**, 830-834.

Hall, C.J. and C.W. Burns, 2002: Mortality and growth responses of *Daphnia carinata* to increases in temperature and salinity. *Freshw. Biol*., **47**, 451–458.

Hall, G., R. D'Souza and M. Kirk, 2002: Foodborne disease in the new millennium: out of the frying pan and into the fire? *Med. J. Australia*, **177**, 614-618.

Hall, J.W., P.B. Sayers and R.J. Dawson, 2005: National-scale assessment of current and future flood risk in England and Wales. *Nat. Hazards*, **36**, 147–164.

Hamlet, A.F., 2003: The role of transboundary agreements in the Columbia River Basin: an integrated assessment in the context of historic development, climate, and evolving water policy. *Climate, Water, and Transboundary Challenges in the Americas*, H. Diaz and B. Morehouse, Eds., Kluwer Press, Dordrecht, 263-289.

Harding, R.J., 1992: The modification of climate by forests. *Growth and Water Use of Forest Plantations,* I.R. Calder, R.L. Hall and P.G. Adlard, Eds., John Wiley and Sons, Chichester, 332-346.

Hareau, A., R. Hofstadter and A. Saizar, 1999: Vulnerability to climate change in Uruguay: potential impacts on the agricultural and coastal resource sectors and response capabilities. *Clim. Res*., **12**, 185–193.

Harman, J., M. Gawith and M. Calley, 2005: Progress on assessing climate impacts through the UK Climate Impacts Programme, *Weather*, **60**, 258–262.

Harrison, G.P. and H.W. Whittington, 2002: Susceptibility of the Batoka Gorge hydroelectric scheme to climate change. *J. Hydrol*., **264**(1–4), 230–241.

Hartmann, J., K. Ebi, J. McConnell, N. Chan and J.P. Weyant, 2002: Stable malaria transmission in Zimbabwe under different climate change scenarios. *Global Change and Human Health*, **3**, 2–14.

Hatfield, J.L. and J.H. Pruger, 2004: Impacts of changing precipitation patterns on water quality. *J. Soil Water Conserv*., **59**, 51-58.

Hay, S.I., D.J. Rogers, S.E. Randolph, D.I. Stern, J. Cox, G.D. Shanks and R.W. Snow, 2002a: Hot topic or hot air? Climate change and malaria resurgence in East African highlands. *Trends Parasitol*., **18**, 530-534.

Hay, S.I., J. Cox, D.J. Rogers, S.E. Randolph, D.I. Stern, G.D. Shanks, M.F. Myers and R.W. Snow, 2002b: Climate change and the resurgence of malaria in the East African highlands. *Nature*, **415**, 905-909.

Hay, S.I., G.D. Shanks, D.I. Stern, R.W. Snow, S.E. Randolph and D.J. Rogers, 2005: Climate variability and malaria epidemics in the highlands of East Africa. *Trends Parasitol*., **21**, 52-53.

Hayhoe, K. and Co-authors, J.H., 2004: Emissions pathways, climate change, and impacts on California. *P. Natl. Acad. Sci. USA*, **101**, 12422-12427.

Haylock, M.R. and C.M. Goodess, 2004: Interannual variability of extreme European winter rainfall and links with mean large-scale circulation. *Int. J. Climatol*., **24**, 759–776.

Haylock, M.R., T. Peterson, L.M. Alves, T. Ambrizzi, Y.M.T. Anunciação, J. Baez, V.R. Barros, M.A. Berlato and Co-authors, 2006: Trends in total and extreme South American rainfall 1960-2000 and links with sea surface temperature. *J. Climate*, **19**, 1490-1512.

Helgason, B.L., H.H. Janzen, M.H. Chantigny, C.F. Drury, B.H. Ellert, E.G. Gregorich, Lemke, E. Pattey, P. Rochette and C. Wagner-Riddle, 2005: Toward improved coefficients for predicting direct N_2O emissions from soil in Canadian agroecosystems. *Nutrient Cycling in Agroecosystems*, **71**, 7-99.

Helms, M., B. Büchele, U. Merkel and J. Ihringer, 2002: Statistical analysis of the flood situation and assessment of the impact of diking measures along the Elbe (Labe) river. *J. Hydrol*., **267**, 94–114.

Hemp, A., 2005: Climate change-driven forest fires marginalize the impact of ice cap wasting on Kilimanjaro. *Glob. Change Biol*., **11**, 1013-1023.

Hendy, C. and J. Morton, 2001: Drought-time grazing resources in Northern Kenya. *Pastoralism, Drought and Planning: Lessons from Northern Kenya and Elsewhere*, J. Morton, Ed., Natural Resources Institute, Chatham, 139-179.

Herath, S. and U. Ratnayake, 2004: Monitoring rainfall trends to predict adverse impacts: a case study from Sri Lanka (1964–1993). *Global Environ. Change*, **14**, 71–79.

Herron, N., R. Davis and R. Jones, 2002: The effects of large-scale afforestation and climate change on water allocation in the Macquarie River catchment, NSW, Australia. *J. Environ. Manage*., **65**, 369–381.

Hewitt, K., 2005: The Karakoram anomaly? Glacier expansion and the "elevation effect", Karakoram Himalaya. *Mountain Research and Development*, **25**(4), 332–340.

Hibbert, A.R., 1967: Forest treatment effects on water yield. *Forest Hydrology. Proc. International Symposium on Forest Hydrology,* W.E. Sopper and H.W. Lull, Eds., Forest hydrology, Pergamon Press, London, 527-543.

Higashi, H., K. Dairaku and T. Matuura, 2006: Impacts of global warming on heavy precipitation frequency and flood risk, *Jour. Hydroscience and Hydraulic Engineering*, **50**, 205–210.

Hild, C. and V. Stordhal, 2004: Human health and well-being. *Arctic Human Development Report (AHDR)*. N. Einarsson, J.N. Larsen, A. Nilsson and O.R. Young, Eds., Steffanson Arctic Institute, Akureyri, 155-168 pp.

Hinzman, L., N. Bettez, W. Bolton, F. Chapin, M. Dyurgerov, C. Fastie, B. Griffith, R. Hollister and Co-authors., 2005: Evidence and implications of recent climate change in northern Alaska and other Arctic regions. *Climatic Change*, **72**, 251–298.

Hoanh, C.T., H. Guttman, P. Droogers and J. Aerts, 2004: Will we produce sufficient food under climate change? Mekong Basin (South-east Asia). *Climate Change in Contrasting River Basins: Adaptation Strategies for Water, Food, and Environment*, Aerts, J.C.J.H. Aerts and P. Droogers, Eds., CABI Publishing, Wallingford, 157–180.

Hobbins, M.T., J.A. Ramirez, and T.C. Brown, 2004: Trends in pan evaporation and actual evapotranspiration across the conterminous U.S.: Paradoxical or complementary? *Geophys. Res. Lett*., **31**, L13503, doi:10/10029/2004GL019846.

Hock, R., P. Jansson and L. Braun, 2005: Modelling the response of mountain glacier discharge to climate warming. *Global Change and Mountain Regions: A State of Knowledge Overview.* Advances in Global Change Series, U.M. Huber, M.A. Reasoner and H. Bugmann, Eds., Springer, Dordrecht, 243–252.

Hodgkins, G.A., R.W. Dudley and T.G. Huntington, 2003: Changes in the timing of high river flows in New England over the 20th century. *J. Hydrol*., **278**(1–4), 244–252.

Hodgkins, G.A., R.W. Dudley and T.G. Huntington, 2005: Summer low flows in New England during the 20th century. *J. Am. Water Resourc. Assoc*., **41**(2), 403–412.

Hoelzle, M., W. Haeberli, M. Dischl and W. Peschke, 2003: Secular glacier mass balances derived from cumulative glacier length changes. *Global Planet*. *Change*, **36**, 295–306.

Holden, N.M., A.J. Brereton, R. Fealy and J. Sweeney, 2003: Possible change in Irish climate and its impact on barley and potato yields. *Agric*. *For. Meteorol*., **116**, 181–196.

Hood, A. and Co-authors, 2002: Options for Victorian Agriculture in a “New” Climate: *A Pilot Study Linking Climate Change Scenario Modelling* and *Land Suitability Modelling*. Volume One - *Concepts and Analysis*. 62 pp. Volume Two - *Modelling Outputs*. Department of Natural Resources and Environment – Victoria, Australia, 83 pp.

Hoogwijk, M., 2004: *On the Global and Regional Potential of Renewable Energy Sources*. PhD thesis, Copernicus Institute, Utrecht University, Utrecht, 256 pp.

Hoogwijk, M., A. Faaij, B. Eickhout, B. de Vries and W. Turkenburg, 2005: Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. *Biomass and Bioenergy,* **29**, 225-257.

Hooijer, M., F. Klijn, G.B.M. Pedroli and A.G. van Os, 2004: Towards sustainable flood risk management in the Rhine and Meuse river basins: synopsis of the findings of IRMA-SPONGE. *River Res*. *Appl*., **20**, 343–357.

Hortle, K. and S. Bush, 2003: Consumption in the Lower Mekong Basin as a measure of fish yield. *New Approaches for the Improvement of Inland Capture Fishery Statistics in the Mekong Basin*, T. Clayton, Ed., FAO RAP Publication 2003/01, Bangkok, 76-88.

Howe, A.D., S. Forster, S. Morton, R. Marshall, K.S. Osborn, P. Wright and P.R. Hunter, 2002: *Cryptosporidium* oocysts in a water supply associated with a cryptosporidiosis outbreak. *Emerg*. *Infect*. *Dis*., **8**, 619–624.

Howe, C., R.N. Jones, S. Maheepala and B. Rhodes, 2005: *Implications of Potential Climate Change for Melbourne’s Water Resources*. CSIRO Urban Water, CSIRO Atmospheric Research and Melbourne Water, Melbourne, 26 pp.

Hu, D.X., W.Y. Han and S. Zhang, 2001: *Land–Ocean Interaction in Changjiang and Zhujiang Estuaries and Adjacent Sea Areas*. China Ocean Press, Beijing, 218 pp (in Chinese).

Huang, H.J., F. Li, J.Z. Pang, K.T. Le and S.G. Li, 2005: *Land–Ocean Interaction between Huanghe Delta and Bohai Gulf and Yellow Sea*. China Science Press, Beijing, 313 pp (in Chinese).

Huang, Z.G. and Xie X.D., 2000: *Sea Level Changes in Guangdong and its Impacts and Strategies*. Guangdong Science and Technology Press, Guangzhou, 263 pp.

Huffaker, R., 2005: Finding a modern role for the prior appropriation doctrine in the American West. *Water Institutions: Policies, Performance and Prospects,* C. Gopalakrishnan, C. Tortajada and A.K. Biswas, Eds., Springer, Berlin, 187–200.

Hunt, M., 2005: *Flood Reduction Master Plan,* Presented to the City of Peterborough City Council, Peterborough, Canada.

Hunter, P.R., 2003: Climate change and waterborne and vector-borne disease. *J*. *Appl*. *Microbiol*., **94**, 37S–46S.

Huntington, T.G., 2006: Evidence for intensification of the global water cycle: review and synthesis. *J*. *Hydrol*., **319**, 83–95.

Hurrell, J.W. and Co-authors, 2003: An overview of the North Atlantic Oscillation. *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*, J.W. Hurrell and Co-authors, Eds., Geophysical Monograph 134, American Geophysical Union, Washington, DC, 1–35.

Hurtado-Díaz, M., H. Riojas-Rodríguez, S.J. Rothenberg, H. Gomez-Dantés and E. Cifuentes-García, 2006: Impacto de la variabilidad climática sobre la incidencia del dengue en México. *International Conference on Environmental Epidemiology and Exposure*, Paris.

Huston, M.A. and G. Marland, 2003: Carbon management and biodiversity. *J*. *Environ*. *Manage*., **67**, 77-86.

Hyvarinen,V., 2003: Trend and characteristics of hydrological time series in Finland. *Nordic Hydrol*.*,* **34**, 71-91.

Iafiazova, R.K., 1997: Climate change impact on mud flow formation in Trans-Ili Alatay mountains. *Hydrometeorology and Ecology*, **3**, 12–23 (in Russian).

ICID (International Commission on Irrigation and Drainage, New Delhi), 2005: *Water Policy Issues of Egypt*, Country Policy Support Programme, 36 pp.

Iglesias, A., T. Estrela and F. Gallart, 2005: Impactos sobre los recursos hídricos. *Evaluación Preliminar de los Impactos en España for Efecto del Cambio Climático*, J.M. Moreno, Ed., Ministerio de Medio Ambiente, Madrid, 303–353.

Inouye, D.W., B. Barr, K.B. Armitage and B.D. Inouye, 2000: Climate change is affecting altitudinal migrants and hibernating species. *P. Natl*. *Acad*. *Sci*. *USA*, **97**(4), 1630–1633.

Instanes, A. and Co-authors, 2005: Infrastructure: buildings, support systems, and industrial facilities. *Arctic Climate Impact Assessment, ACIA*. C. Symon, L. Arris and B. Heal, Eds., Cambridge University Press, Cambridge, 907–944.

IOCI, 2002: *Climate Variability and Change in SouthWest Western Australia*. Indian Ocean Climate Initiative. Perth, Australia, 36 pp. http://www.ioci.org.au/publications/pdf/IOCI_CVCSW02.pdf.

IPCC (Intergovernmental Panel on Climate Change), 2000: *Land Use, Land-Use Change and Forestry*, R. T. Watson, I. R. Noble, B. Bolin, N. H. Ravindranath, D. J. Verardo and D. J. Dokken, Eds., Cambridge University Press, Cambridge, 375 pp.

IPCC (Intergovernmental Panel on Climate Change), 2001a: *Climate Change 2001: The Scientific Basis*. *Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson, Eds., Cambridge University Press, Cambridge, 881 pp.

IPCC (Intergovernmental Panel on Climate Change), 2001b: *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White, Eds., Cambridge University Press, Cambridge, 1032 pp.

IPCC (Intergovernmental Panel on Climate Change), 2001c: *Climate Change 2001*: *Mitigation*. *Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, B. Metz, O. Davidson, R. Swart and J. Pan, Eds., Cambridge University Press, Cambridge, 760 pp.

IPCC (Intergovernmental Panel on Climate Change), 2007a: *Climate Change 2007: The Physical Science Basis*. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, Eds., Cambridge University Press, Cambridge, 996 pp.

IPCC (Intergovernmental Panel on Climate Change), 2007b: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, 976 pp.

IPCC (Intergovernmental Panel on Climate Change), 2007c: *Climate Change 2007*: *Mitigation*. *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, B. Metz, O. Davidson, P.Bosch, R. Dave and L. Meyer, Eds., Cambridge University Press, Cambridge, 851 pp.

IPCC (Intergovernmental Panel on Climate Change), 2007d: *Climate Change 2007: Synthesis Report*. *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Core Writing Team, R.K Pachauri and A. Reisinger, Eds., IPCC, Geneva, 102 pp.

IRDB, 2000: *Gestión de los Recursos Hídricos de Argentina*.

Elementos de Política para su Desarrollo Sustentable en el siglo XXI. Oficina Regional de América Latina y Caribe. Unidad Departamental de Argentina y los Grupos de Finanzas, Sector Privado y Infraestructura, y Medio Ambiente y Desarrollo Social Sustentable. Informe No. 20.729-AR. August 2000.

Isensee, A.R. and A.M. Sadeghi, 1996: Effect of tillage reversal on herbicide leaching to groundwater. *Soil Sci.,* **161**, 382-389.

Ivanov, B. and T. Maximov, Eds., 2003: *Influence of Climate and Ecological Changes on Permafrost Ecosystems*. Yakutsk Scientific Center Publishing House, Yakutsk, 640 pp.

Ivey, J.L., J. Smithers, R.C. de Loe and R.D. Kreutzwiser, 2004: Community capacity for adaptation to climate-induced water shortages: linking institutional complexity and local actors. *Environ. Manage*., **33**(1), 36–47.

Izrael, Y.A. and Y.A. Anokhin, 2001: Climate change impacts on Russia. *Integrated Environmental Monitoring*, Nauka, Moscow, 112–127 (in Russian with an English abstract).

Izrael, Y.A., Y.A. Anokhin and A.V. Pavlov, 2002: Permafrost evolution and the modern climate change. *Meteorol. Hydrol*., **1**, 22–34.

Jackson, R.B., E.G. Jobbágy, R. Avissar, S. Baidya Roy, D. Barrett, C.W. Cook, K.A. Farley, D.C. le Maitre, B.A. McCarl and B.C. Murray, 2005: Trading water for carbon with biological carbon sequestration. *Science*, **310**, 1944-1947.

Jansson, P., R. Hock and T. Schneider, 2003: The concept of glacier storage: a review. *J. Hydrol.,* **282**, 116–129.

Jasper, K., P. Calanca, D. Gyalistras and J. Fuhrer, 2004: Differential impacts of climate change on the hydrology of two alpine rivers. *Clim. Res*., **26**, 113–125.

Jenkins, B., 2006: Overview of Environment Canterbury water issues. managing drought in a changing climate. *Royal Society of New Zealand Drought Workshop, 10 April 2006*, Christchurch, NZ. http://www.rsnz.org/advisory/nz_climate/workshopApr2006/.

Jeppesen, E., J.P. Jensen and M. Søndergaard, 2003: Climatic warming and regime shifts in lake food webs: some comments. *Limnol. Oceanogr*., **48**, 1346–1349.

Jiménez, B., 2003: Health risks in aquifer recharge with recycle water. *State of the Art Report Health Risk in Aquifer Recharge using Reclaimed Water,* R. Aertgeerts and A. Angelakis, Eds., WHO Regional Office for Europe, 54–172.

Jin, Z.Q., C.L. Shi, D.K. Ge and W. Gao, 2001: Characteristic of climate change during wheat growing season and the orientation to develop wheat in the lower valley of the Yangtze River. *Jiangsu J. Agric. Sci*., **17**(4), 193–199.

Jiongxin, X., 2003: Sediment flux to the sea as influenced by changing human activities and precipitation: example of the Yellow River, China. *Environ. Manage*, **31**, 328–341.

Johannessen, O.M., Khvorostovsky, K., Miles, M.W. and Bobylev, L.P., 2005: Recent ice-sheet growth in the interior of Greenland. *Science*, **310**(5750), 1013–1016.

Johnson, W.C., B.V. Millett, T. Gilmanov, R.A. Voldseth, G.R. Guntenspergen and D.E. Naugle, 2005: Vulnerability of northern prairie wetlands to climate change. *BioScience*, **55**(10), 863–872.

Jones, B. and D. Scott, 2006: Implications of climate change to Ontario's provincial parks. *Leisure*, **30** (1), 233-261.

Jones, J.A. and G.E. Grant, 1996: Peak flow response to clear-cutting and roads in small and large basins, western Cascades, Oregon. *Water Resourc. Res*., **32**, 959-974.

Jones, M.L., B.J. Shuter, Y.M. Zhao and J.D. Stockwell, 2006: Forecasting effects of climate change on Great Lakes fisheries: models that link habitat supply to population dynamics can help. *Can. J. Fish. Aquat. Sci*., **63**, 457-468.

Jones, P.D., T.J. Osborn and K.R. Briffa, 2003a: Pressure-based measures of the North Atlantic Oscillation (NAO): A comparison and an assessment of changes in the strength of the NAO and in its influence on surface climate parameters. *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*, Hurrell, J.W. and Co-authors, Eds., Geophysical Monograph 134, American Geophysical Union, Washington, DC, 51–62.

Jones, P.D., D.H. Lister, K.W. Jaggard and J.D. Pidgeon, 2003b: Future climate impact on the productivity of sugar beet (*Beta vulgaris* L.) in Europe. *Climatic Change*, **58**, 93–108.

Jones, R. and P. Durack, 2005: *Estimating the Impacts of Climate Change on Victoria's Runoff using a Hydrological Sensitivity Model*. Consultancy Report for the Victorian Department of Sustainability and Environment, 50 pp.

Jones, R.N. and C.M. Page, 2001: Assessing the risk of climate change on the water resources of the Macquarie River catchment. *Integrating Models for Natural Resources Management Across Disciplines: Issues and Scales*, F. Ghassemi, P.H. Whetton, R. Little and M. Littleboy, Eds., Modelling and Simulation Society of Australia and New Zealand, Canberra, 673–678.

Jordan, E., 1991: *Die gletscher der bolivianischen Anden: eine photogrammetrisch-kartographische Bestandsaufnahme der Gletscher Boliviens als Grundlage für klimatische Deutungen und Potential für die wirtschaftliche Nutzung (The Glaciers of the Bolivian Andes, A Photogrammetric-Cartographical Inventory of the Bolivian Glaciers as a Basis for Climatic Interpretation and Potential for Economic Use)*. Erdwissenschaftliche Forschung 23, Franz Steiner Verlag, Stuttgart, 401 pp.

Jorgenson, M.T., C.H. Racine, J.C. Walters and T.E. Osterkamp, 2001: Permafrost degradation and ecological changes associated with a warming climate in central Alaska. *Climatic Change*, **48**(4), 551–571.

Justic, D., N.N. Rabalais and R.E. Turner, 2005: Coupling between climate variability and coastal eutrophication: evidence and outlook for the northern Gulf of Mexico. *J. Sea Res*., **54**(1), 25–35.

Kabat, P., R.E. Schulze, M.E. Hellmuth and J.A. Veraart, Eds., 2002: *Coping with Impacts of Climate Variability and Climate Change in Water Management: a Scoping Paper.* DWC Report No. DWCSSO-01(2002), International Secretariat of the Dialogue on Water and Climate, Wageningen.

Kajiwara, M., T. Oki and J. Matsumoto, 2003: *Inter-annual Variability of the Frequency of Severe Rainfall in the Past 100 Years over Japan*. Extended abstract for a bi-annual meeting of the Meteorological Society of Japan (in Japanese).

Kanai, S., T. Oki and A. Kashida, 2004: Changes in hourly precipitation at Tokyo from 1890 to 1999. *J. Meteor. Soc. Japan*, **82**, 241–247.

Kane, R.P., 2002: Precipitation anomalies in southern America associated with a finer classification of El Niño and La Niña events. *Int. J. Climatol*., **22**, 357-373.

Kang, G., B.S. Ramakrishna, J. Daniel, M. Mathan and V. Mathan, 2001: Epidemiological and laboratory investigations of outbreaks of diarrhoea in rural South India: implications for control of disease. *Epidemiol. Infect*., **127**, 107.

Karst-Riddoch, T.L., M.F.J. Pisaric and J.P. Smol, 2005: Diatom responses to 20th century climate-related environmental changes in high-elevation mountain lakes of the northern Canadian Cordillera. *J. Paleolimnol*., **33**, 265-282.

Kaser, G. and H. Osmaston, 2002: *Tropical Glaciers*. UNESCO International Hydrological Series. Cambridge University Press, Cambridge, 207 pp.

Kaser, G. and Co-authors, 2003: The impact of glaciers on the runoff and the reconstruction of mass balance history from hydrological data in the tropical Cordillera Blanca, Peru. *J. Hydrol*., **282**, 130–144.

Kashyap, A., 2004: Water governance: learning by developing adaptive capacity to incorporate climate variability and change. *Water Sci. Technol*., **19**(7), 141–146.

Kaspar, F., 2003: *Entwicklung und Unsicherheitsanalyse eines globalen hydrologischen (Model Development and Uncertainty Analysis of* *a Global Hydrological Model)*. University of Kassel, Kassel, PhD thesis.

Kaste, Ø., K. Rankinen and A. Leipistö, 2004: Modelling impacts of climate and deposition changes on nitrogen fluxes in northern catchments of Norway and Finland. *Hydrol. Earth Syst. Sci.*, **8**, 778–792.

Kay, A., V. Bell and H. Davies, 2006a: *Model Quality and Uncertainty for Climate Change Impact*. Centre for Ecology and Hydrology, Wallingford.

Kay, A., N.A. Reynard and R.N. Jones, 2006b: RCM rainfall for UK flood frequency estimation. II. Climate change results. *J. Hydrol.*, **318**, 163–172.

Keddy, P.A., 2000: *Wetland Ecology: Principles and Conservation*. Cambridge University Press, Cambridge, 614 pp.

Keller, F., S. Goyette and M. Beniston, 2005: Sensitivity analysis of snow cover to climate change scenarios and their impact on plant habitats in alpine terrain. *Climatic Change*, **72**(3), 299–319.

Kergoat, L., S. Lafont, H. Douville, B. Berthelot, G. Dedieu, S. Planton and J.-F. Royer, 2002: Impact of doubled CO_2 on global-scale leaf area index and evapotranspiration: conflicting stomatal conductance and LAI responses. *J. Geophys. Res.*, **107**(D24), 4808.

Kerr, R., 2000: A North Atlantic climate pacemaker for the centuries. *Science*, **288**, 1984–1985.

Kerr, S.A., 2005: What is small island sustainable development about? *Ocean Coast. Manage.*, **48**, 503–524.

Khan, T.M.A., O.P. Singh and M.S. Rahman, 2000: Recent sea level and sea surface temperature trends along the Bangladesh coast in relation to the frequency of intense cyclones. *Marine Geodesy*, **23**(2), 103–116.

Kharkina, M.A., 2004: Natural resources in towns. *Energia*, **2**, 44–50.

Kirschbaum, M. and A. Fischlin, 1996: Climate change impacts on forests. *Climate Change 1995: Impacts; Adaptations and Mitigation of Climate Change. Scientific-Technical Analysis. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel of Climate Change.*, R. Watson, M.C. Zinyowera and R.H. Moss, Eds., Cambridge University Press, Cambridge, 95-129.

Kirshen, P., M. McCluskey, R. Vogel and K. Strzepek, 2005a: Global analysis of changes in water supply yields and costs under climate change: a case study in China. *Climatic Change*, **68**(3), 303–330.

Kirshen, P., M. Ruth and W. Anderson, 2005b: Responding to climate change in Metropolitan Boston: the role of adaptation. *New Engl. J. Public Pol.*, **20**(2), 89–104.

Kirshen, P., M. Ruth and W.Anderson, 2006: Climate's long-term impacts on urban infrastructures and services: the case of Metro Boston. *Regional Climate Change and Variability: Impacts and Responses*, M. Ruth, K. Donaghy and P.H. Kirshen, Eds., Edward Elgar Publishers, Cheltenham, 190–252.

Kishor, P.B.K., Z. Hong, G. Miao, C. Hu and D. Verma, 1995: Overexpression of Δ1-pyrroline-5-carboxylase synthase increases praline production and confers osmotolerance in transgenic plants. *J. Plant Physiol.*, **108**, 1387-1394.

Kistemann, T., T. Classen, C. Koch, F. Dagendorf, R. Fischeder, J. Gebel, V. Vacata and M. Exner, 2002: Microbial load of drinking water reservoir tributaries during extreme rainfall and runoff. *Appl. Environ. Microbiol.*, **68**(5), 2188–2197,

Kjellström, E., 2004: Recent and future signatures of climate change in Europe. *Ambio*, **23**, 193-198.

Klanderud, K. and H.J.B. Birks, 2003: Recent increases in species richness and shifts in altitudinal distributions of Norwegian mountain plants. *Holocene,* **13**(1), 1.

Klein, R.J., T.J. Nicholls, and J. Thomalla, 2003: The resilience of coastal mega cities to weather-related hazards in building safer cities*: The Future of Climate Change*, A. Kreimer, M. Arnold and A. Karlin, Eds., World Bank, Washington, DC, 101–121.

Klein Tank, A.M.G., J.B. Wijngaard, G.P. Konnen, R. Bohm, G. Demaree, A. Gocheva, M. Mileta, S. Pashiardis, L. Hejkrlik, C. Kern-Hansen, R. Heino, P. Bessemoulin, G. Muller-Westermeier, M. Tzanakou, S. Szalai, T. Palsdottir, D. Fitzgerald, S. Rubin, M. Capaldo, M. Maugeri, A. Leitass, A. Bukantis, R. Aberfeld, A.F.V. VanEngelen, E. Forland, M. Mietus, F. Coelho, C. Mares, V. Razuvaev, E. Nieplova, T. Cegnar, J.A. López, B. Dahlstrom, A. Moberg, W. Kirchhofer, A. Ceylan, O. Pachaliuk, L.V. Alexander and P. Petrovic, 2002: Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. *Int. J. Climatol.*, **22**, 1441–1453.

Klein Tank, A.M.G. and G.P. Können, 2003: Trends in indices of daily temperature and precipitation extremes in Europe, 1946–1999. *J. Clim.*, **16**, 3665–3680.

Klijn, F., J. Dijkman and W. Silva, 2001: *Room for the Rhine in the Netherlands. Summary of Research Results*. RIZA Report 2001.033, Rijkswaterstaat, Utrecht.

Klijn, F., M. van Buuren and S.A.M. van Rooij, 2004: Flood-risk management strategies for an uncertain future: living with Rhine river floods in the Netherlands? *Ambio*, **33**(3), 141–147.

Knight, C.G., I. Raev, and M. P. Staneva, Eds., 2004: *Drought in Bulgaria: A Contemporary Analog of Climate Change*. Ashgate, Aldershot, Hampshire 336 pp.

Knight, J. and Co-authors, 2005: a signature of persistent natural thermohaline circulation cycles in observed climate. *Geophys. Res. Lett.*, **32**, L20708, doi:1029/2005GL024233.

Knowles, N., M.D. Dettinger and D.R. Cayan, 2006: Trends in snowfall versus rainfall for the western United States, 1949–2004. *J. Climate*, **18**, 1136–1155.

Ko, A., R.M. Galvão, D. Ribeiro, C.M. Dourado, W.D. Johnson Jr. and L.W. Riley, 1999: Urban epidemic of severe leptospirosis in Brazil, Salvador. Leptospirosis Study Group. *Lancet*, **354**, 820-825.

Kobayashi, K., 1987: Hydrologic effects of rehabilitation treatment for bare mountain slops. *Bull. Forestry Forest Products Res. Instit.*, **300**, 151-185.

Koga, N., T. Sawamoto and H. Tsuruta 2006: Life cycle inventory-based analysis of greenhouse gas emissions from arable land farming systems in Hokkaido, northern Japan. *Soil Science and Plant Nutrition,* **52**, 564-574.

Korhola, A. and Co-authors, 2002: A multi-proxy analysis of climate impacts on recent ontogeny of subarctic Lake Sannajärvi in Finnish Lapland. *J. Paleolimnol.*, **1**, 59–77.

Körner, C., 1999: *Alpine Plant Life: Functional Plant Ecology of High Mountain Ecosystems*. Springer, Berlin, 343 pp.

Kosek, M., C. Bern and R.L. Guerrent, 2003: The global burden of diarrhoeal disease, as estimated from studies published between 1992 and 2000. *Bull. World Health Organ.*, **81**, 197-204.

Kovats, R.S. and C. Tirado, 2006: Climate, weather and enteric disease. *Climate Change and Adaptation Strategies for Human Health,* B. Menne and K.L. Ebi, Eds., Springer, Darmstadt, 269–295.

Kovats, R.S., Campbell-Lendrum D. and Matthies, F., 2005: Climate change and human health: estimating avoidable deaths and disease. *Risk Analysis*, **25**(6), 1409–1418.

Kramer, R., D. Richter, S. Pattanayak and N. Sharma, 1997: Economic and ecological analysis of watershed protection in eastern Madagascar. *J. Environ. Manage.,* **49**, 277-295.

Krauss, K.W., J.L. Chambers, J.A. Allen, D.M. Soileau Jr and A.S. DeBosier, 2000: Growth and nutrition of baldcypress families planted under varying salinity regimes in Louisiana, USA. *J. Coast. Res.*, **16**, 153–163.

Kriticos, D.J., T. Yonow and R.C. McFadyen, 2005: The potential distribution of *Chromolaena odorata* (Sim weed) in relation to climate. *Weed Research*, **45**, 246–254

Kron, W. and G. Berz, 2007: Flood disasters and climate change: trends and options – a (re-)insurer's view. *Global Change: Enough Water for All?* J.L. Lozán, H. Graßl, P. Hupfer, L. Menzel and C.-D. Schönwiese, Eds., University of Hamburg, Hamburg, 268-273.

Krüger, A., U. Ulbrich and P. Speth, 2002: Groundwater recharge in Northrhine-Westfalia by a statistical model for greenhouse gas scenarios. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, **26**, 853–861.

Krysanova, V. and F. Wechsung, 2002: Impact of climate change and higher CO_2 on hydrological processes and crop productivity in the state of Brandenburg, Germany. *Climatic Change: Implications for the Hydrological Cycle and for Water Management*, M. Beniston, Ed., Kluwer, Dordrecht, 271–300.

Krysanova, V., F. Hattermann and A. Habeck, 2005: Expected changes in water resources availability and water quality with respect to climate change in the Elbe River basin (Germany). *Nordic Hydrol.*, **36**(4–5), 321–333.

Kumagai, M., K. Ishikawa and J. Chunmeng, 2003: Dynamics and biogeochemical significance of the physical environment in Lake Biwa. *Lakes Reserv. Res. Manage.*, **7**, 345-348.

Kumar, P.K., 2006: Potential vulnerability implications of sea level rise for the coastal zones of Cochin, southwest coast of India. *Environ. Monitor. Assess.*, **123**, 333–344.

Kundzewicz, Z.W., U. Ulbrich, T. Brücher, D. Graczyk, A. Krüger, G. Leckebusch, L. Menzel, I. Pińskwar, M. Radziejewski and M. Szwed, 2005: Summer floods in Central Europe climate change track? *Nat. Hazards*, **36**(1/2), 165–189.

Kundzewicz, Z.W., M. Radziejewski and I. Pińskwar, 2006: Precipitation extremes in the changing climate of Europe. *Clim. Res,* **31**, 51–58.

Kunkel, K.E. and Co-authors, 2003: Temporal variations of extreme precipitation events in the United States: 1895–2000. *Geophys. Res. Lett.*, **30**, 1900, doi:10.1029/2003GL018052.

Kupek, E., M.C. de Sousa Santos Faversani and J.M. de Souza Philippi, 2000: The relationship between rainfall and human leptospirosis in Florianópolis, Brazil, 1991–1996. *Braz. J. Infect. Dis.*, **4**, 131-134.

La Nación, 2002: Buenos Aires, 13 March.

Labat, D. and Co-authors, 2004: Evidence for global runoff increase related to climate warming. *Adv. Water Resources*, **27**, 631–642.

Lal, M., 2002: *Global climate change: India's monsoon and its variability*, Final Report under "Country Studies Vulnerability and Adaptation" Work Assignment with Stratus Consulting's Contract of the U.S. Environmental Protection Agency, September 2002, 58 pp.

Lal, R., 2003: Offsetting global CO_2 emissions by restoration of degraded soils and intensification of world agriculture and forestry. *Land Degradation and Dev.*, **14**, 309–322.

Lal, R., 2004: Soil carbon sequestration impacts on global climate change and food security. *Science,* **304**, 1623-1627.

Lal, R., J.M. Kimble and R.F. Follett, 1999: Agricultural practices and policies for carbon sequestration in soil. *Recommendation and Conclusions of the International Symposium,* 19-23 July 1999, Columbus, OH, 12 pp.

Lama, J.R., C.R. Seas, R. León-Barúa, E. Gotuzzo and R.B. Sack, 2004: Environmental temperature, cholera, and acute diarrhoea in adults in Lima, Peru. *J. Health Popul. Nutr.*, **22**, 399–403.

Larsen, C.F., R.J. Motyka, J.T. Freymueller, K.A. Echelmeyer and E.R. Ivins, 2005: Rapid uplift of southern Alaska caused by recent ice loss. *Geophys. J. Int.*, **158**, 1118-1133.

Laternser, M. and M. Schneebeli, 2003: Long-term snow climate trends of the Swiss Alps (1931–99). *Int. J. Climatol.*, **23**, 733–750.

Latif, M., 2001: Tropical Pacific/Atlantic Ocean interactions at multi-decadal time scales. *Geophys. Res. Lett.*, **28**, 539–542.

Le Maitre, D.C. and D.B. Versfeld, 1997: Forest evaporation models: relationships between stand growth and evaporation. *J. Hydrol.*, **193**, 240-257.

Le Treut, H., R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, A. Mokssit, T. Peterson and M. Prather, 2007: Historical overview of climate change science. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, Eds., Cambridge University Press, Cambridge, 93-128.

Lean, J., C.B. Buntoon, C.A. Nobre and P.R. Rowntree, 1996: The simulated impact of Amazonian deforestation on climate using measured ABRACOS vegetation characteristics. *Amazonian Deforestation and Climate,* J.H.C Gash, C.A. Nobre, J.M. Roberts and T.L. Victoria, Eds., John Wiley and Sons, Chicester, 549-576.

Leary, N., J. Adejuwon, W. Bailey, V. Barros, M. Caffera, S. Chinvanno, C. Conde, A. De Comarmond, A. De Sherbinin, T. Downing, H. Eakin, A. Nyong, M. Opondo, B. Osman, R. Payet, F. Pulhin, J. Pulhin, J. Ratnasiri, E. Sanjak, G. von Maltitz, M. Wehbe, Y. Yin and G. Ziervogel, 2006: For whom the bell tolls: vulnerabilities in a changing climate. *AIACC Working Paper No.* **30**, International START Secretariat, Washington, DC, 31 pp.

Leemans, R. and A. Kleidon, 2002: Regional and global assessment of the dimensions of desertification. *Global Desertification: Do Humans Cause Deserts?* J.F. Reynold and D.S. Smith, Eds., Dahlem University Press, Berlin, 215-232.

Legates, D.R., H.F. Lins and G.J. McCabe, 2005: Comments on "Evidence for global runoff increase related to climate warming" by Labat et al. *Adv. Water Resour.*, **28**, 1310-1315.

Lehner, B., G. Czisch and S. Vassolo, 2005: The impact of global change on the hydropower potential of Europe: a model-based analysis. *Energ. Policy*, **33**, 839–855.

Lehner, B., P. Döll, J. Alcamo, T. Henrichs and F. Kaspar, 2006: Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis. *Climatic Change*, **75**, 273–299.

Leipprand, A. and D. Gerten, 2006: Global effects of doubled atmospheric CO_2 content on evapotranspiration, soil moisture and runoff under potential natural vegetation. *Hydrol. Sci. J.*, **51**, 171–185.

Lemmen, D. S. and F. J. Warren, Eds., 2004: *Climate Change Impacts and Adaptation: A Canadian Perspective*. Climate Change Impacts and Adaptation Directorate, Natural Resources Canada, Ottawa, Canada, 201 pp, http://adaptation.nrcan.gc.ca/perspective_e.asp.

Lenderink, G., A. vanUlden, B. van den Hurk and E. van Meijgaard, 2007: Summertime inter-annual temperature variability in an ensemble of regional model simulations: analysis of the surface energy budget. *Climatic Change*, **81**, S233-S247.

Lewsey, C., Gonzalo, C. and Kruse, E., 2004: Assessing climate change impacts on coastal infrastructure in the Eastern Caribbean. *Marine Policy*, **28**, 393–409.

Li, C., S. Frolking and K. Butterbach-Bahl, 2005: Carbon sequestration in arable soils is likely to increase nitrous oxide emissions, offsetting reductions in climate radiative forcing. *Climatic Change,* **72**, 321-338.

Li, C.X., D.D. Fan, B. Deng and V. Korotaev, 2004: The coasts of China and issues of sea level rise. *J. Coast. Res.*, **43**, 36–47.

Liebig, M.A., J.A. Morgan, J.D. Reeder, B.H. Ellert, H.T. Gollany and G.E. Schuman, 2005: Greenhouse gas contributions and mitigation potential of agricultural practices in northwestern USA and western Canada. *Soil and Tillage Res.,* **83**, 25-52.

Lincoln Environmental, 2000: *Information on Water Allocation in New Zealand.* Report No. 4375/1, prepared for Ministry for the Environment by Lincoln Ventures Ltd, Canterbury, New Zealand. http://www.mfe.govt.nz/publications/water/water-allocation-apr00.pdf.

Lindstrom, G. and S. Bergstrom, 2004: Runoff trends in Sweden

1807–2002. *Hydrol. Sci. J.*, **49**(1), 69–83.

Liniger, H. and R. Weingartner, 1998: Mountains and freshwater supply. *Unasylva,* **195**(49), 39-46.

Lipp, E. and Co-authors, 2001: The effects of seasonal variability and weather on microbial faecal pollution and enteric pathogens in a subtropical estuary. *Estuaries*, **24**, 226–276.

Liu, B.H. and Co-authors, 2004: A spatial analysis of pan evaporation trends in China, 1955–2000. *J. Geophys. Res.*, **109**, D15102, doi:10.1029/2004JD004511.

Liu, C.Z., 2002: Suggestion on water resources in China corresponding with global climate change. *China Water Resources*, **2**, 36–37.

Liu, S.G., Li, C.X., Ding, J., Li, X.Z. and Ivanov, V.V., 2001: The rough balance of progradation and erosion of the Yellow River delta and its geological meaning. *Marine Geology and Quaternary Geology*, **21**(4), 13–17.

Liu, Y.B. and Y.N. Chen, 2006: Impact of population growth and land-use change on water resources and ecosystems of the arid Tarim River Basin in western China. *Int. J. Sust. Dev. World*, **13**, 295-305.

Llasat, M.C., 2001: An objective classification of rainfall intensity in the Northeast of Spain. *Int. J. Climatol.*, **21**, 1385–1400.

Lofgren, B., A. Clites, R. Assel, A. Eberhardt and C. Luukkonen, 2002: Evaluation of potential impacts on Great Lakes water resources based on climate scenarios of two GCMs. *J. Great Lakes Res.*, **28**(4), 537–554.

London Climate Change Partnership, 2004: *London's Warming*: *A Climate Change Impacts in London Evaluation Study*, London, 293 pp.

LOSLR (International Lake Ontario–St. Lawrence River Study Board), 2006: *Options for Managing Lake Ontario and St. Lawrence River Water Levels and Flows*. Final Report to the International Joint Commission. http://www.losl.org/reports/finalreport-e.html.

Luoto, M., R.K. Heikkinen and T.R. Carter, 2004: Loss of palsa mires in Europe and biological consequences. *Environ. Conserv.*, **31**, 30–37.

MacDonald, R., T. Harner, J. Fyfe, H. Loeng and T. Weingartner, 2003: Influence of Global Change on Contaminant Pathways to, within and from the Arctic. *ANAO Assessment 2002*. Arctic Monitoring and Assessment Programme. Oslo, 65 pp.

Machado, P.L.O.A. and C.A. Silva, 2001: Soil management under notillage systems in the tropics with special reference to Brazil. *Nutrient Cycling in Agroecosystems*, **61**, 119-130.

Madari, B., P.L.O.A. Machado, E. Torres, A.G. Andrade and L.I.O. Valencia, 2005: No tillage and crop rotation effects on soil aggregation and organic carbon in a Fhodic Ferralsol from southern Brazil. *Soil and Tillage Research,* **80**, 185-200.

Magadza, C., 2000: Climate change impacts and human settlements in Africa: prospects for adaptation. *Environ. Monit. Assess.*, **61**(1), 193–205.

Magrin, G.O., M.I. Travasso and G.R. Rodríguez, 2005: Changes in climate and crops production during the 20th century in Argentina. *Climatic Change*, **72**, 229–249.

Manton, M.J., P.M. Della-Marta, M.R. Haylock, K.J. Hennessy, N. Nicholls, L.E. Chambers, D.A. Collins, G. Daw, A. Finet, D. Gunawan, K. Inape, H. Isobe, T.S. Kestin, P. Lefale, C.H. Leyu, T. Lwin, L.Maitrepierre, N. Ouprasitwong, C.M. Page, J. Pahalad, N. Plummer, M.J. Salinger, R. Suppiah, V.L. Tran, B. Trewin, I. Tibig and D. Lee, 2001: Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific; 1961–1998, *Int. J. Climatol.*, **21**, 269–284.

Manuel, J., 2006: In Katrina's wake. *Environ. Health Persp.*, **114**, A32-A39.

Marengo, J.A., 2004: Interdecadal variability and trends of rainfall variability in the Amazon basin. *Theor. Appl. Climatol.*, **78**, 79-96.

Mark, B.G. and G.O. Seltzer, 2003: Tropical glacier meltwater contribution to stream discharge: a case study in the Cordillera Blanca, Perú. *J. Glaciol.*, **49**, 271-281.

Marland, G., B.A. McCarl and U.A. Schneider, 2001: Soil carbon: policy and economics. *Climatic Change,* **51**, 101-117.

Marland, G., T.O. West, B. Schlamadinger and L. Canella, 2003: Managing soil organic carbon in agriculture: the net effect on greenhouse gas emissions. *Tellus*, **55B**, 613-621.

Martin, D., Belanger, D., Gosselin, P., Brazeau, J., Furgal, C. and Dery, S., 2005: *Climate change, Drinking Water, and Human Health in Nunavik: Adaptation Strategies*. Final Report submitted to the Canadian Climate Change Action Fund, Natural Resources Canada. CHUL Research Institute, Quebec, 111 pp.

Martin, E. and P. Etchevers, 2005: Impact of climatic change on snow cover and snow hydrology in the French Alps. *Global Change and Mountain Regions (A State of Knowledge Overview),* U.M. Huber, H. Bugmann, and M.A. Reasoner, Eds., Springer, New York, 235–242.

Mata, L.J, M. Campos, E. Basso, R. Compagnucci, P. Fearnside, G. Magri, J. Marengo, A.R. Moreno, A. Suaez, S. Solman, A. Villamizar and L. Villers, 2001: Latin America. *Climate Change 2001, Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change,* J. J McCarthy, O. Canziani, N.Leary, D. Dokken and K.White, Eds., Cambridge University Press, Cambridge, 691–734.

Maya, C., N. Beltran, B. Jiminez and P. Bonilla, 2003: Evaluation of the UV disinfection process in bacteria and amphizoic amoebeae inactivation. *Water Science and Technology*, **3**(4), 285–291.

Mazhitova, G., N. Karstkarel, N. Oberman, V. Romanovsky and P. Kuhty, 2004: Permafrost and infrastructure in the Usa Basin (Northern European Russia): possible impacts of global warming. *Ambio*, **3**, 289–294.

McBean, G. and Co-authors, 2005: Arctic Climate: past and present. *Arctic Climate Impacts Assessment (ACIA)*, C. Symon, L. Arris and B. Heal, Eds., Cambridge University Press, Cambridge, 21–60.

McCabe, G.J., M. Palecki and J.L. Betancourt, 2004: Pacific and Atlantic Ocean influences on multi-decadal drought frequency in the United States. *P. Natl. Acad. Sci. USA*, **101**, 4136–4141.

McClelland, J.W., R.M. Holmes and B.J. Peterson, 2004: Increasing river discharge in the Eurasian Arctic: consideration of dams, permafrost thaw, and fires as potential agents of change. *J. Geophys. Res.-Atmos.*, **109,** D18102, doi:10.1029/2004JD004583.

McKerchar, A.I. and R.D. Henderson, 2003: Shifts in flood and low-flow regimes in New Zealand due to inter-decadal climate variations. *Hydrol. Sci. J.*, **48**(4), 637–654.

McMichael, A. and Co-authors, Eds., 2003: *Climate Change and Human Health: Risks and Responses*. WHO, Geneva, 322 pp.

McPeak, J.G. and C.B. Barrett, 2001: Differential risk exposure and stochastic poverty traps among East African pastoralists. *Am. J. Agr. Econ.*, **83**, 674-679.

MDBC, 2006: *Basin Statistics*. Murray Darling Basin Commission. http://www.mdbc.gov.au/about/basin_statistics.

Meehl, G.A. and C. Tebaldi, 2004: More intense, more frequent, and longer lasting heat waves in the 21st century. *Science*, **305**, 994–997.

Meher-Homji, V.M., 1992: Probable impact of deforestation on hydrological process. *Tropical Forests and Climate,* N. Myers, Ed., Springer, Berlin, 163-174.

Melbourne Water, 2006: Eastern Treatment plant: treating sewage from Melbourne's south-eastern and eastern suburbs. http://www.melbournewater.com.au/content/sewerage/eastern_treatment_plant/eastern_treatment_plant.asp?bhcp=1.

Melnikov B.V. and A. L. Revson, 2003: Remote sensing of northern regions of West Siberia. *Cryosphere of Earth*, **4**, 37–48 (in Russian).

Mendelsohn, R., M. Morrison, M. Schlesinger and N. Andronova, 2000a: Country-specific market impacts from climate change, *Climatic Change,* **45**, 553–569.

Mendelsohn, R., A. Dinar and A. Dalfelt, 2000b: *Climate change impacts on African agriculture*. Paper prepared for the World Bank, Washington, DC, 25 pp

Menzel, A., G. Jakobi, R. Ahas, H. Scheifinger and N. Estrella, 2003: Variations of the climatological growing season (1951-2000) in Germany compared with other countries. *Int. J. Climatol.*, **23**, 793-812.

Menzel, L. and G. Bürger,, 2002: Climate change scenarios and runoff response in the Mulde catchment (Southern Elbe, Germany). *J. Hydrol.*, **267**(1–2), 53–64.

Mercier, F., A. Cazenave and C. Maheu, 2002: Interannual lake level fluctuations (1993–1999) in Africa from Topex/Poseidon: connections with ocean-atmosphere interactions over the Indian Ocean, *Global Planet. Change*, **32**, 141–163.

Metz, B., O. Davidson, H. de Coninck, M. Loos and L. Meyer, Eds., 2005: *Carbon Dioxide Capture and Storage*. Cambridge University Press, Cambridge, 431 pp.

Middelkoop, H. and J.C.J. Kwadijk, 2001: Towards an integrated assessment of the implications of global change for water management: the Rhine experience. *Phys Chem Earth, Part B Hydrology, Oceans and Atmosphere*, **26**(7–8), 553–560.

Middelkoop, H., K. Daamen, D. Gellens, W. Grabs, J.C.J. Kwadijk, H. Lang, B.W.A.H. Parmet, B. Schädler, J. Schulla and K. Wilke, 2001: Impact of climate change on hydrological regimes and water resources management in the Rhine basin. *Climatic Change*, **49**, 105–128.

Miettinen, I., O. Zacheus, C. von Bonsdorff and T. Vartiainen, 2001: Waterborne epidemics in Finland in 1998–1999. *Water Sci. Technol.*, **43**, 67–71.

Miles, E.L., A.K. Snover, A. Hamlet, B. Callahan and D. Fluharty, 2000: Pacific Northwest Regional Assessment: the impacts of climate variability and climate change on the water resources of the Columbia River Basin. *J. Amer. Water Resour. Assoc.*, **36**, 399-420.

Mileti, D., 1999: *Disasters by Design: A Reassessment of Natural Hazards in the United States*. National Academy Press, Washington, DC, 376 pp.

Millennium Ecosystem Assessment, 2005a: *Ecosystems and Human Well-being: Volume 2 – Scenarios*. Island Press, Washington, DC, 515 pp.

Millennium Ecosystem Assessment, 2005b: *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, DC, 155 pp.

Miller, K.A. and D. Yates, 2006: *Climate Change and Water Resources: A Primer for Municipal Water Providers*. AWWA Research Foundation, Denver, CO, 83 pp.

Miller, K.A., S.L. Rhodes and L.J.MacDonnell, 1997: Water allocation in a changing climate: institutions and adaptation. *Climatic Change*, **35**, 157–177.

Miller, M.G. and A. Veltman, 2004: Proposed Canterbury Natural Resources Plan for river and groundwater allocation policies and the implications for irrigation dependent farming in Canterbury. *Proc. New Zealand Grassland Association*, **66**, 11–23.

Mills, E., 2005: Insurance in a climate of change. *Science*, **309**, 1040–1044.

Mills, E. and E. Lecomte, 2006: *From Risk to Opportunity: How Insurers Can Proactively and Profitably Manage Climate Change*. Ceres, Boston, MA, 42 pp.

Mills, P.F., 1994: The agricultural potential of northwestern Canada and Alaska and the impact of climatic change. *Arctic*, **47**(2), 115–123.

Milly, P.C.D., R.T. Wetherald, K.A. Dunne and T.L. Delworth, 2002: Increasing risk of great floods in a changing climate. *Nature*, **415**, 514–517.

Milly, P.C.D., K.A. Dunne and A.V. Vecchia, 2005: Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, **438**(7066), 347–350.

Mimikou, M., E. Blatas, E. Varanaou and K. Pantazis, 2000: Regional impacts of climate change on water resources quantity and quality indicators. *J. Hydrol.*, **234**, 95-109.

Min, S.K., W.T. Kwon, E.H. Park and Y. Choi, 2003: Spatial and temporal comparisons of droughts over Korea with East Asia. *Int. J. Climatol.*, **23**, 223–233.

Ministry for the Environment, 2004: *Climate Effects and Impacts Assessment: a Guidance Manual for Local Government in New Zealand*. Prepared by David Wratt, Brett Mullan and Jim Salinger (NIWA), Sylvia Allen and Tania Morgan (MWH New Zealand Ltd.) and Gavun Kenny (Earthwise Consulting). Ministry for the Environment Report ME 513, Wellington, 153 pp.

Mirza, M.M.Q., 2002: Global warming and changes in the probability of occurrence of floods in Bangladesh and implications. *Global Environ. Chang.*, **12**, 127–138.

Mirza, M.M.Q., 2003: Three recent extreme floods in Bangladesh: a hydro-meteorological analysis. *Nat. Hazards*, **28**, 35–64.

Mirza, M.M.Q., 2004: *Climate Change and the Canadian Energy Sector: Report on Vulnerability and Adaptation*. Adaptation and Impacts Research Group, Atmospheric Climate Science Directorate, Meteorological Service of Canada Downsview, Ontario, 52 pp.

Mirza, M.M.Q., R.A. Warrick and N.J. Ericksen, 2003: The implications of climate change on floods of the Ganges, Brahmaputra and Meghna Rivers in Bangladesh. *Climatic Change*, **57**, 287–318.

Mitchell, T.D. and P.D. Jones, 2005: An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *Int. J. Climatol.*, **25**, 693–712.

Mitchell, W., J. Chittleborough, B. Ronai and G.W. Lennon, 2001: Sea level rise in Australia and the Pacific. *Proc. Science Component. Linking Science and Policy.* Pacific Islands Conference on Climate Change, Climate Variability and Sea Level Rise. 3-7 April 2000, Rarotonga, Cook Islands, National Tidal Facility, The Flinders University of South Australia, Adelaide, 47–58.

Moench, M., A. Dixit, S. Janakarajan, M.S. Rathore and S. Mudrakartha, 2003: *The Fluid Mosaic: Water Governance in the Context of Variability, Uncertainty and Change – A Synthesis Paper*. Nepal Water Conservation Foundation, Kathmandu, 71 pp.

Mohseni, O., H.G. Stefan and J.G. Eaton, 2003: Global warming and potential changes in fish habitat in U.S. streams. *Climatic Change*, **59**, 389-409.

Mölg, T., D.R. Hardy, N. Cullen and G. Kaser, 2005: Tropical glaciers in the context of climate change and society: focus on Kilimanjaro (East Africa). *Contribution to Mountain Glaciers and Society Workshop*. California University Press, Wengen, 28 pp.

Monson, R.K., D.L. Lipson, S.P. Burns, A.A. Turnipseed, A.C. Delany, M.W. Williams and S.K. Schmidt, 2006: Winter forest soil respiration controlled by climate and microbial community composition. *Nature*, **439**(7077), 711–714.

Monteny, G.-J., A. Bannink and D. Chadwick, 2006: Greenhouse gas abatement strategies for animal husbandry. *Agri. Ecosys. Environ.*, **112**, 163-170.

Mool, P.K., D. Wangda and S.R. Bajracharya, 2001: *Inventory of Glaciers, Glacial Lakes and Glacial Lake Outburst Floods: Monitoring and Early Warning Systems in the Hindu Kush-Himalayan Region: Bhutan*. ICIMOD, Kathmandu, 227 pp.

Moonen, A.C., L. Ercoli, M. Mariotti and A. Masoni, 2002: Climate change in Italy indicated by agrometeorological indices over 122 years. *Agr. Forest Meteorol.*, **111**, 13-27.

Mooney, H., A. Cropper and W. Reid, 2005: Confronting the human dilemma. *Nature*, **434**, 561-562.

Moore, M.V., M.L. Pace, J.R. Mather, P.S. Murdoch, R.W. Howarth, C.L. Folt, C.Y. Chen, H.F. Hemond, P.A. Flebbe and C.T. Driscoll, 1997: Potential effects of climate change on freshwater ecosystems of the New England/Mid-Atlantic region. *Hydrol. Process.*, **11**, 925–947.

Morris, J.D. and L.A.J. Thomson, 1983: The role of trees in dryland salinity control. *Proc. Roy. Soc. Victoria*, **95**, 123-131.

Morton, J., 2006: Pastoralist coping strategies and emergency livestock market intervention. *Livestock Marketing in Eastern Africa: Research and Policy Challenges,* J.G. McPeak and P.D. Little, Eds., ITDG Publications, Rugby, 227-246.

Mosier, A.R., A.D. Halvorson, G.A. Peterson, G.P. Robertson and L. Sherrod, 2005: Measurement of net global warming potential in three agroecosystems. *Nutrient Cycling in Agroecosystems,* **72**, 67-76.

Moss, B., D. Mckee, D. Atkinson, S.E. Collings, J.W. Eaton, A.B. Gill, I. Harvey, K. Hatton, T. Heyes and D. Wilson, 2003: How important is climate? Effects of warming, nutrient addition and fish on phytoplankton in shallow lake microcosms. *J. Appl. Ecol.*, **40**, 782–792.

Mote, P., A.F. Hamlet, M.P. Clark and D.P. Lettenmaier, 2005: Declining mountain snowpack in western North America. *Bull. Amer. Meteor. Soc.*, **86**, doi: 10.1175/BAMS-1186-1171-1139.

Mote, P.W., D.J. Canning, D.L. Fluharty, R.C. Francis, J.F. Franklin, A.F. Hamlet, M. Hershman, M. Holmberg, K.N. Gray-Ideker, W.S. Keeton, D.P. Lettenmaier, L.R. Leung, N.J. Mantua, E.L. Miles, B. Noble, H. Parandvash, D.W. Peterson, A.K. Snover and S.R. Willard, 1999: *Impacts of Climate Variability and Change, Pacific Northwest*, 110 pp. http://www.usgcrp.gov/usgcrp/Library/nationalassessment/pnw.pdf.

Mote, P.W., E.A. Parson, A.F. Hamlet, W.S. Keeton, D. Lettenmaier, N. Mantua, E.L. Miles, D.W. Peterson, D.L. Peterson, R. Slaughter and A.K. Snover, 2003: Preparing for climatic change: the water, salmon, and forests of the Pacific Northwest. *Climatic Change*, **61**, 45-88.

Moulton, R. and D. Cuthbert, 2000: Cumulative impacts/risk assessment of water removal or loss from the Great Lakes–St. Lawrence River system. *Can. Water Resour. J.*, **25**, 181-208.

Mountain Agenda, 1997: *Mountains of the World: Challenges of the 21st Century.* Mountain Agenda, Bern, 36 pp.

MRAE (Ministry of Rural Affairs and the Environment, Malta), 2004: *The First Communication of Malta to the United Nations Framework Convention on Climate Change*, Ministry for Rural Affairs and the Environment, Malta.

MRC, 2003: *State of the Basin Report: 2003*. Mekong River Commission, Phnom Penh, 300 pp.

Mueller, D.R., W.F. Vincent and M.O. Jeffries, 2003: Break-up of the largest Arctic ice shelf and associated loss of an epishelf lake. *Geophys. Res. Lett.*, **30**, 2031, doi:10.1029/2003GL017931.

Mullan, A.B., A. Porteous, D. Wratt and M. Hollis, 2005: *Changes in Drought Risk with Climate Change*. NIWA Report WLG2005. http://www.mfe.govt.nz/publications/climate/drought-risk-may05/drought-risk-climate-change-may05.pdf.

Munich Re, 2004: *Annual Review of Natural Catastrophes 2003*. Munich, 8 pp. http://www.munichre.com/app_resources/pdf/ts/geo_risks/topicsgeo_2003_siebert_en.pdf.

MWD, 2005: *The Family of Southern California Water Agencies. Metropolitan Water District of Southern California*. http://www.bewaterwise.com/index.html.

Myers, N., 1997: The world's forests and their ecosystem services. *Nature's Services: Societal Dependence on Natural Ecosystems*. G.C. Daily, Ed., Island Press, Washington, DC, 215-235.

Naess, L.O., G. Bang, S. Eriksen and J. Vevatne, 2005: Institutional adaptation to climate change: flood responses at the municipal level in Norway. *Global Environ. Chang.*, **15**, 125–138.

Nagy, G.J., R.M. Caffera, M. Aparicio, P. Barrenechea, M. Bidegain, J.C. Jiménez, E. Lentini, G. Magrin and Co-authors, 2006: *Understanding the Potential Impact of Climate Change and Variability in Latin America and the Caribbean*. Report prepared for the Stern Review on the Economics of Climate Change, 34 pp. http://www.sternreview.org.uk.

Nakićenović, N. and R. Swart, Eds., 2000: *Special Report on Emissions Scenarios*. Cambridge University Press, Cambridge, 599 pp.

Namjou, P. and Co-authors, 2006: The integrated catchment study of Auckland City (New Zealand): long-term groundwater behaviour and assessment. *Proc. World Environmental and Water Resources Congress 2006,* R. Graham, Ed., May 21-25, 2006, Omaha, Nebraska, doi:10.1061/40856(200)311.

NAST, 2000: *Climate Change Impacts in the United States, Overview.* Report for the U.S. Global Change Research Program. National Assessment Synthesis Team Members (NAST), 154 pp.

Natsagdorj, L., P. Gomboluudev and P. Batima, 2005: Climate change in Mongolia. *Climate Change and its Projections*, P. Batima and B.Myagmarjav, Eds., Admon Publishing, Ulaanbaatar, 39–84.

NC-Colombia, 2001: *1st National Communication to the UNFCCC*, 267 pp. http://unfccc.int/national_reports/non-annex_i_natcom/items/2979.php.

NC-Ecuador, 2000: *1st National Communication to the UNFCCC*, 128 pp. http://unfccc.int/national_reports/non-annex_i_natcom/items/2979.php.

NC-Nicaragua, 2001: *Impacto del Cambio Climático en Nicaragua*. Primera Comunicación Nacional sobre Cambio Climático, PNUD/MARENA, 127 pp.

NC-Perú, 2001: *1st National Communication to the UNFCCC*, 155 pp. http://unfccc.int/resource/docs/natc/pernc1.pdf.

Nchito, M., P. Kelly, S. Sianongo, N.P. Luo, R. Feldman, M. Farthing and K.S. Baboo, 1998: *Cryptosporidiosis* in urban Zambian children: an analysis of risk factors. *Am. J. Trop. Med. Hyg.*, **59**, 435–437.

Ndikumana, J., J. Stuth, R. Kamidi, S. Ossiya, R. Marambii and P. Hamlett, 2000: *Coping Mechanisms and their Efficacy in Disaster-prone Pastoral Systems of the Greater Horn of Africa: Effects of the 1995-97 Drought and the 1997-98 El Niño Rains and the Responses of Pastoralists and Livestock*. ILRI Project Report. A-AARNET (ASARECA-Animal Agriculture Research Network), Nairobi, Kenya, GL-CRSP LEWS (Global Livestock- Collaboratve Research Support Program Livestock Early Warning System), College Station, Texas, USA, and ILRI (International Livestock Research Institute), Nairobi, 124 pp.

NEAB (National Environment Advisory Board, St Vincent and the Grenadines), 2000: *Initial National Communication on Climate Change*, National Environment Advisory Board and Ministry of Health and the Environment, 74 pp.

Nearing, M.A., F.F. Pruski and M.R. O'Neal, 2004: Expected climate change impacts on soil erosion rates: a review. *J. Soil Water Conserv.*, **59**, 43-50.

NEB, 2006: *Canada's Oil Sands: Opportunities and Challenges to 2015: An Update*. National Energy Board, Calgary, Alberta, 85 pp.

Neff, R., H. Chang, C. Knight, R. Najjar, B. Yarnal and H. Walker, 2000: Impact of climate variation and change on Mid-Atlantic Region hydrology and water resources. *Climate Res.*, **14**, 207-218.

Nelson, F.E., 2003: (Un)frozen in time. *Science*, **299**, 1673–1675.

New, M., 2002: Climate change and water resources in the southwestern Cape, South Africa. *S. Afri. J. Sci.*, **96**, 369–373.

Nicholls, K.H., 1999: Effects of temperature and other factors on summer phosphorus in the inner Bay of Quinte, Lake Ontario: implications for climate warming. *J. Great Lakes Res.*, **25**(5), 250–262.

Nicholson, S., 2005: On the question of the "recovery" of the rains in the West African Sahel. *J. Arid Environ.*, **63**, 615–641.

Nicholson, S.E. and J.C. Selato, 2000: The influence of La Niña on African rainfall. *Int. J. Climatol.,* **20**, 1761–1776.

Nicholson, S.E., B. Some and B. Kone, 2000: An analysis of recent rainfall conditions in West Africa, including the rainy seasons of the 1997 El Niño and the 1998 La Niña years. *J. Clim.*, **13**, 2628–2640.

Nilsson, C., C.A. Reidy, M. Dynesius and C. Revenga, 2005: Fragmentation and flow regulation of the world's large river systems. *Science*, **308**, 405–408.

NLWRA, 2001: *Australian Water Resources Assessment 2000*. National Land and Water Resources Audit, Land and Water Australia.

NOAA, 2005: *Hazards/Climate Extremes*. National Climatic Data Center, U.S. Department of Commerce, http://www.ncdc.noaa.gov/oa/climate/research/2005/aug/hazards.html.Flooding.

Noone, D. and I. Simmonds, 2002: Annular variations in moisture transport mechanisms and the abundance of $\delta^{18}O$ in Antarctic snow. *J. Geophys. Res.*, **107**, 4742, doi:10.1029/2002JD002262.

Norrant, C. and A. Douguédroit, 2006: Monthly and daily precipitation trends in the Mediterranean. *Theor. Appl. Climatol.*, **83**, 89–106.

Nurse, L. and Co-authors, 2001: Small Island States. *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change,* J.J. McCarthy, O. F. Canziani, N.A. Leary, D.J. Dokken and K.S. White, Eds., Cambridge University Press, Cambridge, 843–876.

Nuttall, M., F. Berkes, B. Forbes, G. Kofinas, T. Vlassova and G. Wenzel, 2005: Hunting, herding, fishing and gathering: indigenous peoples and renewable resource use in the Arctic. *Arctic Climate Impacts Assessment, ACIA*, C. Symon, L. Arris and B. Heal, Eds., Cambridge University Press, Cambridge, 649–690.

O'Reilly, C., S. Alin, P. Plisnier, A. Cohen and B. McKee, 2003: Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. *Nature*, **424**, 766-768.

Oba, G., 2001: The importance of pastoralists' indigenous coping strategies for planning drought management in the arid zone of Kenya. *Nomadic Peoples*, **5**, 89-119.

OECD, 2003: *Development and climate change in Nepal: focus on water resources and hydropower*. COM/ENV/EPOC/DCD/DAC(2003)1/FINAL, Organisation for Economic Co-operation and Development, Paris, 64 pp.

Oenema, O., N. Wrage, G.L. Velthof, J.W. van Groenigen, J. Dolfing and P.J. Kuikman, 2005: Trends in global nitrous oxide emissions from animal production systems. *Nutrient Cycling in Agroecosystems,* **72**, 51-65.

Ogle, S.M., F.J. Breidt and K. Paustian, 2005: Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. *Biogeochem.,* **72,** 87-121.

Oki, T. and S. Kanae, 2006: Global hydrological cycles and world water resources. *Science*, **313**, 1068–1072.

Oki, T., Y. Agata, S. Kanae, T. Saruhashi and K. Musiake, 2003: Global water resources assessment under climatic change in 2050 using TRIP. *Water Resources: Systems Water Availability and Global Change,* S.W. Franks, G. Böschl, M. Kumagai, K. Musiake and D. Rosbjerg, Eds., IAHS Publication, 124–133.

Olesen, J.E. and M. Bindi, 2002: Consequences of climate change for European agricultural productivity, land use and policy. *European J. Agronomy*, **16**, 239–262.

Olesen, J.E., T.R. Carter, C.H. Díaz-Ambrona, S. Fronzek, T. Heidmann, T. Hickler, T. Holt, M.I. Minguez, P. Morales, J. Palutikov, M. Quemada, M. Ruiz-Ramos, G. Rubæk, F. Sau, B. Smith, B. and M. Sykes, 2006: Uncertainties in projected impacts of climate change on European agriculture and terrestrial ecosystems based on scenarios from regional climate models. *Climatic Change*, **81**(Suppl. 1), doi: 10.1007/s10584-006-9216-1.

Olsen, J.R., 2006: Climate change and floodplain management in the United States, *Climatic Change*, **76**, 407–426.

Oltchev, A., J. Cermak, J. Gurtz, A. Tishenko, G. Kiely, N. Nadezhdina, M. Zappa, N. Lebedeva, T. Vitvar, J.D. Albertson, F. Tatarinov, D. Tishenko, V. Nadezhdin, B. Kozlov, A. Ibrom, N. Vygodskaya and G. Gravenhorst 2002: The response of the water fluxes of the boreal forest region at the Volga source area to climatic and land-use changes. *Phys. Chem. Earth, Parts A/B/C*, **27**, 675–690.

Opopol, N., R. Corobov, A. Nicolenco and V. Pantya, 2003: Climate change and potential impacts of its extreme manifestations on health. *Curier Medical,* **5**, 6-9.

Orlove, B.S., J.C.H. Chiang and M.A. Cane, 2000: Forecasting Andean rainfall and crop yield from the influence of El Niño on Pleiades visibility. *Nature*, **403**, 68-71.

Osman-Elasha, B., N. Goutbi, E. Spanger-Siegfried, B. Dougherty, A. Hanafi, S. Zakieldeen, A. Sanjak, H.A. Atti and H.M. Elhassan, 2006: *Adaptation Strategies to Increase Human Resilience Against Climate Variability and Change: Lessons from the Arid Regions of Sudan*. AIACC Working Paper No. 42, Assessment of Impacts and Adaptation to Climate Change in Multiple Regions and Sectors Programme, 42 pp.

Osterkamp, T.E., L. Vierek, Y. Shur, M.T. Jorgenson, C. Racine, A. Doyle and R.D. Boone, 2000: Observations of thermokarst and its impact on boreal forests in Alaska, U.S.A. *Arct. Antarct. Alp. Res.*, **32**, 303–315.

Ouranos, 2004: *Adapting to Climate Change*. Ouranos, Montreal, ON, 91 pp. http://www.ouranos.ca/cc/climang5.pdf.

Paavola, J. and W. Adger, 2002: *Justice and Adaptation to Climate Change*. Tyndall Centre for Climate Change Research, Norwich, 24 pp. http://www.tyndall.ac.uk/publications/working_papers/wp23.pdf.

Pabón, J.D., 2003: El cambio climático global y su manifestación en Colombia. *Cuadernos Geograf.*, **12**, 111-119.

Pachauri, R., 2004: Climate change and its implications for development: the role of IPCC assessments. *Inst. Devel. Stud. Bull.*, **35**, 11.

PAGASA (Philippine Atmospheric, Geophysical and Astronomical Services Administration), 2001: *Documentation and Analysis of Impacts of and Responses to Extreme Climate Events*. Climatology and Agrometeorology Branch Technical Paper No. 2001-2, 55 pp.

PAHO, 2003: *Status Report on Malaria Programs in the Americas*. 44th Directing Council, 55th Session of the Regional Comité. Pan American Health Organization, Washington, DC.

Palmer, T.N. and J. Räisänen, 2002: Quantifying the risk of extreme seasonal precipitation events in a changing climate. *Nature*, **415**, 512–514.

Pan, X.L., W. Deng and D.Y. Zhang, 2003: Classification of hydrological landscapes of typical wetlands in northeast China and their vulnerability to climate change. *Res. Environ. Sci.*, **16**(1), 14–18.

Pan, Z.T.,M. Segal, R.W.Arritt and E.S. Takle, 2004: On the potential change in solar radiation over the US due to increases of atmospheric greenhouse gases. *Renew. Energ.*, **29**, 1923-1928.

Parkinson, A.J. and J.C. Butler, 2005: Potential impacts of climate change on infectious diseases in the Arctic. *Int. J. Circumpolar Health*, **64**, 478–486.

Parrotta, J.A., 2002: Restoration and management of degraded tropical forest landscapes. *Modern Trends in Applied Terrestrial Ecology,* R.S. Ambasht and N.K. Ambasht, Eds., Kluwer Academic/Plenum Press, New York, 135-148.

Parry, M., C.A. Rosenzweig, M. Iglesias, M. Livermore and G. Fisher, 2004: Effects of climate change on global food production under SRES emissions and socioeconomic scenarios. *Global Environ. Chang.,* **14**(1), 53–67.

Parry, M.L., Ed., 2000: *Assessment of potential effects and adaptations to climate change in Europe: The Europe Acacia Project*. Report of concerted action of the environment programme of the Research Directorate General of the Commission of the European Communities, Jackson Environmental Institute, University of East Anglia, Norwich, 320 pp.

Parson, E.A., P.W. Mote, A. Hamlet, N. Mantua, A. Snover, W. Keeton, E. Miles, D. Canning and K.G. Ideker, 2001: Potential consequences of climate variability and change for the Pacific Northwest. *Climate Change Impacts on the United States - The Potential Consequences of Climate Variability and Change-Foundation Report*, National Assessment Synthesis Team, Ed., Cambridge University Press, Cambridge, 247-280.

Parson, E.A., R.W. Corell, E.J. Barron, V. Burkett, A. Janetos, L. Joyce, T.R. Karl, M. MacCracken, J. Melillo, M.G. Morgan, D.S. Schimel and T. Wilbanks, 2003: Understanding climatic impacts, vulnerabilities and adaptation in the United States: building a capacity for assessment. *Climatic Change*, **57**, 9-42.

Pascual, M., J.A. Ahumada, L.F. Chaves, X. Rodo and M. Bouma, 2006: Malaria resurgence in the East African highlands: temperature trends revisited. *P. Natl. Acad. Sci. USA*, **103**, 5829-5834.

Pattanayak, S. and R. Kramer, 2000: Worth of watersheds: a producer surplus approach for valuing drought control in eastern Indonesia. *Environment and Development Economics,* **6**, 123-146.

Patz, J.A., 2002: A human disease indicator for the effects of recent global climate change. *P. Natl. Acad. Sci. USA*, **99**, 12506-12508.

Patz, J.A., D. Campbell-Lendrum, T. Holloway and J.A.N. Foley, 2005: Impact of regional climate change on human health. *Nature*, **438**, 310-317.

Paustian, K., B.A. Babcock, J. Hatfield, R. Lal, B.A. McCarl, S. McLaughlin, A. Mosier, C. Rice, G.P. Robertson, N.J. Rosenberg, C. Rosenzweig, W.H. Schlesinger and D. Zilberman, 2004: *Agricultural Mitigation of Greenhouse Gases: Science and Policy Options*. CAST (Council on Agricultural Science and Technology) Report, R141 2004, Ames, Iowa, 120 pp.

Payne, J.T., A.W. Wood, A.F. Hamlet, R.N. Palmer and D.P. Lettenmaier, 2004: Mitigating the effects of climate change on the water resources of the Columbia River basin. *Climatic Change*, **62**(1–3), 233–256.

Penalba, O.C. and W.M. Vargas, 2004: Interdecadal and interannual variations of annual and extreme precipitation over central-northeastern Argentina. *Int. J. Climatol.*, **24**, 1565-1580.

Peters, D.L., T.D. Prowse, A. Pietroniro and R. Leconte, 2006: Establishing the flood hydrology of the Peace–Athabasca Delta, northern Canada. *Hydrol. Process.*, **20**, 4073-4096.

Petersen, T.C., M.A. Taylor, R. Demeritte, D.L. Duncombe, S. Burton, F. Thompson, A. Porter, M. Mercedes, E. Villegas, R. Semexant Fils, A. Klein Tank, A. Martis, R. Warner, A. Joyette, W. Mills, L. Alexander and B. Gleason, 2002: Recent changes in climate extremes in the Caribbean region. *J. Geophys. Res.*, **107 D21**, 4601, doi:10.1029/2002JD002251.

Peterson, A.T. and J. Shaw, 2003: *Lutzomyia* vectors for cutaneous leishmaniasis in southern Brazil: ecological niche models, predicted geographic distributions, and climate change effects. *Int. J. Parasitol.*, **33**, 919-931.

Peterson, A.T., C. Martínez-Campos, Y. Nakazawa and E. Martínez-Meyer, 2005: Time-specific ecological niche modeling predicts spatial dynamics of vector insects and human dengue cases. *T. Roy. Soc. Trop. Med. H.*, **99**, 647-655.

Peterson, B.J., R.M. Holmes, J.W. McClelland, C.J. Vorosmarty, R.B. Lammers, A.I. Shiklomanov, I.A. Shiklomanov and S. Rahmstorf, 2002: Increasing river discharge to the Arctic Ocean. *Science*, **298**, 2172–2173.

Peterson, T.C. and R.S. Vose, 1997: An overview of the Global Historical Climatology Network temperature database. *Bull. Am. Meteorol. Soc.*, **78**, 2837–2848.

Peterson, T.C., V.S. Golubev and P.Y. Groisman, 1995: Evaporation losing its strength. *Nature*, **377**, 687–688.

Petheram, C., G. Walker, R. Grayson, T. Thierfelder and L. Zhang, 2001: Towards a framework for predicting impacts of land-use on recharge. *Aust. J. Soil Res.*, **40**, 397-417.

Pielke, R.A., Jr and M.W. Downton, 2000: Precipitation and damaging floods: trends in the United States, 1932–97. *J. Climate*, **13**, 3625-3637.

Pienitz, R., M.S.V. Douglas and J.P. Smol, 2004: *Long-term Environmental Change in Arctic and Antarctic Lakes*. Springer Verlag, Berlin, 562 pp.

Pilon-Smits, E.A.H., M.J. Ebskamp, M. Ebskamp, M. Paul, M. Jeuken, P. Weisbeek and S. Smeekens, 1995: Improved performance of transgenic fructan-accumulating tobacco under drought stress. *Plant Physiol.*, **107**, 125-130.

Pittock, B., 2003: *Climate Change: An Australian Guide to the Science and Potential Impacts*. Australian Greenhouse Office, Canberra, 239 pp.

Polemio, M. and D. Casarano, 2004: *Rainfall and Drought in Southern Italy (1821–2001)*. UNESCO/IAHS/IWHA, Pub. 286.

Polsky, C. and W.E. Easterling, 2001: Adaptation to climate variability and change in the US Great Plains: a multi-scale analysis of Ricardian climate sensitivities. *Agr. Ecosyst. Environ.*, **85**, 133-144.

Porter, J.R. and M.A. Semenov, 2005: Crop responses to climatic variation. *Philos. Trans. R. Soc. B: Biological Sciences*, **360**, 2021–2035.

Pounds, J.A. and R. Puschendorf, 2004: Ecology: clouded futures. *Nature*, **427**, 107–109.

Pounds, J. A., M. R. Bustamante, L.A. Coloma, J.A. Consuegra, M.P.L. Fogden, P.N. Foster, E. La Marca, K.L. Masters, A. Merino-Viteri, R. Puschendorf, S.R. Ron, G.A. Sanchez-Azofeifa, C.J. Still and B. E. Young, 2006: Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature*, **439**(7073), 161–167.

Premier of Victoria, 2006: Ballarat's future water supplies secured by major Bracks government action plan. Media release, 17 October 2006. http://www.premier.vic.gov.au/newsroom/news_item.asp?id=978.

Protopapas, L., S. Katchamart and A. Platonova, 2000: Weather effects on daily water use in New York City. *J. Hydrol. Eng.*, **5**, 332–338.

Prowse, T.D. and S. Beltaos, 2002: Climatic control of river-ice hydrology: a review. *Hydrol. Process.*, **16**, 805-822.

Prowse, T.D., F.J. Wrona and G. Power, 2004: *Threats to Water Availability in Canada*. Environment Canada, NWRI Scientific Assessment Report No. 3, 9–18.

Prowse, T.D. and Co-authors, 2006: Historical changes in Arctic freshwater ecosystems. *Ambio*, **35**(7), 339–346.

Prudhomme, C. and H. Davies, 2006: Comparison of different sources of uncertainty in climate change impact studies in Great Britain. Hydrological Processes: Special Issue of International Workshop "Climatic and Anthropogenic Impacts on Water Resources Variability". *Technical Document in Hydrology No.* **80** / *Document technique en hydrologie No.* **80**, UNESCO, Paris / UMR 5569, HydroSciences Montpellier, 2007, 183-190. http://unesdoc.unesco.org/images/0015/001502/150251M.pdf.

Prudhomme, C., D. Jakob and C. Svensson, 2003: Uncertainty and climate change impact on the flood regime of small UK catchments. *J. Hydrol.*, **277**, 1–23.

Psenner, R. and R. Schmidt, 1992: Climate-driven pH control of remote Alpine lakes and effects of acid deposition. *Nature*, **356**, 781-783.

Pulwarty, R., K. Jacobs and R. Dole, 2005: The hardest working river: drought and critical water problems on the Colorado. *Drought and Water Crises: Science, Technology and Management,* D. Wilhite Ed., Taylor and Francis Press, Boca Raton, FL, 249-285.

Pulwarty, R.S. and T.S. Melis, 2001: Climate extremes and adaptive management on the Colorado River: lessons from the 1997–1998 ENSO event. *J. Environ. Manage.*, **63**, 307-324.

Qian, T. and Co-authors, 2006a: Simulation of global land surface conditions from 1948–2004. Part I: Forcing data and evaluations. *J. Hydrometeorol.*, **7**, 953–975.

Qian, Y. and Co-authors, 2006b: More frequent cloud-free sky and less surface solar radiation in China from 1955 to 2000. *Geophys. Res. Lett.*, **33**, L01812, doi:10.1029/2005GL024586.

Qin, D.H., 2002: *Assessment of Environment Change in Western China, 2nd Volume, Prediction of Environment Change in Western China*. Science Press, Beijing, 64, 73, 115, 132, 145-154, 160-161.

Quadrelli, R. and J.M. Wallace, 2004: A simplified linear framework for interpreting patterns of Northern Hemisphere wintertime climate variability. *J. Climate*, **17**, 3728–3744.

Quayle, W.C., L.S. Peck, H. Pet, J.C. Ellis-Evans and P.R. Harrigan, 2002: Extreme responses to climate change in Antarctic lakes. *Science*, **295**(5555), 645–645.

Quayle, W.C., P. Convey, L.S. Peck, J.C. Ellis-Evans, H.G. Butler and H.J. Peat, 2003: Ecological responses of maritime Antarctic lakes to regional climate change. *Antarctic Peninsula Climate Variability: Historical and Palaeoenvironmental Perspectives*. E. Domack, A. Leventer, A. Burnett, R. Bindschadler, P. Convey and M. Kirby, Eds., American Geophysical Union, Washington, DC, 159–170.

Queensland Government, 2005: *Queensland Water Plan 2005-2010*. Queensland Government, 27 pp. http://www.nrw.qld.gov.au/water/pdf/qld_water_plan_05_10.pdf.

Ragab, R. and C. Prudhomme, 2002: Climate change and water resources management in arid and semi-arid regions: prospective and challenges for the 21st century. *Biosys. Engineering*, **81**, 3–34.

Räisänen, J., Hansson, U., Ullerstieg, A., Döscher, R., Graham, L.P., Jones, C., Meier, H.E.M., Samuelson, P. and Willén, U., 2004: European climate in the late twenty-first century: regional simulations with two driving global models and two forcing scenarios. *Clim. Dyn.*, **22**, 13–31.

Ramírez, E., B. Francou, P. Ribstein, M. Descloitres, R. Guérin, J. Mendoza, R.Gallaire, B. Pouyaud and E. Jordan, 2001: Small glaciers disappearing in the tropicalAndes: a case study in Bolivia: the Chacaltaya glacier, 16°S. *J. Glaciol.*, **47**, 187–194.

Rawlins, S. C., A. Chen, M. Ivey, D. Amarakoon and K. Polson, 2005: The impact of climate change/variability events on the occurrence of dengue fever in parts of the Caribbean: a retrospective study for the period 1980-2002. *West Indian Med. J. Suppl.*, **53**(2), 54.

Reay, D.S., K.A. Smith and A.C. Edwards, 2003: Nitrous oxide emission from agricultural drainage waters. *Global Chang. Biol.,* **9**, 195-203.

Reilly, J. and Co-authors, 2003: U.S. agriculture and climate change: new results. *Climatic Change*, **57**, 43–69.

Reilly, J.M., Ed., 2002: *Agriculture: The Potential Consequences of Climate Variability and Change*. Cambridge University Press, Cambridge, 136 pp.

Reist, J.D. and Co-authors, 2006a: General effects of climate change on arctic fishes and fish populations. *Ambio*, **35**(7), 370–380.

Reist, J.D. and Co-authors, 2006b: An overview of effects of climate change on selected arctic freshwater and anadromous fishes. *Ambio,* **35**(7), 381–387.

Reist, J.D. and Co-authors, 2006c: Effects of climate change and UV radiation on fisheries for arctic freshwater and anadromous species. *Ambio*, **35**(7), 402–410.

Republic of Vanuatu, 1999: *Vanuatu National Communication to the Conference of the Parties to the United Nations Framework Convention on Climate Change*, 55 pp.

Resck, D.V.S., C.A. Vasconcellos, L. Vilela and M.C.M Macedo, 2000: Impact of conversion of Brazilian cerrados to cropland and pastureland on soil carbon pool and dynamics. *Global Climate Change and Tropical Ecosystems,* R. Lal, J.M. Kimble and B.A. Stewart, Eds., CRC-Lewis Publishers, Boca Raton, FL, 169-195.

Reynard, N., S. Crooks, R. Wilby and A. Kay, 2004: Climate Change and Flood Frequency in the UK. *Proc. 39th DEFRA Flood and Coastal Management Conference*, York. Defra, London, 11.1.1-11.1.12.

Richardson, D., 2002: Flood risk: the impact of climate change. *Proc. Inst. Civil Engineers-Civil Engineering*, **150**, 22–24.

Riebsame, W.E., K.M. Strzepek, J.L. Wescoat, Jr, R. Perrit, G.L. Graile, J. Jacobs, R. Leichenko, C. Magadza, H. Phien, B.J. Urbiztondo, P. Restrepo, W.R. Rose, M. Saleh, L.H. Ti, C. Tucci and D. Yates, 1995: Complex river basins. *As Climate Changes: International Impacts and Implications,* K.M. Strzepek and J.B. Smith, Eds., Cambridge University Press, Cambridge, 57–91.

Rivera, A., G. Casassa, R. Thomas, E. Rignot, R. Zamora, D. Antúnez, C. Acuña and F. Ordenes, 2005: Glacier wastage on Southern Adelaide Island and its impact on snow runway operations. *Ann. Glaciol.*, **41**, 57-62.

Robeson, S.M., 2002: Increasing growing-season length in Illinois during the 20th century. *Climatic Change*, **52**, 219-238.

Robock, A. and Co-authors, 2000: The global soil moisture data bank. *Bull. Amer. Meteor. Soc.*, **81**, 1281–1299.

Robock, A. and Co-authors, 2005: Forty five years of observed soil moisture in Ukraine: no summer desiccation (yet). *Geophys. Res. Lett.*, **32**, L03401, doi:10.0129/2004GL021914.

Rockstrom, J., 2003: Water for food and nature in drought-prone tropics: vapour shift in rain-fed agriculture. *Philos. Trans. Roy. Soc. London - Series B*, **358**, 1997–2009.

Roderick, M.L. and G.D. Farquhar, 2004: Changes in Australian pan evaporation from 1970 to 2002. *Int. J. Climatol.*, **24**, 1077-1090.

Roderick, M.L. and G.D. Farquhar, 2005: Changes in New Zealand pan evaporation since the 1970s. *Int. J. Climatol.*, **25**, 2031-2039.

Rogora, M., R. Mosello and S. Arisci, 2003: The effect of climate warming on the hydrochemistry of Alpine lakes. *Water Air Soil Pollut.*, **148**, 347-361.

Ronchail, J., L. Bourrel, G. Cochonneau, P. Vauchel, L. Phillips, A. Castro, J.L. Guyot and E. Oliveira, 2005: Inundations in the Mamoré Basin (south-western Amazon-Bolivia) and sea-surface temperature in the Pacific and Atlantic Oceans. *J. Hydrol.*, **302**, 223-238.

Root, T.L. and S.H. Schneider, 2002: Climate change: overview and implications for wildlife. *Wildlife Responses to Climate Change: North American Case Studies*, S.H. Schneider and T.L. Root, Eds., Island Press, Washington, DC, 1–56.

Root, T.L., J.T. Price, K.R. Hall, S.H. Schneider, C. Rosenzweig and J.A. Pounds, 2003: Fingerprints of global warming on wild animals and plants. *Nature*, **421**(6918), 57–60.

Rosenberg, N.J., D.J. Epstein, D. Wang, L. Vail, R. Srinivasan and J.G. Arnold, 1999: Possible impacts of global warming on the hydrology of the Ogallala aquifer region. *Climatic Change*, **42**, 677-692.

Rosenberg, N.J., R.A. Brown, C. Izaurralde and A.M. Thomson, 2003: Integrated assessment of Hadley Centre HadCM2 climate change projections on agricultural productivity and irrigation water supply in the conterminous United States. I. Climate change scenarios and impacts on irrigation water supply simulated with the HUMUS model. *Agri. Forest Meteorol.*, **117**(1–2), 73–96.

Rosenzweig, C. and F.N. Tubiello, 2007: Adaptation and mitigation strategies in agriculture: an analysis of potential synergies. *Mitigation and Adaptation Strategies for Global Change*, **12**, 855-873.

Rosenzweig, C., F.N. Tubiello, R. Goldberg, E. Mills and J. Bloomfield, 2002: Increased crop damage in the US from excess precipitation under climate change. *Global Environ. Chang.*, **12**, 197–202.

Ross, M.S., J.F. Meeder, J.P. Sah, P.L. Ruiz and G.J. Telesnicki, 2000: The southeast saline Everglades revisited: 50 years of coastal vegetation change. *J. Vegetation Sci.,* **11**, 101–112.

Rowell, A. and P.F. Moore, 2000: *Global Review of Forest Fires*. WWF/IUCN, Gland, 66 pp. http://www.iucn.org/themes/fcp/publications/files/global_review_forest_fires.pdf.

Ruhland, K.M., A. Priesnitz and J.P. Smol, 2003: Paleolimnological evidence from diatoms for recent environmental changes in 50 lakes across Canadian Arctic treeline. *Arct. Antarct. Alp. Res.*, **35**, 110–123.

Ruosteenoja, K., T.R. Carter, K. Jylhä, and H. Tuomenvirta, 2003: *Future Climate in World Regions: An Intercomparison of Model-Based Projections for the New IPCC Emissions Scenarios*. The Finnish Environment **644**, Finnish Environment Institute, Helsinki, 83 pp.

Ruth, M., B. Davidsdottir and A. Amato, 2004: Climate change policies and capital vintage effects: the case of U.S. pulp and paper, iron and steel, and ethylene, *J. Environ. Manage.*, **70**, 235–252.

Saintilan, N. and R.J. Williams 1999: Mangrove transgression into saltmarsh environments in south east Australia. *Global Ecol. Biogeogr.*, **8**(2), 117–124.

Sala, O.A., F.S. Chapin III, J.J. Armesto, E. Berlow, J. Bloomfield, R. Dirzo, E. Huber-Sanwald, L.F. Huenneke, R.B. Jackson, A. Kinzig, R. Leemans, D.M. Lodge, H.A. Mooney, M. Oesterheld, N.L. Poff, M.T. Sykes, B.H. Walker, M. Walker and D.H. Wall, 2000: Global biodiversity scenarios for the year 2100. *Science*, **287**, 1770-1774.

Salewicz, A., 1995: Impact of climate change on the operation of Lake Kariba hydropower scheme on the Zambezi River. *Water Resources Management in the Face of Climatic and Hydrologic Uncertainties,* Z. Kaczmarek, Ed., Kluwer Academic Publishers, Dordrecht, 395 pp.

Salinger, M. J., 2001: Climate variation in New Zealand and the Southwest Pacific. *The Physical Environment. A New Zealand Perspective*, A. Sturman and R. Spronken-Smith, Eds., Oxford University Press, Victoria, 35 pp.

Sanders, C. and M. Phillipson, 2003: UK adaptation strategy and technical measures: the impacts of climate change on buildings. *Build. Res. Inf.*, **31**(3–4), 210–221

Sand-Jensen, K. and N.L. Pedersen, 2005: Broad-scale differences in temperature, organic carbon and oxygen consumption among lowland streams. *Freshw. Biol.*, **50**, 1927–1937.

Sankaran, M., N.P. Hanan, R.J. Scholes, J. Ratnam, D.J. Augustine, B.S. Cade, J. Gignoux, S.I. Higgins, X. le Roux, F. Ludwig, J. Ardo, F. Banyikwa, A. Bronn, G. Bucini, K.K. Caylor, M.B. Coughenour, A. Diouf, W. Ekaya, C.J. Feral, E.C. February, P.G.H. Frost, P. Hiernaux, H. Hrabar, K.L. Metzger, H.H.T. Prins, S. Ringrose, W. Sea, J. Tews, J. Worden and N. Zambatis, 2005: Determinants of woody cover in African savannas. *Nature*, **438**, 846-849.

Santos**,** F.D., K. Forbes and R. Moita, Eds., 2002: *Climate Change in Portugal: Scenarios, Impacts and Adaptation Measures*. SIAM Project Report, Gradiva, Lisbon, 456 pp.

Sanz, J.J., T.J. Potti, J. Moreno, S. Merion and O. Frias, 2003: Climate change and fitness components of a migratory bird breeding in the Mediterranean region, *Global Change Biol.*, **9**, 461–472.

Scaife, A., J. Knight, G. Vallis and C.K. Folland, 2005: A stratospheric influence on the winter NAO and North Atlantic surface climate. *Geophys. Res. Lett.*, **32**, L18715, doi: 10.1029/2005GL023226.

Scavia, D., J.C. Field, D.F. Boesch, R. Buddemeier, D.R. Cayan, V. Burkett, M. Fogarty, M. Harwell, R. Howarth, C. Mason, D.J. Reed, T.C. Royer, A.H. Sallenger and J.G. Titus, 2002: Climate change impacts on U.S. coastal and marine ecosystems. *Estuaries*, **25**, 149–164.

Schallenberg, M., C.J. Hall and C.W. Burns, 2003: Consequences of climate-induced salinity increases on zooplankton abundance and diversity in coastal lakes. *Marine Ecol. Prog. Ser.*, **251**, 181–189.

Schär, C., P.L. Vidale, D. Luthi, C. Frei, C. Haberli, M.A. Liniger and C. Appenzeller, 2004: The role of increasing temperature variability in European summer heatwaves. *Nature*, **427**(6972), 332–336.

Scheffer, M., S. Carpenter, J.A. Foley, C. Folke and B. Walker, 2001: Catastrophic shifts in ecosystems. *Nature*, **413**, 591-596.

Schiermeier, Q., 2006: Insurers' disaster files suggest climate is culprit. *Nature*, **441**(7094), 674–675.

Schijven, J.F. and A.M. de Roda Husman, 2005: Effect of climate changes on waterborne disease in the Netherlands. *Water Sci. Technol.*, **51**, 79-87.

Schlenker, W., W.M. Hanemann and A.C. Fisher, 2005: Will U.S. agriculture really benefit from global warming? Accounting for irrigation in the hedonic approach. *American Economic Review*, **95**, 395–406.

Schlesinger, M.E. and N. Ramankutty, 1994: An oscillation in the global climate system of period 65–70 years. *Nature*, **367**, 723–726.

Schlesinger, W.H., 1999: Carbon sequestration in soils. *Science,* **284**, 2095.

Schneeberger, C., H. Blatter, A. Abe-Ouchi and M. Wild, 2003: Modelling changes in the mass balance of glaciers of the northern hemisphere for a transient 2× CO_2 scenario. *J. Hydrol.*, **282**(1–4), 145–163.

Schofield, N.J., 1992: Tree planting for dryland salinity control in Australia. *Agroforestry Sys.,* **20**, 1-23.

Schreider, S.Y., D.I. Smith and A.J. Jakeman, 2000: Climate change impacts on urban flooding. *Climatic Change*, **47**(1–2), 91–115.

Schröter D., W. Cramer, R. Leemans, I.C. Prentice, M.B. Araújo, N.W. Arnell, A. Bondeau, H. Bugmann, T.R. Carter, C.A. Gracia, A.C. de la Vega-Leinert, M. Erhard, F. Ewert, M. Glendining, J.I. House, S. Kankaanpää, R.J.T. Klein, S. Lavorell, M. Linder, M.J. Metzger, J. Meyer, T.D. Mitchell, I. Reginster, M. Rounsevell, S. Sabaté, S. Sitch, B. Smith, J. Smith, P. Smith, M.T. Sykes, K. Thonicke, W. Thuiller, G. Tuck, S. Zaehle and B. Zierl, 2005. Ecosystem service supply and vulnerability to global change in Europe. *Science*, **310**, 1333–1337.

Schulze, E.-D., 1982: Plant life forms and their carbon, water and nutrient relations. *Physiology and Plant Ecology II. Water Relations and Carbon Assimilation,* O.L. Lange, C.B. Osmond and H. Ziegler, Eds., Springer-Verlag, Berlin, 615-676.

Schuster, C.J., A. Ellis, W.J. Robertson, J.J. Aramini, D.F. Charron and B. Marshall, 2005: Drinking water related infectious disease outbreaks in Canada, 1974-2001. *Can. J. Public Health*, **94**, 254-258.

Scott, D., 2005: Ski industry adaptation to climate change: hard, soft and policy strategies. *Tourism and Global Environmental Change*, S. Gossling and M. Hall, Eds. Routledge, Oxford. 265–285.

Scott, D. and B. Jones, 2006: *Climate Change and Seasonality in Canadian Outdoor Recreation and Tourism,* Climate Change Action Fund, University of Waterloo, Faculty of Environmental Studies, Waterloo, ON, 33 pp.

Scudder, T., 2005: *The Future of Large Dams*. Earthscan, London, 408 pp.

Semenov, S.M., V.V. Yasukevich and E.S. Gel'ver, 2006: *Identification of Climatogenic Changes*. Publishing Centre, Meteorology and Hydrology, Moscow, 325 pp.

Senate of Canada, 2003: *Climate change: We are at Risk*. Final Report, Standing Senate Committee on Agriculture and Forestry, Ottawa.

Senhorst, H.A. and J.J. Zwolsman, 2005: Climate change and effects on water quality: a first impression. *Water Sci. Technol.*, **51**, 53–59.

Seo, S. N. and R. Mendelsohn, 2006: Climate change impacts on animal husbandry in Africa: a Ricardian analysis. *CEEPA Discussion Paper No.***9**. Special Series on Climate Change and Agriculture in Africa. The Centre for Environmental Economics and Policy in Africa, University of Pretoria, Pretoria, 42 pp.

Serreze, M.C. and Co-authors, 2003: Large-scale hydro-climatology of the terrestrial Arctic drainage system. *J. Geophys. Res.*, **108**(D2), 8160.

Shabbar, A. and W. Skinner, 2004: Summer drought patterns in Canada and the relationship to global sea surface temperatures. *J. Clim.*, **17**, 2866–2880.

Shanks, G.D., S.I. Hay, D.I. Stern, K. Biomndo and R.W. Snow, 2002: Meteorologic influences on *Plasmodium falciparum* malaria in the highland tea estates of Kericho, western Kenya. *Emerg. Infect. Dis.*, **8**, 1404-1408.

Shen, X.T., Z.C. Mao and J.R. Zhu, 2003: *Saltwater Intrusion in the Changjiang Estuary*. China Ocean Press, Beijing, 175 pp (in Chinese).

Sherbinin, A., A. Schiller and A. Pulsipher, 2007: The vulnerability of global cities to climate hazards. *Environ. Urbaniz.*, **12**(2), 93–102.

Shiklomanov, I.A., Shiklomanov, A.I., Lammers, R.B., Peterson, B.J. and Vorosmarty, C.J., 2000: The dynamics of river water inflow to the Arctic Ocean. *The Freshwater Budget of the Arctic Ocean*, E.L. Lewis, E.P. Jones, T.D. Prowse and P. Wadhams, Eds., Kluwer Academic Publishers, Dordrecht, 281–296.

Shrestha, A.B., C.P. Wake, J.E. Dibb and P.A. Mayewski, 2000: Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large-scale climatological parameters. *Int. J. Climatol.*, **20**, 317–327.

Shrestha, M.L. and A.B. Shrestha, 2004: *Recent Trends and Potential Climate Change Impacts on Glacier Retreat/Glacier Lakes in Nepal and Potential Adaptation Measures*. ENV/EPOC/GF/SD/RD(2004)6/FINAL, OECD, Paris, 23 pp.

Shukla, P.R., M. Kapshe and A. Garg, 2005: Development and climate: impacts and adaptation for infrastructure assets in India. *Proc. OECD Global Forum on Sustainable Development: Development and Climate Change*, Organisation for Economic Co-operation and Development, Paris, 38 pp.

Silander, J., B. Vehviläinen, J. Niemi, A. Arosilta, T. Dubrovin, J. Jormola, V. Keskisarja, A. Keto, A. Lepistö, R. Mäkinen, M. Ollila, H. Pajula, H. Pitkänen, I. Sammalkorpi, M. Suomalainen and N. Veijalainen, 2006: *Climate Change Adaptation for Hydrology and Water Resources*. FINADAPT Working Paper 6, Finnish Environment Institute Mimeographs 336, Helsinki, 54 pp.

Silvestri, G.E. and C.S. Vera, 2003: Antarctic Oscillation signal on precipitation anomalies over southeastern South America. *Geophys. Res. Lett.*, **30**, 2115, doi:10.1029/2003GL018277.

Simonovic, S.P. and L.H. Li, 2003: Methodology for assessment of climate change impacts on large-scale flood protection system. *J. Water Res. Pl.-ASCE*, **129**(5), 361–371.

Sims, R.E.H., A. Hastings, B. Schlamadinger, G. Taylor and P. Smith, 2006: Energy crops: current status and future prospects. *Global Change Biol.*, **12**, 1-23.

Sinclair, M.R., J.A. Renwick and J.W. Kidson, 1997: Low-frequency variability of Southern Hemisphere sea level pressure and weather system activity. *Mon. Weather Rev.*, **125**, 2531–2543.

Sinclair, T.R. and L.C. Purcell, 2005: Is a physiological perspective relevant in a 'genocentric' age? *J. Exp. Bot.*, **56**, 2777-2782.

Singh, R.B.K., S. Hales, N. de Wet, R. Raj, M. Hearnden and P. Weinstein, 2001: The influence of climate variation and change on diarrhoeal disease in the Pacific Islands. *Environ. Health Persp.*, **109**, 155–1594.

Small, C. and R.J. Nicholls, 2003: A global analysis of human settlement in coastal zones. *J. Coastal Res.*, **19**, 584–599.

Smeets, E.M.W., A.P.C. Faaij, I.M. Lewandowski and W.C. Turkenburg, 2007: A bottom up quickscan and review of global bio-energy potentials to 2050. *Prog. Energy Comb. Sci.*, **33**, 56-106.

Smit, B. and E. Wall, 2003: *Adaptation to Climate Change Challenges and Opportunities: Implications and Recommendations for the Canadian Agri-Food Sector,* Senate Standing Committee on Forestry and Agriculture, Ottawa, Canada. http://www.parl.gc.ca/37/2/parlbus/commbus/senate/Com-e/agri-e/power-e/smith-e.htm.

Smith, K.A. and F. Conen, 2004: Impacts of land management on fluxes of trace greenhouse gases. *Soil Use Manage.,* **20**, 255-263.

Smith, L.C., Y. Sheng, G.M. MacDonald and L.D. Hinzman, 2005: Disappearing Arctic lakes. *Science*, **308**, 1429.

Smith, S.D., T.E. Huxman, S.F. Zitzer, T.N. Charlet, D.C. Housman, J.S. Coleman, L.K. Fenstermaker, J.R. Seemann and R.S. Nowak, 2000: Elevated CO_2 increases productivity and invasive species success in an arid ecosystem. *Nature*, **408**, 79 - 82.

Smith, V.R., 2002: Climate change in the sub-Antarctic: an illustration from Marion Island. *Climatic Change,* **52**(3), 345–357.

Smol, J.P. and Co-authors, 2005: Climate driven regime shifts in the biological communities of arctic lakes. *P. Natl. Acad. Sci. USA*, **102**(12), 4397–4402.

SOE, 2001: *Australia State of the Environment 2001*, Independent Report to the Commonwealth Minister for the Environment and Heritage. Australian State of the Environment Committee, CSIRO Publishing on behalf of the Department of the Environment and Heritage, 129 pp. http:/www.ea.gov.au/soe/2001.

Solanes, M. and A. Jouravlev, 2006: *Water Governance for Development and Sustainability*. Economic Commission for Latin America and the Caribbean, Santiago, 84 pp.

Somlyódy, L., 2002: *Strategic Issues of the Hungarian Water Resources Management*. Academy of Science of Hungary, Budapest, 402 pp (in Hungarian).

Sommaruga-Wograth, S., K.A. Koinig, R. Schmidt, R. Sommaruga, R. Tessadri and R. Psenner, 1997: Temperature effects on the acidity of remote alpine lakes. *Nature*, **387**, 64-67.

Sorensen, I., P. Stone and B. Rogers, 2000: Effect of time of sowing on yield of a short and a long-season maize hybrid. *Agronomy New Zealand*, **30**, 63–66.

SRA, 2005: Sequía en el Chaco genera fuerte pérdidas. Comunicado de prensa de la Sociedad Rural Argentina. http://www.ruralarg.org.ar/.

Stakhiv, E.Z., 1998: Policy implications of climate change impacts on water resource management. *Water Policy*, **1**, 159–175.

Steenvoorden, J. and T. Endreny, 2004: *Wastewater Re-use and Groundwater Quality*. IAHS Publication 285, 112 pp.

Stern, N., 2007: *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge, 692 pp.

Stewart, I.T., D.R. Cayan and M.D. Dettinger, 2005: Changes toward earlier streamflow timing across western North America. *J. Climate*, **18**, 1136–1155.

Stige, L.C., J. Stave, K.S. Chan, L. Ciannelli, N. Pettorelli, Glantz, P., H.R Herren and N.C. Stenseth, 2006: The effect of climate variation on agro-pastoral production in Africa. *P. Natl. Acad. Sci. USA*, **103**, 3049–3053.

Straile, D., D.M. Livingstone, G.A. Weyhenmeyer and D.G. George, 2003: The response of freshwater ecosystems to climate variability associated with the North Atlantic Oscillation. *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*, Geophysical Monograph, 134. American Geophysical Union, Washington, DC, 279 pp.

Suarez, P., W. Anderson, V. Mahal and T.R. Lakshmanan, 2005: Impacts of flooding and climate change on urban transportation: a systemwide performance assessment of the Boston Metro Area. *Transportation Research Part D-Transport and Environment*, **10**(3), 231–244.

Summit Environmental Consultants, 2004: *Trepanier Landscape Unit (Westside) Water Management Plan*. Regional District of Central Okanagan and British Columbia, Ministry of Sustainable Resource Management, Kelowna, 300 pp.

Sutherland, K., B. Smit, V. Wulf, and T. Nakalevu, 2005: Vulnerability to climate change and adaptive capacity in Samoa: the case of Saoluafata village. *Tiempo*, **54**, 11–15.

Sutherst, R.W., 2004: Global change and human vulnerability to vector-borne diseases. *Clin. Microb. Rev.*, **17**, 136–173.

Sutton, R.T. and D.L.R. Hodson, 2003: Influence of the ocean on North Atlantic climate variability 1871–1999. *J. Clim.*, **16**, 3296–3313.

Sutton, R.T. and D.L.R. Hodson, 2005: Atlantic Ocean forcing of North American and European summer climate. *Science*, **290**, 2133–2137.

Swank, W.T. and J.E. Douglass, 1974: Streamflow greatly reduced by converting deciduous hardwood stands to pine. *Science*, **185**, 857-859.

Swarup, A., M.C. Manna and G.B. Singh, 2000: Impact of land use and management practices on organic carbon dynamics in soils of India. *Global Climate Change and Tropical Ecosystems*, R. Lal, J.M. Kimble and B.A. Stewart, Eds., CRC-Lewis Publishers, Boca Raton, FL, 261-282.

Swiss Re, 1998: *Floods: An Insurable Risk*, Swiss Reinsurance Company, Zurich, 51 pp.

Syvitski, J.P.M., 2002: Sediment discharge variability in Arctic rivers: implications for a warmer future. *Polar Res.*, **21**(2), 323–330.

Syvistki, J.P.M., C.J. Vorosmarty, A.J. Kettner and P. Green, 2005: Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science*, **308**, 376–380.

Szolgay, J., K. Hlavcova, S. Kohnová and R. Danihlik, 2004: Assessing climate change impact on river runoff in Slovakia. *Characterisation of the Runoff Regime and its Stability in the Tisza Catchment. Proc. XXII Conference of the Danubian Countries on the Hydrological Forecasting and Hydrological Bases of Water Management*. Brno, 30 August–2 September 2004. Brno, 2004. CD-edition.

Tao, F., M. Yokozawa, Y. Hayashi and E. Lin, 2003a: Changes in agricultural water demands and soil moisture in China over the last half-century and their effects on agricultural production. *Agri. Forest Meteorol.*, **118**, 251–261.

Tao, F., M. Yokozawa, Y. Hayashi and E. Lin, 2003b: Future climate change, the agricultural water cycle, and agricultural production in China. *Agri. Eco. Environ.*, **95**, 203–215.

Tao, F., M. Yokozawa, Z. Zhang, Y. Hayashi, H. Grassl and C. Fu, 2004: Variability in climatology and agricultural production in China in association with the East Asia summer monsoon and El Niño South Oscillation, *Clim. Res.*, **28**, 23–30.

Tao, F.L., M. Yokozawa, Y. Hayashi and E. Lin, 2005: A perspective on water resources in China: interactions between climate change and soil degradation. *Climatic Change*, **68**(1–2), 169–197.

Tebakari, T., J. Yoshitani, and C. Suvanpimol, 2005: Time-space trend analysis in pan evaporation over kingdom of Thailand. *J. Hydrol. Eng.*, **10**, 205-215.

Thanh, T.D., Y. Saito, D.V. Huy, V.L. Nguyen, T.K.O. Ta and M. Tateishi, 2004: Regimes of human and climate impacts on coastal changes in Vietnam. *Reg. Environ. Change*, **4**, 49–62.

The Water Page, 2001: BPD business partners for development water and sanitation clusters. http://www.africanwater.org/bpd.htm.

Thomas, C.D., A. Cameron, R.E. Green, M. Bakkenes, L.J. Beaumont, Y.C. Collingham, B.F.N. Erasmus, M.F. de Siqueira and Co-authors, 2004: Extinction from climate change. *Nature*, **427**, 145-148.

Thomas, J.M.G., K.J. Boote, L.H. Allen Jr., M. Gallo-Meagher and J.M. Davis, 2003: Elevated temperature and carbon dioxide effects on soybean seed composition and transcript abundance. *Crop Science*, **43**(4), 1548–1557.

Thomas, M.K., D.F. Charron, D. Waltner-Toews, C. Schuster, A.R. Maarouf and J.D. Holt, 2006: A role of high impact weather events in waterborne disease outbreaks in Canada, 1975-2001. *Int. J. Environ. Health Res.*, **16**, 167-180.

Thomson, A.M., N.J. Rosenberg, R.C. Izaurralde and R.A. Brown, 2005a: Climate change impacts for the conterminous USA: an integrated assessment Part 5. Irrigated agriculture and national grain crop production. *Climatic Change*, **69**, 89-105.

Thomson, M.C., S.J. Mason, T. Phindela and S.J. Connor, 2005b: Use of rainfall and sea surface temperature monitoring for malaria early warning in Botswana. *Am. J. Trop. Med. Hyg.*, **73**, 214-221.

Thomson, M.C., F.J. Doblas-Reyes, S.J. Mason, R. Hagedorn, S.J. Connor, T. Phindela, A.P. Morse and T.N. Palmer, 2006: Malaria early warnings based on seasonal climate forecasts from multi-model ensembles. *Nature*, **439**, 576-579.

Thornton, P.K., P.G. Jones, T.M. Owiyo, R.L. Kruska, M. Herero, P. Kristjanson, A. Notenbaert, N. Bekele and A Omolo, with contributions from V. Orindi, B. Otiende, A. Ochieng, S. Bhadwal, K. Anantram, S. Nair, V. Kumar and U. Kulkar, 2006: *Mapping Climate Vulnerability and Poverty in Africa*. Report to the Department for International Development, ILRI, Nairobi, 200 pp.

Treacy, J.M., 1994: *Las Chacras de Coparaque: Andenes y Riego en el Valle de Colca*. Instituto de Estudios Peruanos, Lima, 298 pp.

Trenberth, K.E., 1990: Recent observed interdecadal climate changes in the Northern Hemisphere. *Bull. Am. Meteorol. Soc.*, **71**, 988–993.

Trenberth, K.E. and J.M. Caron, 2000: The Southern Oscillation revisited: sea level pressures, surface temperatures and precipitation. *J. Clim.*, **13**, 4358–4365.

Trenberth, K.E and T.J. Hoar, 1997. El Niño and climate change. *Geophys. Res. Lett.*, **24**, 3057–3060.

Trenberth, K.E., and D.J. Shea, 2006: Atlantic hurricanes and natural variability in 2005, *Geophys. Res. Lett.*, **33**, L12704, doi:10.1029/2006GL026894.

Trenberth, K.E. and D.P. Stepaniak, 2001: Indices of El Niño evolution. *J. Clim.*, 14, 1697–1701.

Trenberth, K.E., A.G. Dai, R.M. Rasmussen and D.B. Parsons, 2003: The changing character of precipitation. *Bull. Am. Meteorol. Soc.*, **84**, 1205–1217.

Trenberth, K.E., D.P. Stepaniak and L. Smith, 2005: Interannual variability of the patterns of atmospheric mass distribution. *J. Clim.*, **18**, 2812–2825.

Trnka, M., M. Dubrovski and Z. Zalud, 2004: Climate change impacts and adaptation strategies in spring barley production in the Czech Republic. *Climatic Change*, **64**, 227–255.

Tuchman, N.C., K.A. Wahtera, R.G. Wentzel and J.A. Teeri, 2003: Elevated atmospheric CO_2 alters leaf litter quality for stream ecosystems: an *in situ* leaf decomposition study. *Hydrobiologica*, **495**, 203-211.

Tumerbaatar, D., 2003: *Annual report on permafrost: potential impacts of climate change, vulnerability and adaptation assessment for grassland ecosystem and livestock sector in Mongolia*, AIACC Project Report.

UCV, 2005: Análisis de las lluvias diarias y acumuladas durante Febrero de 2005 en la región central capital. Facultad de Ingeniería, Instituto de Mecánica de Fluidos Departamento de Ingeniería Hidrometeorológica, Universidad Central de Venezuela, Caracas.

UK Water Industry Research, 2004: *Climate Change and the Hydraulic Design of Sewerage Systems: Summary Report*. Report 03/CC/10/0, UKWIR, London.

UN, 2002: *CEO Briefing on Climate Change and the Financial Services Industry.* Environment Programme Finance Initiatives (UNEP FI).

UN, 2003: *World Water Development Report: Water for Life, Water for People*. UNESCO, Paris and Berghahn Books, Barcelona, 36 pp.

UN, 2006: *World Water Development Report 2: Water, a Shared Responsibility*. UNESCO, Paris, 601 pp.

UNCHS, 2003: *Local Action for Global Goals: Water and Sanitation in the World's Cities 2003*. Earthscan, London.

UNCHS, 2006: *Meeting Development Goals in Small Urban Centres:*

Water and Sanitation in the World's Cities 2006. Earthscan, London, 273 pp.

UNDP, 2006: *Beyond Scarcity: Power, Poverty, and the Global Water Crisis*. Human Development Report 2006. United Nations Development Program, New York.

UNEP/GRID-Arendal, 2002: *Vital Climate Graphics*. United Nations Environment Programme. http://www.grida.no/climate/vital/index.htm.

UN-HABITAT, 2003: *The Challenge of Slums: Global Report on Human Settlements 2003*, Earthscan Publications, London, 310 pp.

United States Environmental Protection Agency, 1997: Need for American Indian and Alaska Native water systems. *Drinking Water Infrastructure Needs Survey First Report to Congress*. EPA 812-R-97-001, UNEPA, Washington, DC, 27-33. http://www.epa.gov/ogwdw/needssurvey/pdfs/1997/report_needssurvey_1997_findings-tribal.pdf

Unkovich, M., 2003: Water use, competition, and crop production in low rainfall, alley farming systems of south-eastern Australia. *Australian J. Agri. Res.*, **54**, pp. 751-762.

UNMSM, 2004: Calor intenso y largas sequías. Especials, Perú. http://www.unmsm.edu.pe/Destacados/contenido.php?mver=11.

UNWWAP (United Nations World Water Assessment Programme), 2003: *Water for People, Water for Life - UN World Water Development Report,* UNESCO, Paris, and Berghahn Books, Oxford, 688 pp.

UNWWAP (United Nations World Water Assessment Programme), 2006: *Water: A Shared Responsibility*. UNESCO, Paris, and Berghahn Books, Oxford, 600 pp.

US Department of the Interior, 2005: *Water 2025: Preventing Crises and Conflict in the West*. Water 2025 Status Report, Washington, DC, 36 pp. http://www.doi.gov/water2025.

US Global Change Research Program, 2000: *Water: the Potential Consequences of Climate Variability and Change for the Water Resources of the United States*. National Water Assessment Group, U.S. Global Change Research Program, 160 pp. http://www.gcrio.org/NationalAssessment/water/water.pdf.

Uyarra, M., I. Cote, J. Gill, R. Tinch, D. Viner and A.L Watkinson, 2005: Island-specific preferences of tourists for environmental features: implications of climate change for tourism-dependent states. *Environ. Cons.*, **32**(1), 11–19.

van Lieshout, M., R.S. Kovats, M.T.J. Livermore and P. Martens, 2004: Climate change and malaria: analysis of the SRES climate and socio-economic scenarios. *Global Environ. Chang.*, **14**, 87-99.

Van Rheenen, N.T., A.W. Wood, R.N. Palmer and D.P. Lettenmaier, 2004: Potential implications of PCM climate change scenarios for Sacramento–San Joaquin River Basin hydrology and water resources. *Climatic Change*, **62**, 257-281.

Vandenberghe, J., 2002: The relation between climate and river processes, landforms and deposits during the Quaternary. *Quaternary Int.*, **91**, 17–23.

VanRheenen, Vasilev, V., 2003: Variability of Shigella flexneri serotypes during a period in Israel, 2000-2001. *Epidemiol. Infect.*, **132**, 51–56.

Vásquez, O.C., 2004: *El Fenómeno El Niño en Perú y Bolivia: Experiencias en Participación Local*. Memoria del Encuentro Binacional Experiencias de prevención de desastres y manejo de emergencias ante el Fenómeno El Niño, Chiclayo, Peru. ITDG, 209 pp.

Vasquez-Leon, M., C.T. West, and T.J. Finan, 2003: A comparative assessment of climate vulnerability: agriculture and ranching on both sides of the US-Mexico border. *Global Environ. Chang.*, **13,** 159-173.

Venegas, S.A. and L.A. Mysak, 2000: Is there a dominant timescale of natural climate variability in the Arctic? *J. Clim.*, **13**, 3412–3434.

Vesely, J., V. Majer, J. Kopacek and S.A. Norton, 2003: Increasing temperature decreases aluminium concentrations in Central European lakes recovering from acidification. *Limnol. Oceanogr.*, **48**, 2346-2354.

Vic DSE, 2006: *Wimmera Mallee Pipeline*. Department of Sustainability and Environment, Victoria.

Villagrán de León, J., J. Scott, C. Cárdenas and S. Thompson, 2003: *Early Warning Systems in the American Hemisphere: Context, Current Status, and Future Trends*. Final Report. Hemispheric Consultation on Early Warning, Antigua, 15 pp.

Vincent, J.R., 1995: Timber trade, economics and tropical forest management. *Ecology, Conservation and Management of Southeast Asia Rainforests*, B.R. Primack and T.E. Lovejoy, Eds., Yale University Press, New Haven, CN, 241-261.

Viner, D., M. Sayer, M. Uyarra and N. Hodgson, 2006: *Climate Change and the European Countryside: Impacts on Land Management and Response Strategies*. Report prepared for the Country Land and Business Association, CLA, Norwich, 180 pp.

Viney, N.R., Bates, B.C., Charles, S.P., Webster, I.T., Bormans, M. and Aryal, S.K., 2003: Impacts of climate variability on riverine algal blooms. *Proc. International Congress on Modelling and Simulation, MODSIM 2003 14–17 July*, Modelling and Simulation Society of Australia and New Zealand Inc., 23–28. http://mssanz.org.au/modsim03/Media/Articles/Vol%201%20Articles/23-28.pdf.

Vörösmarty, C.J., P.J. Green, J. Salisbury and R.B. Lammers, 2000: Global water resources: vulnerability from climate change and population growth. *Science*, **289**, 284–288.

Vörösmarty, C.J., E.M. Douglas, A.A. Green and C. Ravenga, 2005: Geospatial indicators of emerging water stress: an application to Africa. *Ambio*, **34**(3), 230–236.

Vuille, M., R.S. Bradley, M. Werner and F. Keimig, 2003: 20th century climate change in the tropical Andes: observations and model results. *Climatic Change*, **59**, 75-99.

Wahab, H.M., 2005: The impact of geographical information system on environmental development. *Unpublished MSc Thesis*, Faculty of Agriculture, Al-Azhar University, Cairo, 149 pp.

Wall, E., and B. Smit, 2005: Climate change adaptation in light of sustainable agriculture. *J. Sustainable Agric.*, **27**, 113–123.

Walsh, J.E. and Co-authors, 2005: Cryosphere and hydrology. *Arctic Climate Impacts Assessment, ACIA*, C. Symon, L. Arris and B. Heal, Eds., Cambridge University Press, Cambridge, 183–242.

Walsh, M.E., D.G. de la Torre Ugarte, H. Shapouri and S.P. Slinsky, 2003: Bioenergy crop production in the United States. *Environ. Res. Econ.*, **24**, 313-333.

Walter, M.T., D.S. Wilks, J.Y. Parlange and B.L. Schneider, 2004: Increasing evapotranspiration from the conterminous United States. *J. Hydrometeorol.*, **5**, 405-408.

Wang, T., 2003: Study on desertification in China. Contents of desertification research. *J. Desert Res.*, **23**(5), 477–482.

Warren, J., J. Berner and J. Curtis, 2005: Climate change and human health: infrastructure impacts to small remote communities in the North. *Int. J. Circumpolar Health*, **64**(5), 498.

Warren, R., N. Arnell, R. Nicholls, P. Levy and J. Price, 2006: *Understanding the Regional Impacts of Climate Change*. Research Report prepared for the Stern Review on the Economics of Climate Change. Tyndall Centre for Climate Change Research, Working Paper 90, UEA, Norwich, 223 pp

Wassmann, R., X.H. Nguyen, T.H. Chu and P.T. To, 2004: Sea-level rise affecting the Vietnamese Mekong Delta: water elevation in the flood season and implications for rice production. *Climatic Change*, **66**, 89-107.

Water 21, 2002: Joining forces. *Magazine of the International Water Association*, **October**, 55-57.

Water Corporation, 2006: *Planning for New Sources of Water.* West Australian Water Corporation. http://www.watercorporation.com.au/W/water_sources_new.cfm.

Waters, D., W.E. Watt, J. Marsalek and B.C. Anderson, 2003: Adaptation of a storm drainage system to accommodate increased rainfall resulting from climate change *J. Environ. Plan. Manag.*, **46**, 755–770.

Watson, R.T. and W. Haeberli, 2004: Environmental threats, mitigation strategies and high mountain areas. Mountain Areas: A Global Resource. *Ambio*, **13**, 2-10.

Watson, R.T., M.C. Zinyowera and R.H. Moss, Eds., 1997: *The Regional Impacts of Climate Change: An Assessment of Vulnerability*. Cambridge University Press, Cambridge, 517 pp.

WDR, 2003: *World Disaster Report: Focus on Ethics in Aid*. International Federation of Red Cross and Red Crescent Societies, Geneva, 240 pp.

WDR, 2004: *World Disaster Report: Focus on Community Resilience*. International Federation of Red Cross and Red Crescent Societies, Geneva, 240 pp.

Webster, P.J., V.O. Magana, T.N. Palmer, J. Shukla, R.A. Tomas, M. Yanagi and T. Yasunari, 1998: Monsoons: processes, predictability and the prospects for prediction. *J. Geophys. Res.*, **103**, 14451–14510.

Werritty, A., 2001: Living with uncertainty: climate change, river flow and water resources management in Scotland. *Sci. Total Environ.*, **294**, 29–40.

West, T.O. and G. Marland, 2003: Net carbon flux from agriculture: carbon emissions, carbon sequestration, crop yield, and land-use change. *Biogeochem.*, **63**, 73-83.

West, T.O. and W.M. Post, 2002: Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. *Soil Sci. Soc. Am. J.,* **66**, 1930-1946.

Wheaton, E., V. Wittrock, S. Kulshretha, G. Koshida, C. Grant, A. Chipanshi and B. Bonsal, 2005: *Lessons Learned from the Canadian Drought Years of 2001 and 2002: Synthesis Report*. Saskatchewan Research Council Publication No. 11602-46E03, Saskatoon, Saskatchewan. http://www.agr.gc.ca/pfra/drought/info/11602-46E03.pdf.

White, M.A., N.S. Diffenbaugh, G.V. Jones, J.S. Pal and F. Giorgi, 2006: Extreme heat reduces and shifts United States premium wine production in the 21st century. *P. Natl. Acad. Sci. USA*, **103**, 11217-11222.

Whittington, H. and S.W. Gundry, 1998: Global climate change and hydroelectric resources. *Eng. Sci. Ed. J.*, **7**, 29-34.

WHO (World Health Organization), 2003: *Report of Synthesis Workshop on Climate Change and Health in Small Islands States*, 1-4 December 2003, Republic of the Maldives. World Health Organization, Geneva, 95 pp.

WHO (World Health Organization), 2004: *Guidelines for Drinking Water Quality. Volume 1: Recommendations*, Third Edition, WHO, Geneva, 366 pp.

WHO (World Health Organization), 2005: *Water Safety Plans: Managing Drinking Water Quality from Catchment to Consumer*. Prepared by A. Davison and Co-authors, WHO/SDE/WSH/05.06, WHO, Geneva, 235 pp.

WHO/UNICEF, 2000: *Global water supply and sanitation assessment 2000 report*. World Health Organization with UNICEF, Geneva, 79 pp. http://www.who.int/docstore/water_sanitation_healt/Globassessment/GlobalTOC.htmWHO/UNICEF.

Wijeratne, M.A., 1996: Vulnerability of Sri Lanka tea production to global climate change. *Water Air Soil Poll.,* Historical Archive, 87–94.

Wilby, R.L., 2006: When and where might climate change be detectable in UK river flows? *Geophys. Res. Lett.*, **33**(19), L19407, doi:10.1029/2006GL027552.

Wilby R.L. and I. Harris, 2006: A framework for assessing uncertainties in climate change impacts: low-flow scenarios for the River Thames, UK. *Water Resour. Res.*, **42**, W02419, doi:10.1029/2005WR004065.

Williams, K.L., K.C. Ewel, R.P. Stumpf, F.E. Putz and T.W. Workman, 1999: Sea-level rise and coastal forest retreat on the west coast of Florida. *Ecology*, **80**, 2045–2063.

Williams, R.H., E.D. Larson and H. Jin, 2006: Synthetic fuels in a world of high oil and carbon prices. *Proc. 8th International Conference on Greenhouse Gas Control Technologies*, Trondheim, Norway, June.

Williams, S.E., E.E. Bolitho and S. Fox, 2003: Climate change in Australian tropical rainforests: an impending environmental catastrophe. *P. Roy. Soc. Lond. B Bio.*, **270**, 1887-1892.

Winter, T.C. and M.K. Woo, 1990: Hydrology of lakes and wetlands. *Surface Water Hydrology,* M.G. Wolman and H.C. Riggs, Eds., Geological Society of America, Boulder, CO, Vol. 0-1, 159–188.

Woo, M.K., R.D. Rowsell and R.G. Clark, 1993: *Hydrological Classification of Canadian Prairie Wetlands and Prediction of Wetland Inundation in Response to Climatic Variability.* Canadian Wildlife Service, Environment Canada, Ottawa, ON, 23 pp.

Woodruff, R.E. and Co-authors, 2002: Predicting Ross River virus epidemics from regional weather data. *Epidemiology*, **13**, 384–393.

Woodruff, R.E., C.S. Guest, M.G. Garner, N. Becker and M. Lindsay, 2006: Early warning of Ross River virus epidemics: combining surveillance data on climate and mosquitoes. *Epidemiology*, **17**(5), 569–575.

Woods, R.A. and C. Howard-Williams, 2004: Advances in freshwater sciences and management. *Freshwaters of New Zealand*, J.S. Harding, M.P. Mosley, C.P. Pearson and B.K. Sorrell, Eds., New Zealand Hydrological Society Inc. and New Zealand Limnological Society Inc., Christchurch, 764 pp.

Woodworth, P.L. and D.L. Blackman, 2004: Evidence for systematic changes in extreme high waters since the mid-1970s. *J. Climate*, **17**, 1190-1197.

World Bank, 2000: *Cities, Seas and Storms: Managing Change in Pacific Island Economies. Vol. IV, Adapting to Climate Change*. The World Bank, Washington, DC, 72 pp.

World Bank, 2002: *World Development Indicators*, CD-ROM, The World Bank, Washington, DC.

World Bank, 2004a: *Water Resources Sector Strategy: Strategic Directions for World Bank Engagement*. Pub. No. 28114, The World Bank, Washington, DC, 88 pp.

World Bank, 2004b: *Modelled Observations on Development Scenarios in the Lower Mekong Basin*. Mekong Regional Water Resources Assistance Strategy, prepared for theWorld Bank with Mekong River Commission cooperation, Washington, DC and Vientiane, 142 pp. http://www. mrcmekong.org/free_download/report.htm.

World Commission on Dams, 2000: *Dams and Development: A New Framework for Decision-Making*. Earthscan, London, 442 pp.

World Water Council, 2006: *Final* R*eport of the 4th World Water Forum.* National Water Commission of Mexico, Mexico City, 262 pp.

World Water Forum, 2000: *The Africa Water Vision for 2025: Equitable and Sustainable Use of Water for Socioeconomic Development*. World Water Forum, The Hague, 30 pp.

Wright, K.R. and A. Valencia Zegarra, 2000: *Machu Picchu: A Civil Engineering Marvel*. American Society of Civil Engineers Press, Reston, Virginia, 144 pp.

Wrona, F.J. and Co-authors, 2005: Freshwater ecosystems and fisheries. *Arctic Climate Impact Assessment, ACIA*, C. Symon, L. Arris and B. Heal, Eds., Cambridge University Press, Cambridge, 353–452.

Wrona, F.J., T.D. Prowse, J.D. Reist, J.E. Hobbie, L.M.J. Lévesque and W.F. Vincent, 2006: Climate change effects on aquatic biota, ecosystem structure and function. *Ambio*, **35**(7), 359–369.

WWF, 2005: *An Overview of Glaciers, Glacier Retreat, and Subsequent Impacts in Nepal, India and China*. WWF Nepal Programme, 79 pp. http://assets.panda.org/downloads/himalayaglaciersreport2005.pdf.

Xu, C.X., 2003: *China National Offshore and Coastal Wetlands Conservation Action Plan*. China Ocean Press, Beijing, 116 pp (in Chinese).

Yamada, T., 1998: *Glacier Lake and its Outburst Flood in the Nepal Himalaya*. Monograph No. 1, March 1998, Data Center for Glacier Research, Japanese Society of Snow and Ice, Tokyo, 96 pp.

Yan, X., T. Ohara and H. Akimoto, 2003: Development of region-specific emission factors and estimation of methane emission from rice field in East, Southeast and South Asian countries. *Global Change Biology,* **9**, 237-254.

Yang, D., B. Ye and A. Shiklomanov, 2004a: Discharge characteristics and changes over the Ob River watershed in Siberia. *J. Hydrometeorol*., **5**, 595–610.

Yang, D., B. Ye and D.L. Kane, 2004b: Streamflow changes over Siberian Yenisei River basin. *J. Hydrol*., **296**, 59–80.

Yang, D.Q., D.L. Kane, L.D. Hinzman, X. Zhang, T. Zhang and H. Ye, 2002: Siberian Lena River hydrologic regime and recent change. *J. Geophys. Res*., **107**(D23), 4694, doi:10.1029/2002JD002542.

Yin, Y.Y., Q.L. Miao and G.S. Tian, 2003: *Climate Change and Regional Sustainable Development*. Science Press, Beijing, 224 pp.

Yoshikawa, K. and L.D. Hinzman, 2003: Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost. *Permafrost Periglac. Proc*., **14**(2), 151–160.

Young, R.A., 2005: *Determining the Economic Value of Water: Concepts and Methods*. Resources for the Future Press, Washington, DC, 300 pp.

Zavaleta, E.S. and K.B. Hulvey, 2004: Realistic species losses disproportionately reduce grassland resistance to biological invaders. *Science*, **306**, 1175-1177.

Zebisch, M., T. Grothmann, D. Schroeter, C. Hasse, U. Fritsch and W. Cramer, 2005: *Climate Change in Germany: Vulnerability and Adaptation of Climate Sensitive Sectors*. Federal Environmental Agency (Umweltbundesamt), Dessau, 205 pp.

Zeidler, R.B., 1997: Continental shorelines: climate change and integrated coastal management. *Ocean Coast. Manage*., **37**(1), 41–62.

Zhai P. and X. Pan, 2003: Trends in temperature extremes during 1951–1999 in China. *Geophys. Res. Lett*., **30**(17), 1913, doi:10.1029/2003GL018004.

Zhai, P.M., 2004: Climate change and meteorological disasters. *Sci. Techn. Rev*., **193**(7), 11–14.

Zhai, P.M., A. Sun, F. Ren, X. Liu, B. Gao and Q. Zhang, 1999: Changes of climate extremes in China. *Climatic Change*, **42**, 203–218.

Zhang, T.J., O.W. Frauenfeld, M.C. Serreze, A. Etringer, C. Oelke, J. McCreight, R.G. Barry, D. Gilichinsky, D.Q. Yang, H.C. Ye, F. Ling and S. Chudinova, 2005: Spatial and temporal variability in active layer thickness over the Russian Arctic drainage basin. *J. Geophys. Res*., **110**(D16), D16101, doi:10.1029/2004JD005642.

Zhang, Y., W. Chen and J. Cihlar, 2003: A process-based model for quantifying the impact of climate change on permafrost thermal regimes, *J. Geophys. Res*., **108**(D22), 4695 doi:10.1029/2002JD003354.

Zhou, G., N. Minakawa, A.K. Githeko and G. Yan, 2004: Association between climate variability and malaria epidemics in the East African highlands. *P. Natl. Acad. Sci. USA*, **101**, 2375-2380.

Zhou, Y. and R.S.J. Tol, 2005: Evaluating the costs of desalination and water transport. *Water Resourc. Res*., **41**, 1–10.

Zierl, B. and H. Bugmann, 2005: Global change impacts on hydrological processes in Alpine catchments. *Water Resourc. Res*., **41**(2), 1–13.

Appendix I: Climate model descriptions

Model	Originating group	Resolution (lat/lon)	Reference for description of model (see below)
CGCM1	Canadian Centre for Climate Modelling and Analysis, Canada	Atmospheric component: ~3.7° x 3.7° Ocean component: ~1.8° x 1.8°	Flato et al., 2000
HadCM2	Met Office Hadley Centre, UK	2.5° x 3.75°	Johns et al., 1997
HadCM3	Met Office Hadley Centre, UK	2.5° x 3.75°	Gordon et al., 2000 Pope et al., 2000
RegCM2	National Center for Atmospheric Research, USA	~50 km	Giorgi et al., 1993a, b
ECHAM4 (with OPYC3)	Max Planck Institut für Meteorologie (MPI) and the Deutsches Klimarechenzentrum (DKRZ), Germany	~2.8° x 2.8°	Roeckner et al., 1996

References:

Flato, G.M., G.J. Boer, W.G. Lee, N.A. McFarlane, D. Ramsden, M.C. Reader and A.J. Weaver, 2000: The Canadian Centre for Climate Modelling and Analysis global coupled model and its climate. *Clim. Dyn.*, **16**, 451-467.

Johns, T.C., R.E. Carnell, J.F. Crossley, J.M. Gregory, J.F.B. Mitchell, C.A. Senior, S.F.B. Tett and R.A. Wood, 1997: The second Hadley Centre coupled ocean-atmosphere GCM: model description, spinup and validation. *Clim. Dyn.*, **13**, 103-134.

Gordon, C., C. Cooper, C.A. Senior, H.T. Banks, J.M. Gregory, T.C. Johns, J.F.B. Mitchell and R.A. Wood, 2000: The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Clim. Dyn.*, **16**, 147-168.

Pope, V., M.L. Gallani, P.R. Rowntree and R.A. Stratton, 2000: The impact of new physical parameterizations in the Hadley Centre climate model: HadAM3. *Clim. Dyn.*, **16**, 123-146.

Giorgi, F., M.R. Marinucci and G. T. Bates, 1993: Development of a second generation regional climate model (RegCM2). Part I Boundary layer and radiative transfer processes. *Mon. Weather Rev.*, **121**, 2794-2813.

Giorgi, F., M.R. Marinucci, G. T. Bates and G. DeCanio, 1993: Development of a second generation regional climate model (RegCM2). Part II Convective processes and assimilation of lateral boundary conditions. *Mon. Weather Rev.*, **121**, 2814-2832.

Roeckner, E., K. Arpe, L. Bengtsson, M. Christoph, M. Claussen, L. Dümenil, M. Esch, M. Giorgetta, U. Schlese and U. Schulzweida, 1996: *The atmospheric general circulation model ECHAM-4: model description and simulation of present-day climate*. Max-Planck Institute for Meteorology, Report No.218, Hamburg, Germany, 90 pp.

Appendix II: Glossary

Editor: Jean Palutikof (United Kingdom)

Co-Editors: Clair Hanson (United Kingdom), Bryson Bates (Australia)

This Glossary is based on the glossaries published in the IPCC Fourth Assessment Report.

The italics used have the following meaning: *Glossary word reference; Glossary secondary reference* (i.e., terms which are either contained in a glossary of the IPCC Working Group contributions to the AR4, or defined within the text of an entry of this glossary).

A.

Abrupt climate change

The nonlinearity of *the climate system* may lead to abrupt *climate change*, sometimes called *rapid climate change*, *abrupt events* or even *surprises*. The term *abrupt* often refers to time scales faster than the typical time scale of the responsible forcing. However, not all abrupt climate changes need be *externally forced*. Some possible abrupt events that have been proposed include a dramatic reorganisation of the thermohaline circulation, rapid deglaciation and massive melting of *permafrost* or increases in soil respiration leading to fast changes in the *carbon cycle*. Others may be truly unexpected, resulting from a strong, rapidly changing, forcing of a non-linear system.

Active layer

The layer of ground that is subject to annual thawing and freezing in areas underlain by *permafrost*.

Adaptation

Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected *climate change* effects. Various types of adaptation exist, e.g., *anticipatory* and *reactive*, *private* and *public*, and *autonomous* and *planned*. Examples are raising river or coastal dikes, the substitution of more temperature-shock resistant plants for sensitive ones, etc.

Adaptive capacity

The whole of capabilities, resources and institutions of a country or *region* to implement effective *adaptation* measures.

Aerosols

A collection of airborne solid or liquid particles, with a typical size between 0.01 and 10 micrometre (a millionth of a metre) that reside in the atmosphere for at least several hours. Aerosols may be of either natural or *anthropogenic* origin. Aerosols may influence *climate* in several ways: directly through scattering and *absorbing* radiation, and indirectly through acting as cloud condensation nuclei or modifying the optical properties and lifetime of clouds.

Afforestation

Planting of new forests on lands that historically have not contained forests (for at least 50 years). For a discussion of the term *forest* and related terms such as afforestation, *reforestation*, and *deforestation* see the IPCC Report on Land Use, Land-Use Change and Forestry (IPCC, 2000).

Albedo

The fraction of *solar radiation* reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo, the surface albedo of soils ranges from high to low, and vegetation-covered surfaces and oceans have a low albedo. The Earth's planetary albedo varies mainly through varying cloudiness, snow, ice, leaf area and land cover changes.

Algal bloom

A reproductive explosion of algae in a lake, river, or ocean.

Alpine

The biogeographic zone made up of slopes above the tree line, characterised by the presence of rosette-forming herbaceous plants and low shrubby slow-growing woody plants.

Annex I countries

The group of countries included in Annex I (as amended in 1998) to the *United Nations Framework Convention on Climate Change (UNFCCC)*, including all the OECD countries in the year 1990 and countries with economies in transition. Under Articles 4.2 (a) and 4.2 (b) of the Convention, Annex I countries committed themselves specifically to the aim of returning individually or jointly to their 1990 levels of *greenhouse gas* emissions by the year 2000. By default, the other countries are referred to as *non-Annex I countries*.

Annex II countries
The group of countries included in Annex II to the *United Nations Framework Convention on Climate Change (UNFCCC)*, including all OECD countries in the year 1990. Under Article 4.2 (g) of the Convention, these countries are expected to provide financial resources to assist developing countries to comply with their obligations, such as preparing national reports. Annex II countries are also expected to promote the transfer of environmentally sound technologies to developing countries.

Annex B countries
The countries included in Annex B to the *Kyoto Protocol* that have agreed to a target for their greenhouse-gas emissions, including all the *Annex I countries* (as amended in 1998) except for Turkey and Belarus. See *Kyoto Protocol*

Annular modes
Preferred patterns of change in atmospheric circulation corresponding to changes in the zonally averaged mid-latitude westerlies. The *Northern Annular Mode* has a bias to the North Atlantic and has a large correlation with the *North Atlantic Oscillation*. The *Southern Annular Mode* occurs in the Southern Hemisphere. The variability of the mid-latitude westerlies has also been known as *zonal flow* (or *wind*) vacillation, and defined through a *zonal index*. [WGI Box 3.4]

Anthropogenic
Resulting from or produced by human beings.

Aquaculture
The managed cultivation of aquatic plants or animals such as salmon or shellfish held in captivity for the purpose of harvesting.

Aquifer
A stratum of permeable rock that bears water. An unconfined aquifer is recharged directly by local rainfall, rivers and lakes, and the rate of recharge will be influenced by the permeability of the overlying rocks and soils.

Arid region
A land region of low rainfall, where *low* is widely accepted to be less than 250 mm precipitation per year.

Atlantic Multi-decadal Oscillation (AMO)
A multi-decadal (65 to 75 year) fluctuation in the North Atlantic, in which *sea surface temperatures* showed warm phases during roughly 1860 to 1880 and 1930 to 1960 and cool phases during 1905 to 1925 and 1970 to 1990 with a range of order 0.4º C.

Atmosphere
The gaseous envelope surrounding the Earth. The dry atmosphere consists almost entirely of nitrogen (78.1% volume mixing ratio) and oxygen (20.9% volume mixing ratio), together with a number of trace gases, such as argon (0.93% volume mixing ratio), helium and radiatively active greenhouse gases such as *carbon dioxide* (0.035% volume mixing ratio) and *ozone*. In addition, the atmosphere contains the greenhouse gas water vapour, whose amounts are highly variable but typically around 1% volume mixing ratio. The atmosphere also contains clouds and *aerosols*.

Atmospheric boundary layer
The atmospheric layer adjacent to the Earth's surface that is affected by friction against that boundary surface, and possibly by transport of heat and other variables across that surface (AMS, 2000). The lowest 10 metres or so of the boundary layer, where mechanical generation of turbulence is dominant, is called the *surface boundary layer* or *surface layer*.

Attribution
See *Detection and attribution*.

B.
Barrier
Any obstacle to reaching a goal, *adaptation* or *mitigation* potential that can be overcome or attenuated by a policy, programme, or measure. *Barrier removal* includes correcting market failures directly or reducing the transactions costs in the public and private sectors by e.g., improving institutional capacity, reducing risk and uncertainty, facilitating market transactions, and enforcing regulatory policies.

Baseline
Reference for measurable quantities from which an alternative outcome can be measured, e.g., a non-intervention *scenario* used as a reference in the analysis of intervention scenarios.

Basin
The drainage area of a stream, river, or lake.

Biodiversity
The total diversity of all organisms and ecosystems at various spatial scales (from genes to entire *biomes*).

Bioenergy
Energy derived from biomass.

Biofuel
A fuel produced from organic matter or combustible oils produced by plants. Examples of biofuel include alcohol, black liquor from the paper-manufacturing process, wood, and soybean oil.

Biomass
The total mass of living organisms in a given area or volume; recently dead plant material is often included as dead biomass. The quantity of biomass is expressed as a dry weight or as the *energy*, carbon, or nitrogen content.

Biome
A major and distinct regional element of the *biosphere*, typically consisting of several ecosystems (e.g., *forests*, rivers, ponds, swamps within a *region* of similar climate). Biomes are characterised by typical communities of plants and animals.

Biosphere (terrestrial and marine)

The part of the Earth system comprising all *ecosystems* and living organisms, in the *atmosphere*, on land (*terrestrial biosphere*) or in the oceans (*marine biosphere*), including derived dead organic matter, such as litter, soil organic matter and oceanic detritus.

Biota

All living organisms of an area; the flora and fauna considered as a unit.

Black carbon

Operationally defined *aerosol* species based on measurement of light absorption and chemical reactivity and/or thermal stability; consists of soot, charcoal and/or possible light absorbing refractory organic matter.

Bog

Peat-accumulating acidic *wetland*.

Boreal forest

Forests of pine, spruce, fir, and larch stretching from the east coast of Canada westward to Alaska and continuing from Siberia westward across the entire extent of Russia to the European Plain.

Boundary layer

See *Atmospheric boundary layer*.

C.

C_3 plants

Plants that produce a three-carbon compound during *photosynthesis*, including most trees and agricultural crops such as rice, wheat, soybeans, potatoes and vegetables.

C_4 plants

Plants, mainly of tropical origin, that produce a four-carbon compound during *photosynthesis*, including many grasses and the agriculturally important crops maize, sugar cane, millet and sorghum.

Carbon (dioxide) capture and storage (CCS)

A process consisting of separation of *carbon dioxide* from industrial and energy-related sources, transport to a storage location, and long-term isolation from the *atmosphere*.

Carbon cycle

The term used to describe the flow of carbon (in various forms, e.g., as *carbon dioxide*) through the *atmosphere*, ocean, terrestrial *biosphere* and lithosphere.

Carbon dioxide (CO_2)

A naturally occurring gas, also a by-product of burning fossil fuels from fossil carbon deposits, such as oil, gas and coal, of burning *biomass* and of *land use changes* and other industrial processes. It is the principal *anthropogenic greenhouse gas* that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a *Global Warming Potential* of 1.

Carbon dioxide (CO_2) enrichment

See *Carbon dioxide (CO_2) fertilisation*.

Carbon dioxide (CO_2) fertilisation

The enhancement of the growth of plants as a result of increased atmospheric *carbon dioxide* (CO_2) concentration. Depending on their mechanism of *photosynthesis*, certain types of plants are more sensitive to changes in atmospheric CO_2 concentration.

Carbon sequestration

The uptake of carbon containing substances, in particular *carbon dioxide*. See *Sequestration*.

Catchment

An area that collects and drains rainwater.

Cholera

A water-borne intestinal infection caused by a bacterium (*Vibrio cholerae*) that results in frequent watery stools, cramping abdominal pain, and eventual collapse from dehydration and shock.

Clean Development Mechanism (CDM)

Defined in Article 12 of the *Kyoto Protocol*, the CDM is intended to meet two objectives: (1) to assist parties not included in *Annex I* in achieving *sustainable development* and in contributing to the ultimate objective of the Convention; and (2) to assist parties included in Annex I in achieving compliance with their quantified emission limitation and reduction commitments. Certified Emission Reduction Units from CDM projects undertaken in non-Annex I countries that limit or reduce greenhouse gas emissions, when certified by operational entities designated by Conference of the Parties/Meeting of the Parties, can be accrued to the investor (government or industry) from parties in *Annex B*. A share of the proceeds from the certified project activities is used to cover administrative expenses as well as to assist developing country parties that are particularly vulnerable to the adverse effects of *climate change* to meet the costs of *adaptation*.

Climate

Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the *climate system*.

Climate change

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

Climate feedback
An interaction mechanism between processes in the *climate system* is called a climate feedback when the result of an initial process triggers changes in a second process that in turn influences the initial one. A positive feedback intensifies the original process, and a negative feedback reduces it.

Climate model
A numerical representation of the *climate system* based on the physical, chemical and biological properties of its components, their interactions and *feedback* processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parameterisations are involved. Coupled atmosphere-ocean general circulation models (AOGCMs) provide a representation of the climate system that is near the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology (see WGI Chapter 8). Climate models are applied as a research tool to study and simulate the *climate*, and for operational purposes, including monthly, seasonal and interannual climate predictions.

Climate projection
A *projection* of the response of the *climate system* to *emissions* or concentration *scenarios* of *greenhouse gases* and *aerosols*, or *radiative forcing* scenarios, often based upon simulations by *climate models*. Climate projections are distinguished from climate predictions in order to emphasise that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised and are therefore subject to substantial *uncertainty*.

Climate scenario
A plausible and often simplified representation of the future *climate*, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of *anthropogenic climate change*, often serving as input to impact models. *Climate projections* often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate. A *climate change scenario* is the difference between a climate scenario and the current climate.

Climate system
The climate system is the highly complex system consisting of five major components: the *atmosphere*, the *hydrosphere*, the *cryosphere*, the land surface and the *biosphere*, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of *external forcings* such as volcanic eruptions, solar variations and *anthropogenic* forcings such as the changing composition of the atmosphere and *land-use change*.

Climate variability
Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the *climate* on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the *climate system* (*internal variability*), or to variations in natural or *anthropogenic external forcing* (*external variability*). See also *Climate change*.

CO_2
See *Carbon dioxide*.

CO_2-fertilisation
See *Carbon dioxide fertilisation*.

Confidence
The level of confidence in the correctness of a result is expressed in this Technical Paper using a standard terminology defined in Box 1.1. See also *Likelihood*; *Uncertainty*.

Control run
A model run carried out to provide a *baseline* for comparison with climate-change experiments. The control run uses constant values for the *radiative forcing* due to *greenhouse gases,* appropriate to present-day or *pre-industrial* conditions.

Coral
The term *coral* has several meanings, but is usually the common name for the Order *Scleractinia*, all members of which have hard limestone skeletons, and which are divided into reef-building and non-reef-building, or cold- and warm-water corals. See *Coral reefs*

Coral reefs
Rock-like limestone structures built by *corals* along ocean coasts (*fringing reefs*) or on top of shallow, submerged banks or shelves (*barrier reefs*, *atolls*), most conspicuous in tropical and subtropical oceans.

Cost
The consumption of resources such as labour time, capital,

materials, fuels, etc. as a consequence of an action. In economics all resources are valued at their *opportunity cost*, being the value of the most valuable alternative use of the resources. Costs are defined in a variety of ways and under a variety of assumptions that affect their value. Cost types include: *administrative costs***,** *damage costs* (to ecosystems, people and economies due to negative effects from *climate change*), and *implementation costs* of changing existing rules and regulation, capacity building efforts, information, training and education, etc. *Private costs* are carried by individuals, companies or other private entities that undertake the action, whereas *social costs* include also the external costs on the environment and on society as a whole. The negative of costs are benefits (also sometimes called *negative costs*). Costs minus benefits are *net costs*.

Cryosphere
The component of the *climate system* consisting of all snow, ice and *frozen ground* (including *permafrost*) on and beneath the surface of the Earth and ocean. See also *Glacier*; *Ice sheet*.

D.

Deforestation
Conversion of forest to non-forest. For a discussion of the term *forest* and related terms such as *afforestation, reforestation*, and deforestation see the IPCC Report on Land Use, Land-Use Change and Forestry (IPCC, 2000).

Dengue fever
An *infectious* viral *disease* spread by mosquitoes, often called breakbone fever because it is characterised by severe pain in the joints and back. Subsequent infections of the virus may lead to dengue haemorrhagic fever (DHF) and dengue shock syndrome (DSS), which may be fatal.

Desert
A region of very low rainfall, where 'very low' is widely accepted to be less than 100 mm per year.

Desertification
Land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities. Further, the United Nations Convention to Combat Desertification (UNCCD) defines land degradation as a reduction or loss in arid, semi-arid, and dry sub-humid areas of the biological or economic productivity and complexity of rain-fed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process or combination of processes, including those arising from human activities and habitation patterns, such as: (i) soil *erosion* caused by wind and/or water; (ii) deterioration of the physical, chemical, and biological or economic properties of soil; and (iii) long-term loss of natural vegetation.

Detection and attribution
Climate varies continually on all time scales. ***Detection*** of *climate change* is the process of demonstrating that climate has changed in some defined statistical sense, without providing a reason for that change. ***Attribution*** of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of *confidence*.

Development path or pathway
An evolution based on an array of technological, economic, social, institutional, cultural, and biophysical characteristics that determine the interactions between natural and *human systems*, including production and consumption patterns in all countries, over time at a particular scale. *Alternative development paths* refer to different possible trajectories of development, the continuation of current trends being just one of the many paths.

Disturbance regime
Frequency, intensity, and types of disturbances, such as fires, insect or pest outbreaks, floods and *droughts*.

Downscaling
Downscaling is a method that derives local-to-regional-scale (10 to 100km) information from larger-scale models or data analyses. Two main methods are distinguished: *dynamical downscaling* and *empirical/statistical downscaling*. The dynamical method uses the output of regional *climate models*, global models with variable spatial resolution or high-resolution global models. The empirical/statistical methods develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the downscaled product depends on the quality of the driving model.

Drought
In general terms, drought is a 'prolonged absence or marked deficiency of precipitation', a 'deficiency that results in water shortage for some activity or for some group', or a 'period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance' (Heim, 2002). Drought has been defined in a number of ways. *Agricultural drought* relates to moisture deficits in the topmost 1 metre or so of soil (the root zone) that affect crops, *meteorological drought* is mainly a prolonged deficit of precipitation, and *hydrologic drought* is related to below-normal streamflow, lake and groundwater levels. A *megadrought* is a longdrawn out and pervasive drought, lasting much longer than normal, usually a decade or more.

Dyke
A human-made wall or embankment along a shore to prevent flooding of low-lying land.

Dynamic global vegetation model (DGVM)
Models that simulate vegetation development and dynamics through space and time, as driven by *climate* and other environmental changes.

Dynamical ice discharge
Discharge of ice from *ice sheets* or *ice caps* caused by the dynamics of the ice sheet or ice cap (e.g., in the form of *glacier* flow, ice streams and calving icebergs) rather than by melt or *runoff*.

E.

Ecological community
A community of plants and animals characterised by a typical assemblage of species and their abundances. See also *Ecosystem*.

Ecosystem
A system of living organisms interacting with each other and their physical environment. The boundaries of what could be called an ecosystem are somewhat arbitrary, depending on the focus of interest or study. Thus, the extent of an ecosystem may range from very small spatial scales to, ultimately, the entire Earth.

El Niño-Southern Oscillation (ENSO)
The term *El Niño* was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Perú, disrupting the local fishery. It has since become identified with a basinwide warming of the tropical Pacific east of the dateline. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the *Southern Oscillation*. This coupled *atmosphere*-ocean phenomenon, with preferred time scales of two to about seven years, is collectively known as *El Niño-Southern Oscillation*, or *ENSO*. It is often measured by the surface pressure anomaly difference between Darwin and Tahiti and the sea surface temperatures in the central and eastern equatorial Pacific. During an ENSO event, the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This event has a great impact on the wind, sea surface temperature and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific *region* and in many other parts of the world, through global teleconnections. The cold phase of ENSO is called *La Niña*.

Emissions scenario
A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., *greenhouse gases, aerosols)*, based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships. *Concentration scenarios*, derived from emission scenarios, are used as input to a *climate model* to compute *climate projections*. See *SRES scenarios*.

Endemic
Restricted or peculiar to a locality or region. With regard to human health, endemic can refer to a disease or agent present or usually prevalent in a population or geographical area at all times.

Energy
The amount of work or heat delivered. Energy is classified in a variety of types and becomes useful to human ends when it flows from one place to another or is converted from one type into another. *Primary energy* (also referred to as *energy sources*) is the energy embodied in natural resources (e.g., coal, crude oil, natural gas, uranium) that has not undergone any anthropogenic conversion. This primary energy needs to be converted and transported to become *usable energy* (e.g., light). *Renewable energy* is obtained from the continuing or repetitive currents of energy occurring in the natural environment, and includes non-carbon technologies such as solar energy, hydropower, wind, tide and waves, and geothermal heat, as well as carbon neutral technologies such as biomass. *Embodied energy* is the energy used to produce a material substance (such as processed metals, or building materials), taking into account energy used at the manufacturing facility (zero order), energy used in producing the materials that are used in the manufacturing facility (first order), and so on.

Ensemble
A group of parallel model simulations used for *climate projections*. Variation of the results across the ensemble members gives an estimate of *uncertainty*. Ensembles made with the same model but different initial conditions only characterise the uncertainty associated with internal *climate variability*, whereas multi-model ensembles including simulations by several models also include the impact of model differences. Perturbed-parameter ensembles, in which model parameters are varied in a systematic manner, aim to produce a more objective estimate of modelling uncertainty than is possible with traditional multi-model ensembles.

Epidemic
Occurring suddenly in incidence rates clearly in excess of normal expectancy, applied especially to *infectious diseases* but may also refer to any disease, injury, or other health-related event occurring in such outbreaks.

Equilibrium line
The boundary between the region on a *glacier* where there is a net annual loss of ice mass (ablation area) and that where there is a net annual gain (accumulation area). The altitude of this boundary is referred to as *equilibrium line altitude*.

Erosion
The process of removal and transport of soil and rock by weathering, mass wasting, and the action of streams, *glaciers*, waves, winds, and underground water.

Eutrophication
The process by which a body of water (often shallow) becomes (either naturally or by pollution) rich in dissolved nutrients, with a seasonal deficiency in dissolved oxygen.

Evaporation
The transition process from liquid to gaseous state.

Evapotranspiration
The combined process of water evaporation from the Earth's surface and transpiration from vegetation.

External forcing
External forcing refers to a forcing agent outside the *climate*

system causing a change in the climate system. Volcanic eruptions, solar variations and *anthropogenic* changes in the composition of the *atmosphere* and *land-use change* are external forcings.

Extinction
The complete disappearance of an entire biological species.

Extirpation
The disappearance of a species from part of its range; local *extinction*.

Extreme weather event
An event that is rare at a particular place and time of year. Definitions of "rare" vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of the observed probability density function. By definition, the characteristics of what is called *extreme weather* may vary from place to place in an absolute sense. Single extreme events cannot be simply and directly attributed to *anthropogenic climate change*, as there is always a finite chance the event in question might have occurred naturally. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an *extreme climate event*, especially if it yields an average or total that is itself extreme (e.g., *drought* or heavy rainfall over a season).

F.

Feedback
See *Climate feedback*.

Food chain
The chain of *trophic relationships* formed if several species feed on each other. See *Food web*.

Food security
A situation that exists when people have secure access to sufficient amounts of safe and nutritious food for normal growth, development and an active and healthy life. *Food insecurity* may be caused by the unavailability of food, insufficient purchasing power, inappropriate distribution, or inadequate use of food at the household level.

Food web
The network of *trophic relationships* within an *ecological community* involving several interconnected *food chains*.

Forcing
See *External forcing*.

Forest
A vegetation type dominated by trees. Many definitions of the term forest are in use throughout the world, reflecting wide differences in biogeophysical conditions, social structure, and economics. Particular criteria apply under the *Kyoto Protocol*. For a discussion of the term *forest* and related terms such as *afforestation*, *reforestation*, and *deforestation* see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000).

Fossil fuels
Carbon-based fuels from fossil hydrocarbon deposits, including coal, peat, oil, and natural gas.

Framework Convention on Climate Change
See *United Nations Framework Convention on Climate Change (UNFCCC)*.

Freshwater lens
A lenticular fresh groundwater body that underlies an oceanic island. It is underlain by saline water.

Frozen ground
Soil or rock in which part or all of the pore water is frozen. Frozen ground includes *permafrost*. Ground that freezes and thaws annually is called *seasonally frozen ground*.

G.

General circulation model
See *Climate model*.

Glacial lake
A lake formed by *glacier* meltwater, located either at the front of a glacier (known as a *proglacial lake*), on the surface of a glacier (*supraglacial lake*), within the glacier (*englacial lake*) or at the glacier bed (*subglacial lake*).

Glacier
A mass of land ice which flows downhill under gravity (through internal deformation and/or sliding at the base) and is constrained by internal stress and friction at the base and sides. A glacier is maintained by accumulation of snow at high altitudes, balanced by melting at low altitudes or discharge into the sea. See *Mass balance*.

Global warming
Global warming refers to the gradual increase, observed or projected, in global average surface temperature, as one of the consequences of radiative forcing caused by anthropogenic emissions.

Globalisation
The growing integration and interdependence of countries worldwide through the increasing volume and variety of cross-border transactions in goods and services, free international capital flows, and the more rapid and widespread diffusion of technology, information and culture.

Governance
The way government is understood has changed in response to social, economic and technological changes over recent decades. There is a corresponding shift from government defined strictly by the nation-state to a more inclusive concept of governance, recognising the contributions of various levels of government (global, international, regional, local) and the roles of the private sector, of non-governmental actors and of civil society.

Greenhouse effect
Greenhouse gases effectively absorb thermal infrared radiation, emitted by the Earth's surface, by the *atmosphere* itself due to the same gases, and by clouds. Atmospheric radiation is emitted to all sides, including downward to the Earth's surface. Thus greenhouse gases trap heat within the surface-*troposphere* system. This is called the *greenhouse effect*. Thermal infrared radiation in the troposphere is strongly coupled to the temperature of the atmosphere at the altitude at which it is emitted. In the troposphere, the temperature generally decreases with height. Effectively, infrared radiation emitted to space originates from an altitude with a temperature of, on average, –19°C, in balance with the net incoming solar radiation, whereas the Earth's surface is kept at a much higher temperature of, on average, +14°C. An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore to an effective radiation into space from a higher altitude at a lower temperature. This causes a *radiative forcing* that leads to an enhancement of the greenhouse effect, the so-called *enhanced greenhouse effect*.

Greenhouse gas (GHG)
Greenhouse gases are those gaseous constituents of the *atmosphere*, both natural and *anthropogenic*, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the *greenhouse effect*. Water vapour (H_2O), *carbon dioxide* (CO_2), *nitrous oxide* (N_2O), *methane* (CH_4) and *ozone* (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine and bromine containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the *Kyoto Protocol* deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

Gross Domestic Product (GDP)
Gross Domestic Product (GDP) is the monetary value of all goods and services produced within a nation.

Gross National Product (GNP)
Gross National Product (GNP) is the monetary value of all goods and services produced by a nation's economy, including income generated abroad by domestic residents, but without income generated by foreigners.

Gross primary production
The total carbon fixed by plant through *photosynthesis*.

Groundwater recharge
The process by which external water is added to the zone of saturation of an *aquifer*, either directly into a formation or indirectly by way of another formation.

H.

Habitat
The locality or natural home in which a particular plant, animal, or group of closely associated organisms lives.

Hadley Circulation
A direct, thermally driven overturning cell in the *atmosphere* consisting of poleward flow in the upper *troposphere*, subsiding air into the subtropical anticyclones, return flow as part of the trade winds near the surface, and with rising air near the equator and the so-called Inter-Tropical Convergence Zone.

Herbaceous
Flowering, non-woody.

Heterotrophic respiration
The conversion of organic matter to *carbon dioxide* by organisms other than plants.

Holocene
The Holocene is a geological epoch extending from about 11,600 years ago to the present.

Human system
Any system in which human organisations play a major role. Often, but not always, the term is synonymous with *society* or *social system* e.g., agricultural system, political system, technological system, economic system.

Hydrological cycle
The cycle in which water evaporates from the oceans and the land surface, is carried over the Earth in atmospheric circulation as water vapour, condensates to form clouds, precipitates again as rain or snow, is intercepted by trees and vegetation, provides *runoff* on the land surface, infiltrates into soils, recharges groundwater, discharges into streams and, ultimately, flows out into the oceans, from which it will eventually evaporate again (AMS, 2000). The various systems involved in the hydrological cycle are usually referred to as *hydrological systems*.

Hydrological systems
See *Hydrological cycle*.

Hydrosphere
The component of the *climate system* comprising liquid surface and subterranean water, such as oceans, seas, rivers, fresh water lakes, underground water, etc.

Hypolimnetic
Referring to the part of a lake below the *thermocline* made up of water that is stagnant and of essentially uniform temperature except during the period of overturn.

I.

Ice cap
A dome shaped ice mass, usually covering a highland area, which is considerably smaller in extent than an *ice sheet*.

Ice sheet
A mass of land ice that is sufficiently deep to cover most of the underlying bedrock topography, so that its shape is mainly

determined by its dynamics (the flow of the ice as it deforms internally and/or slides at its base). An ice sheet flows outwards from a high central ice plateau with a small average surface slope. The margins usually slope more steeply, and most ice is discharged through fast-flowing ice streams or outlet *glaciers*, in some cases into the sea or into ice shelves floating on the sea. There are only three large ice sheets in the modern world, one on Greenland and two on Antarctica (the East and West Antarctic ice sheets, divided by the Transantarctic Mountains). During glacial periods there were others.

Ice shelf
A floating slab of ice of considerable thickness extending from the coast (usually of great horizontal extent with a level or gently sloping surface), often filling embayments in the coastline of the *ice sheets*. Nearly all ice shelves are in Antarctica.

(Climate change) Impacts
The effects of *climate change* on natural and *human systems*. Depending on the consideration of *adaptation*, one can distinguish between potential impacts and residual impacts:
- *Potential impacts*: all impacts that may occur given a projected change in climate, without considering *adaptation*.
- *Residual impacts*: the impacts of climate change that would occur after *adaptation*.

See also *Market impacts and Non-market impacts*.

Indigenous peoples
No internationally accepted definition of indigenous peoples exists. Common characteristics often applied under international law, and by United Nations agencies to distinguish indigenous peoples include: residence within or attachment to geographically distinct traditional habitats, ancestral territories, and their natural resources; maintenance of cultural and social identities, and social, economic, cultural and political institutions separate from mainstream or dominant societies and cultures; descent from population groups present in a given area, most frequently before modern states or territories were created and current borders defined; and self-identification as being part of a distinct indigenous cultural group, and the desire to preserve that cultural identity.

Indirect aerosol effect
Aerosols may lead to an indirect *radiative forcing* of the *climate system* through acting as cloud condensation nuclei or modifying the optical properties and lifetime of clouds. Two indirect effects are distinguished:
Cloud albedo effect: A radiative forcing induced by an increase in *anthropogenic aerosols* that cause an initial increase in droplet concentration and a decrease in droplet size for fixed liquid water content, leading to an increase in cloud *albedo*.
Cloud lifetime effect: A forcing induced by an increase in *anthropogenic aerosols* that cause a decrease in droplet size, reducing the precipitation efficiency, thereby modifying the liquid water content, cloud thickness and cloud life time.
Apart from these indirect effects, *aerosols* may have a semi-direct effect. This refers to the absorption of solar radiation by absorbing aerosol, which heats the air and tends to increase the static stability relative to the surface. It may also cause *evaporation* of cloud droplets.

Infectious disease
Any disease caused by microbial agents that can be transmitted from one person to another or from animals to people. This may occur by direct physical contact, by handling of an object that has picked up infective organisms, through a disease carrier, via contaminated water, or by spread of infected droplets coughed or exhaled into the air.

Infrastructure
The basic equipment, utilities, productive enterprises, installations, and services essential for the development, operation, and growth of an organisation, city, or nation.

Integrated water resources management (IWRM)
The prevailing concept for water management which, however, has not been defined unambiguously. IWRM is based on four principles that were formulated by the International Conference on Water and the Environment in Dublin, 1992: 1) fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment; 2) water development and management should be based on a participatory approach, involving users, planners and policymakers at all levels; 3) women play a central part in the provision, management and safeguarding of water; 4) water has an economic value in all its competing uses and should be recognised as an economic good.

Interdecadal Pacific Oscillation (IPO)
Also known as the *Pacific Decadal Oscillation* (PDO). See *North Pacific Index*. [For more detail see WGI Box 3.4]

Internal variability
See *Climate variability*.

Irrigation water-use efficiency
Irrigation *water-use efficiency* is the amount of *biomass* or seed yield produced per unit irrigation water applied, typically about 1 tonne of dry matter per 100 mm water applied.

IS92 scenarios
See *Emissions scenarios*.

Isostacy
Isostacy refers to the way in which the lithosphere and mantle respond visco-elastically to changes in surface loads. When the loading of the lithosphere and/or the mantle is changed by alterations in land ice mass, ocean mass, sedimentation, erosion or mountain building, vertical isostatic adjustment results, in order to balance the new load.

K.

Kyoto Protocol
The Kyoto Protocol to the *United Nations Framework Convention on Climate Change (UNFCCC)* was adopted in 1997 in Kyoto, Japan, at the Third Session of the Conference of the Parties (COP)

to the UNFCCC. It contains legally binding commitments, in addition to those included in the UNFCCC. Countries included in *Annex B* of the Protocol (most Organization for Economic Cooperation and Development countries and countries with economies in transition) agreed to reduce their *anthropogenic greenhouse gas* emissions (*carbon dioxide*, *methane*, *nitrous oxide*, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride) by at least 5% below 1990 levels in the commitment period 2008 to 2012. The *Kyoto Protocol* entered into force on 16 February 2005.

L.

La Niña
See *El Niño-Southern Oscillation (ENSO)*.

Land use and Land-use change
Land use refers to the total of arrangements, activities and inputs undertaken in a certain land cover type (a set of human actions). The term *land use* is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, and conservation).
Land-use change refers to a change in the use or management of land by humans, which may lead to a change in land cover. Land cover and land-use change may have an impact on the surface *albedo*, *evapotranspiration*, *sources* and *sinks* of *greenhouse gases*, or other properties of the *climate system* and may thus have a *radiative forcing* and/or other impacts on *climate*, locally or globally. See also: the IPCC Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000).

Landfill
A landfill is a solid waste disposal site where waste is deposited below, at or above ground level. Limited to engineered sites with cover materials, controlled placement of waste and management of liquids and gases. It excludes uncontrolled waste disposal.

Landslide
A mass of material that has slipped downhill by gravity, often assisted by water when the material is saturated; the rapid movement of a mass of soil, rock or debris down a slope.

Lapse rate
The rate of change of an atmospheric variable, usually temperature, with height. The lapse rate is considered positive when the variable decreases with height.

Latent heat flux
The flux of heat from the Earth's surface to the *atmosphere* that is associated with evaporation or condensation of water vapour at the surface; a component of the surface energy budget.

Leaching
The removal of soil elements or applied chemicals by water movement through the soil.

Likelihood
The likelihood of an occurrence, an outcome or a result, where this can be estimated probabilistically, is expressed in this Technical Paper using a standard terminology defined in Box 1.1.
See also *Confidence*; *Uncertainty*.

Little Ice Age (LIA)
An interval between approximately AD 1400 and 1900 when temperatures in the Northern Hemisphere were generally colder than today's, especially in Europe.

M.

Malaria
Endemic or epidemic parasitic disease caused by species of the genus *Plasmodium* (Protozoa) and transmitted to humans by mosquitoes of the genus *Anopheles*; produces bouts of high fever and systemic disorders, affects about 300 million and kills approximately 2 million people worldwide every year.

Market impacts
Impacts that can be quantified in monetary terms, and directly affect *gross domestic product* – e.g., changes in the price of agricultural inputs and/or goods. See *Non-market impacts*.

Mass balance (of glaciers, ice caps or ice sheets)
The balance between the mass input to an ice body (accumulation) and the mass loss (ablation, iceberg calving). Mass balance terms include the following:
Specific mass balance: net mass loss or gain over a *hydrological cycle* at a point on the surface of a *glacier*.
Total mass balance (of the glacier): the specific mass balance spatially integrated over the entire glacier area; the total mass a glacier gains or loses over a hydrological cycle.
Mean specific mass balance: the total mass balance per unit area of the glacier. If *surface* is specified (*specific surface mass balance*, etc.) then ice-flow contributions are not considered; otherwise, mass balance includes contributions from ice flow and iceberg calving. The specific surface mass balance is positive in the accumulation area and negative in the ablation area.

Meningitis
Inflammation of the meninges (part of the covering of the brain), usually caused by bacteria, viruses or fungi.

Meridional overturning circulation (MOC)
A zonally averaged, large scale meridional (north-south) overturning circulation in the oceans. In the Atlantic such a circulation transports relatively warm upper-ocean waters northward, and relatively cold deep waters southward. The *Gulf Stream* forms part of this Atlantic circulation.

Methane (CH_4)
Methane is one of the six *greenhouse gases* to be mitigated under the *Kyoto Protocol* and is the major component of natural gas and associated with all hydrocarbon fuels, animal husbandry and agriculture. *Coal-bed methane* is the gas found in coal seams.

Millennium Development Goals (MDGs)
A set of time-bound and measurable goals for combating poverty, hunger, disease, illiteracy, discrimination against

women and environmental degradation, agreed at the UN Millennium Summit in 2000.

Mires

Peat-accumulating *wetlands*. See *Bog*.

Mitigation

Technological change and substitution that reduce resource inputs and emissions per unit of output. Although several social, economic and technological policies would produce an emissions reduction, with respect to *climate change*, mitigation means implementing policies to reduce *greenhouse gas* emissions and enhance *sinks*.

Monsoon

A monsoon is a tropical and subtropical seasonal reversal in both the surface winds and associated precipitation, caused by differential heating between a continental-scale land mass and the adjacent ocean. Monsoon rains occur mainly over land in summer.

Montane

The biogeographic zone made up of relatively moist, cool upland slopes below the *sub-alpine* zone that is characterised by the presence of mixed deciduous at lower and coniferous evergreen forests at higher elevations.

Morbidity

Rate of occurrence of disease or other health disorder within a population, taking account of the age-specific morbidity rates. Morbidity indicators include chronic disease incidence/ prevalence, rates of hospitalisation, primary care consultations, disability-days (i.e., days of absence from work), and prevalence of symptoms.

Mortality

Rate of occurrence of death within a population; calculation of mortality takes account of age-specific death rates, and can thus yield measures of life expectancy and the extent of premature death.

N.

Net ecosystem production (NEP)

Net ecosystem production is the difference between *net primary production (NPP)* and *heterotrophic respiration* (mostly decomposition of dead organic matter) of that *ecosystem* over the same area.

Net primary production (NPP)

Net primary production is the *gross primary production* minus autotrophic *respiration*, i.e., the sum of metabolic processes for plant growth and maintenance, over the same area.

Nitrous oxide (N_2O)

One of the six types of *greenhouse gases* to be curbed under the *Kyoto Protocol*. The main anthropogenic source of nitrous oxide is agriculture (soil and animal manure management), but important contributions also come from sewage treatment, combustion of fossil fuel, and chemical industrial processes. Nitrous oxide is also produced naturally from a wide variety of biological sources in soil and water, particularly microbial action in wet tropical forests.

No-regrets policy

A policy that would generate net social and/or economic benefits irrespective of whether or not *anthropogenic climate change* occurs.

Non-Governmental Organisation (NGO)

A non-profit group or association organised outside of institutionalised political structures to realise particular social and/or environmental objectives or serve particular constituencies.

Non-linearity

A process is called non-linear when there is no simple proportional relation between cause and effect. The *climate system* contains many such non-linear processes, resulting in a system with a potentially very complex behaviour.

Non-market impacts

Impacts that affect *ecosystems* or human welfare, but that are not easily expressed in monetary terms, e.g., an increased risk of premature death, or increases in the number of people at risk of hunger. See also *Market impacts*.

North Atlantic Oscillation (NAO)

The North Atlantic Oscillation consists of opposing variations of barometric pressure near Iceland and near the Azores. It therefore corresponds to fluctuations in the strength of the main westerly winds across the Atlantic into Europe, and thus to fluctuations in the embedded cyclones with their associated frontal systems. See WGI Box 3.4.

North Pacific Index (NPI)

The NPI is the average mean sea level pressure anomaly in the Aleutian Low over the Gulf of Alaska (30°N- 65°N, 160°E-140°W). It is an index of the *Pacific Decadal Oscillation* (also known as the *Interdecadal Pacific Oscillation*). See WGI Box 3.4 for further information.

O.

Oil sands and oil shale

Unconsolidated porous sands, sandstone rock and shales containing bituminous material that can be mined and converted to a liquid fuel.

Ombrotrophic bog

An acidic *peat*-accumulating *wetland* that is rainwater (instead of groundwater) fed and thus particularly poor in nutrients.

Ozone (O_3)

Ozone, the tri-atomic form of oxygen, is a gaseous *atmospheric* constituent. In the *troposphere*, ozone is created both naturally and by photochemical reactions involving gases resulting from human activities (smog). Troposphere ozone acts as a *greenhouse gas*. In the *stratosphere*, ozone is created by the interaction between solar ultraviolet radiation and molecular oxygen (O_2). Stratospheric ozone plays a dominant role in the stratospheric radiative balance. Its concentration is highest in the ozone layer.

P.

Pacific Decadal Oscillation (PDO)
Also known as the Interdecadal Pacific Oscillation (IPO). See *North Pacific Index*. [WGI Box 3.4]

Pacific-North American (PNA) pattern
An atmospheric large-scale wave pattern featuring a sequence of tropospheric high- and low-pressure anomalies stretching from the subtropical west Pacific to the east coast of North America. [WGI Box 3.4]

Peat
Peat is formed from dead plants, typically *Sphagnum* mosses, which are only partially decomposed due to their permanent submergence in water and the presence of conserving substances such as humic acids.

Peatland
Typically a *wetland* such as a *mire* slowly accumulating *peat*.

Percentile
A percentile is a value on a scale of zero to one hundred that indicates the percentage of the data set values that is equal to or below it. The percentile is often used to estimate the extremes of a distribution. For example, the 90^{th} (10^{th}) percentile may be used to refer to the threshold for the upper (lower) extremes.

Permafrost
Ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years. See also *Frozen ground*.

pH
pH is a dimensionless measure of the acidity of water (or any solution). Pure water has a pH=7. Acid solutions have a pH smaller than 7 and basic solutions have a pH larger than 7. pH is measured on a logarithmic scale. Thus, a pH decrease of 1 unit corresponds to a 10-fold increase in the acidity.

Phenology
The study of natural phenomena in biological systems that recur periodically (e.g., development stages, migration) and their relation to *climate* and seasonal changes.

Photosynthesis
The process by which green plants, algae and some bacteria take *carbon dioxide* from the air (or bicarbonate in water) to build carbohydrates. There are several pathways of photosynthesis with different responses to atmospheric carbon dioxide concentrations. See *Carbon dioxide fertilisation*.

Plankton
Micro-organisms living in the upper layers of aquatic systems. A distinction is made between *phytoplankton*, which depend on photosynthesis for their energy supply, and *zooplankton*, which feed on phytoplankton.

Policies
In *United Nations Framework Convention on Climate Change (UNFCCC)* parlance, policies are taken and/or mandated by a government—often in conjunction with business and industry within its own country, or with other countries—to accelerate *mitigation* and *adaptation* measures. Examples of policies are carbon or other energy taxes, fuel efficiency standards for automobiles, etc. *Common and co-ordinated or harmonised policies* refer to those adopted jointly by parties.

Primary production
All forms of production accomplished by plants, also called primary producers. See *Gross primary production*, *Net primary production* and *Net ecosystem production*.

Projection
A potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Projections are distinguished from predictions in order to emphasise that projections involve assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised, and are therefore subject to substantial *uncertainty*. See also *Climate projection*.

Proxy
A proxy *climate* indicator is a local record that is interpreted, using physical and bio-physical principles, to represent some combination of climate-related variations back in time. Climate-related data derived in this way are referred to as proxy data. Examples of proxies include pollen analysis, tree-ring records, characteristics of corals and various data derived from ice cores.

R.

Radiative forcing
Radiative forcing is the change in the net, downward minus upward, irradiance (expressed in Watts per square metre, W/m^2) at the tropopause due to a change in an external driver of *climate change*, such as, for example, a change in the concentration of *carbon dioxide* or the output of the Sun. Radiative forcing is computed with all *tropospheric* properties held fixed at their unperturbed values, and after allowing for *stratospheric* temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is called *instantaneous* if no change in stratospheric temperature is accounted for. For the purposes of this Technical Paper, radiative forcing is further defined as the change relative to the year 1750 and, unless otherwise noted, refers to a global and annual average value.

Rangeland
Unmanaged grasslands, shrublands, *savannas* and *tundra*.

Reconstruction
The use of *climate* indicators to help determine (generally past) climates.

Reforestation
Planting of *forests* on lands that have previously contained forests but that have been converted to some other use. For a discussion of the term *forest* and related terms such as *afforestation*, reforestation and *deforestation*, see the IPCC Report on Land Use, Land-Use Change and Forestry (IPCC, 2000).

Regime
A regime is a preferred state of the *climate system*, often representing one phase of dominant patterns or modes of climate variability.

Region
A region is a territory characterised by specific geographical and climatological features. The *climate* of a region is affected by regional and local scale forcings such as topography, *land-use* characteristics, lakes etc., as well as remote influences from other regions.

Reservoir
An artificial or natural storage place for water, such as a lake, pond or *aquifer*, from which the water may be withdrawn for such purposes as irrigation or water supply.

Resilience
The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change.

Respiration
The process whereby living organisms convert organic matter to *carbon dioxide*, releasing energy and consuming oxygen.

Riparian
Relating to or living or located on the bank of a natural watercourse (such as a river) or sometimes of a lake or a tidewater.

Runoff
That part of precipitation that does not evaporate and is not transpired, but flows over the ground surface and returns to bodies of water. See *Hydrological cycle*.

S.
Salinisation
The accumulation of salts in soils.

Saltwater intrusion
Displacement of fresh surface water or groundwater by the advance of saltwater due to its greater density. This usually occurs in coastal and estuarine areas due to reducing land-based influence (e.g., either from reduced *runoff* and associated groundwater recharge, or from excessive water withdrawals from aquifers) or increasing marine influence (e.g., relative *sea-level rise*).

Savanna
Tropical or sub-tropical grassland or woodland *biomes* with scattered shrubs, individual trees or a very open canopy of trees, all characterised by a dry (arid, semi-arid or semi-humid) *climate*.

Scenario
A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from *projections*, but are often based on additional information from other sources, sometimes combined with a *narrative storyline*. See also *SRES scenarios*; *Climate scenario*; *Emissions scenarios*.

Sea ice
Any form of ice found at sea that has originated from the freezing of sea water. Sea ice may be discontinuous pieces (*ice floes*) moved on the ocean surface by wind and currents (*pack ice*), or a motionless sheet attached to the coast (*land-fast ice*).

Sea-ice biome
The *biome* formed by all marine organisms living within or on the floating sea ice (frozen seawater) of the polar oceans.

Sea-level change/sea-level rise
Sea level can change, both globally and locally, due to (i) changes in the shape of the ocean basins, (ii) changes in the total mass of water and (iii) changes in water density. Factors leading to sea-level rise under global warming include both increases in the total mass of water from the melting of land-based snow and ice, and changes in water density from an increase in ocean water temperatures and salinity changes. *Relative sea-level rise* occurs where there is a local increase in the level of the ocean relative to the land, which might be due to ocean rise and/or land-level subsidence.

Sea-level equivalent (SLE)
The change in global average sea level that would occur if a given amount of water or ice were added to or removed from the oceans.

Sea surface temperature (SST)
The sea surface temperature is the subsurface bulk temperature in the top few metres of the ocean, measured by ships, buoys and drifters. From ships, measurements of water samples in buckets were mostly switched in the 1940s to samples from engine intake water. Satellite measurements of skin temperature (uppermost layer; a fraction of a millimetre thick) in the infrared or the top centimetre or so in the microwave are also used, but must be adjusted to be compatible with the bulk temperature.

Seasonally frozen ground
See *Frozen ground*.

Semi-arid regions
Regions of moderately low rainfall, which are not highly productive and are usually classified as *rangelands*. 'Moderately low' is widely accepted as between 100 and 250 mm precipitation per year. See also *Arid region*.

Sensitivity
Sensitivity is the degree to which a system is affected, either adversely or beneficially, by *climate variability* or *climate change*. The effect may be *direct* (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or *indirect* (e.g., damages caused by an increase in the frequency of coastal flooding due to *sea-level rise*).

Sequestration
Carbon storage in terrestrial or marine *reservoirs*. *Biological sequestration* includes direct removal of CO_2 from the atmosphere through *land-use change*, *afforestation*, *reforestation*, carbon storage in *landfills* and practices that enhance soil carbon in agriculture.

Silviculture
Cultivation, development and care of *forests*.

Sink
Any process, activity or mechanism which removes a *greenhouse gas*, an *aerosol* or a precursor of a greenhouse gas or aerosol from the *atmosphere*.

Snow pack
A seasonal accumulation of slow-melting snow.

Snow water equivalent
The equivalent volume/mass of water that would be produced if a particular body of snow or ice was melted.

Soil moisture
Water stored in or at the land surface and available for *evaporation*.

Source
Source mostly refers to any process, activity or mechanism that releases a *greenhouse gas*, an *aerosol*, or a precursor of a greenhouse gas or aerosol into the *atmosphere*. Source can also refer to e.g., an *energy* source.

Southern Oscillation Index (SOI)
See El Niño-Southern Oscillation.

Spatial and temporal scales
Climate may vary on a large range of spatial and temporal scales. *Spatial scales* may range from local (less than 100,000 km^2), through regional (100,000 to 10 million km^2) to continental (10 to 100 million km^2). *Temporal scales* may range from seasonal to geological (up to hundreds of millions of years).

SRES scenarios
SRES scenarios are *emissions scenarios* developed by Nakićenović and Swart (2000) and used, among others, as a basis for some of the *climate projections* used in the IPCC Fourth Assessment Report. The following terms are relevant for a better understanding of the structure and use of the set of SRES scenarios:

- *Scenario family*: Scenarios that have a similar demographic, societal, economic and technical-change storyline. Four scenario families comprise the SRES scenario set: A1, A2, B1 and B2.
- *Illustrative scenario*: A scenario that is illustrative for each of the six scenario groups reflected in the Summary for Policymakers of Nakićenović and Swart (2000). They include four revised 'scenario markers' for the scenario groups A1B, A2, B1, B2, and two additional scenarios for the A1FI and A1T groups. All scenario groups are equally sound.
- *Marker scenario*: A scenario that was originally posted in draft form on the SRES website to represent a given scenario family. The choice of markers was based on which of the initial quantifications best reflected the storyline, and the features of specific models. Markers are no more likely than other scenarios, but are considered by the SRES writing team as illustrative of a particular storyline. They are included in revised form in Nakićenović and Swart (2000). These scenarios received the closest scrutiny of the entire writing team and via the SRES open process. Scenarios were also selected to illustrate the other two scenario groups.
- *Storyline*: A narrative description of a scenario (or family of scenarios), highlighting the main scenario characteristics, relationships between key driving forces and the dynamics of their evolution.

Stakeholder
A person or an organisation that has a legitimate interest in a project or entity, or would be affected by a particular action or *policy*.

Storm surge
The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place.

Storm tracks
Originally, a term referring to the tracks of individual cyclonic weather systems, but now often generalised to refer to the *regions* where the main tracks of extratropical disturbances occur as sequences of low (cyclonic) and high (anticyclonic) pressure systems.

Storyline
A narrative description of a scenario (or a family of scenarios) that highlights the scenario's main characteristics, relationships between key driving forces, and the dynamics of the scenarios.

Stratosphere
The highly stratified region of the *atmosphere* above the *troposphere* extending from about 10 km (ranging from 9 km in high latitudes to 16 km in the tropics on average) to about 50 km altitude.

Streamflow
Water flow within a river channel, for example expressed in m^3/s. A synonym for river discharge.

Subsidy
Direct payment from the government or a tax reduction to a private party for implementing a practice the government wishes to encourage. The reduction of *greenhouse-gas emissions* is stimulated by lowering existing subsidies that have the effect of raising emissions (such as subsidies to fossil fuel use) or by providing subsidies for practices that reduce emissions or enhance sinks (e.g., for insulation of buildings or for planting trees).

Succulent
Succulent plants, e.g., cactuses, possessing organs that store water, thus facilitating survival during *drought* conditions.

Sustainable development
Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

T.

Taiga
The northernmost belt of *boreal forest* adjacent to the Arctic *tundra*.

Technology
The practical application of knowledge to achieve particular tasks that employs both technical artefacts (hardware, equipment) and (social) information ("software", know-how for production and use of artefacts).

Teleconnection
A connection between *climate variations* over widely separated parts of the world. In physical terms, teleconnections are often a consequence of large-scale wave motions, whereby energy is transferred from source regions along preferred paths in the *atmosphere*.

Thermal expansion
In connection with *sea-level rise*, this refers to the increase in volume (and decrease in density) that results from warming water. A warming of the ocean leads to an expansion of the ocean volume and hence an increase in sea level. See *Sea-level change*.

Thermocline
The region in the world's ocean, typically at a depth of 1 km, where temperature decreases rapidly with depth and which marks the boundary between the surface and the ocean.

Thermohaline circulation (THC)
Large-scale, density-driven circulation in the ocean, caused by differences in temperature and salinity. In the North Atlantic, the thermohaline circulation consists of warm surface water flowing northward and cold deepwater flowing southward, resulting in a net poleward transport of heat. The surface water sinks in highly restricted regions located in high latitudes. Also called *Meridional Overturning Circulation* (MOC).

Thermokarst
A ragged landscape full of shallow pits, hummocks and depressions often filled with water (ponds), which results from thawing of ground ice or *permafrost*. Thermokarst processes are the processes driven by warming that lead to the formation of thermokarst.

Threshold
The level of magnitude of a system process at which sudden or rapid change occurs. A point or level at which new properties emerge in an ecological, economic or other system, invalidating predictions based on mathematical relationships that apply at lower levels.

Transpiration
The *evaporation* of water vapour from the surfaces of leaves through stomata. See *Evapotranspiration*.

Trend
In this Technical Paper, the word *trend* designates a change, generally monotonic in time, in the value of a variable.

Trophic relationship
The ecological relationship which results when one species feeds on another.

Troposphere
The lowest part of the *atmosphere* from the surface to about 10 km in altitude in mid-latitudes (ranging from 9 km in high latitudes to 16 km in the tropics on average), where clouds and weather phenomena occur. In the troposphere, temperatures generally decrease with height.

Tundra
A treeless, level, or gently undulating plain characteristic of the Arctic and sub-Arctic regions characterised by low temperatures and short growing seasons.

U.

Uncertainty
An expression of the degree to which a value (e.g., the future state of the *climate system*) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain *projections* of human behaviour. Uncertainty can therefore be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative statements, for example, reflecting the judgement of a team of experts. See also *Likelihood; Confidence*.

United Nations Framework Convention on Climate Change (UNFCCC)
The Convention was adopted on 9 May 1992 in New York and

signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the 'stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'. It contains commitments for all Parties. Under the Convention, Parties included in *Annex I* (all OECD member countries in the year 1990 and countries with economies in transition) aim to return *greenhouse gas* emissions not controlled by the Montreal Protocol to 1990 levels by the year 2000. The Convention entered in force in March 1994. See *Kyoto Protocol*.

Urbanisation
The conversion of land from a natural state or managed natural state (such as agriculture) to cities; a process driven by net rural-to-urban migration through which an increasing percentage of the population in any nation or region come to live in settlements that are defined as *urban centres*.

V.

Vector
An organism, such as an insect, that transmits a pathogen from one host to another.

Vector-borne diseases
Diseases that are transmitted between hosts by a *vector* organism (such as a mosquito or tick); e.g., *malaria*, *dengue fever* and leishmaniasis.

Vulnerability
Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of *climate change*, including *climate variability* and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its *sensitivity*, and its *adaptive capacity*.

W.

Water consumption
Amount of extracted water irretrievably lost during its use (by evaporation and goods production). Water consumption is equal to water withdrawal minus return flow.

Water security
Reliable availability of water in sufficient quantity and quality to sustain human health, livelihoods, production and the environment.

Water stress
A country is water stressed if the available freshwater supply relative to water withdrawals acts as an important constraint on development. In global-scale assessments, basins with water stress are often defined as having a per capita water availability below 1,000 m^3/yr (based on long-term average runoff). Withdrawals exceeding 20% of renewable water supply have also been used as an indicator of water stress. A crop is water stressed if soil available water, and thus actual *evapotranspiration*, is less than potential evapotranspiration demands.

Water-use efficiency
Carbon gain in *photosynthesis* per unit water lost in *evapotranspiration*. It can be expressed on a short-term basis as the ratio of photosynthetic carbon gain per unit transpirational water loss, or on a seasonal basis as the ratio of *net primary production* or agricultural yield to the amount of available water.

Wetland
A transitional, regularly waterlogged area of poorly drained soils, often between an aquatic and a terrestrial *ecosystem*, fed from rain, surface water or groundwater. Wetlands are characterised by a prevalence of vegetation adapted for life in saturated soil conditions.

References

AMS, 2000: *AMS Glossary of Meteorology*, 2nd Edition. American Meteorological Society, Boston, MA. http://amsglossary.allenpress.com/glossary/browse.

Heim, R.R., 2002: A review of twentieth century drought indices used in the United States. *Bull. Am. Meteorol. Soc.*, **83**, 1149-1165.

IPCC (Intergovernmental Panel on Climate Change), 2000: *Land Use, Land-Use Change and Forestry*, R. T. Watson, I. R. Noble, B. Bolin, N. H. Ravindranath, D. J. Verardo and D. J. Dokken, Eds., Cambridge University Press, Cambridge, 375 pp.

IUCN, 1980: *The World Conservation Strategy: living resource conservation for sustainable development*. IUCN/UNEP/WWF, Gland.

Nakićenović, N. and R. Swart, Eds., 2000: *Special Report on Emissions Scenarios*. Cambridge University Press, 599 pp.

Appendix III: Acronyms, chemical symbols, scientific units

III.1 Acronyms and chemical symbols

ACIA	Arctic Climate Impact Assessment
AIDS	Acquired immune deficiency syndrome
AMO	Atlantic Multi-decadal Oscillation
AOGCM	Atmosphere–ocean general circulation model
AR4	Fourth Assessment Report (of the IPCC)
ARD	Afforestation, reforestation and deforestation
CCS	Carbon capture and storage
CDM	Clean Development Mechanism
CH_4	Methane, see Glossary
CO_2	Carbon dioxide, see Glossary
CRU	Climatic Research Unit
DJF	December, January, February
ECLAC	Economic Commission for Latin America and the Caribbean
ENSO	El Niño–Southern Oscillation
EROS	Earth Resources Observation and Science
ES	Executive Summary
EU	European Union
FAO	Food and Agriculture Organization
FAQ	Frequently Asked Questions
FAR	First Assessment Report (of the IPCC)
GCM	General circulation model
GDP	Gross domestic product
GHCN	Global Historical Climatology Network
GHG	Greenhouse gas(es)
GLOF	Glacial lake outburst flood
GNP	Gross national product
GPCC	Global Precipitation Climatology Centre
GPCP	Global Precipitation Climatology Project
HABs	Harmful algal blooms
HIV	Human immunodeficiency virus
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
IPO	Inter-decadal Pacific Oscillation
IUCN	International Union for the Conservation of Nature and Natural Resources (World Conservation Union)
JJA	June, July, August
LIA	Little Ice Age
LULUCF	Land use, land-use change and forestry
MARA/ARMA	Mapping Malaria Risk in Africa/Atlas du Risque de la Malaria en Afrique
MDG	Millennium Development Goal
MOC	Meridional overturning circulation
N_2O	Nitrous oxide, see Glossary
NAM	Northern Annular Mode
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NGO	Non-governmental organisation
NH	Northern Hemisphere
OECD	Organisation for Economic Co-operation and Development
PCBs	Polychlorinated biphenyls
PDO	Pacific Decadal Oscillation
PDR	People's Democratic Republic
PDSI	Palmer Drought Severity Index
pH	See Glossary under *pH*
PNA	Pacific–North American (pattern)
ppm	Parts per million, see Appendix III.2
PREC/L	Precipitation Reconstruction over Land
PSA	Pacific–South American (pattern)
SAM	Southern Annular Mode
SAR	Second Assessment Report (of the IPCC)
SD	Standard deviation
SI	Suitability index
SIDS	Small Island Developing States
SLE	Sea-level equivalent
SM	Supplementary Material
SOI	Southern Oscillation Index
SPCZ	South Pacific Convergence Zone
SPM	Summary for Policymakers
SRES	Special Report on Emissions Scenarios
SST	Sea surface temperature
SWE	Snow water equivalent
SYR	Synthesis Report (of the IPCC Fourth Assessment)
TAR	Third Assessment Report (of the IPCC)
TS	Technical Summary
UK	United Kingdom
UN	United Nations
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations Children's Fund
US$	United States dollar
USA	United States of America
WCP	World Climate Programme
WGI	Working Group I (of the IPCC)
WGII	Working Group II (of the IPCC)
WGIII	Working Group III (of the IPCC)
WHO	World Health Organization
WSP	Water safety plan

III.2 Scientific units

SI (Système Internationale) units

Physical quantity	*Name of unit*	*Symbol*
length	metre	m
mass	kilogram	kg
time	second	s
thermodynamic temperature	kelvin	K
energy	joule	J

Fractions and multiples

Fraction	*Prefix*	*Symbol*	*Multiple*	*Prefix*	*Symbol*
10^{-1}	deci	d	10	deca	da
10^{-2}	centi	c	10^{2}	hecto	h
10^{-3}	milli	m	10^{3}	kilo	k
10^{-6}	micro	μ	10^{6}	mega	M
10^{-9}	nano	n	10^{9}	giga	G
10^{-12}	pico	p	10^{12}	tera	T
10^{-15}	femto	f	10^{15}	peta	P
10^{-18}	atto	a	10^{18}	exa	E

Non-SI units, quantities and related abbreviations

°C	degree Celsius (0°C = 273 K approximately); temperature differences are also given in °C (=K) rather than the more correct form of "Celsius degrees"
ppm	mixing ratio (as concentration measure of GHGs): parts per million (10^{6}) by volume
watt	power or radiant flux; 1 watt = 1 joule / second = 1 kg m^{2} / s^{3}
yr	year

Appendix IV: List of Authors

Bates, Bryson
CSIRO
Australia

Kundzewicz, Zbigniew W.
Polish Academy of Sciences, Poland, and
Potsdam Institute for Climate Impact Research, Germany

Wu, Shaohong
Institute of Geographical Sciences and Natural Resources Research
Chinese Academy of Sciences
China

Arnell, Nigel
Walker Institute for Climate System Research at the University of Reading
UK

Burkett, Virginia
US Geological Survey
USA

Döll, Petra
University of Frankfurt
Germany

Gwary, Daniel
University of Maiduguri
Nigeria

Hanson, Clair
Met Office Hadley Centre
UK

Heij, BertJan
Bergonda Science Communication
The Netherlands

Jiménez, Blanca Elena
Universidad Nacional Autónoma de México
Mexico

Kaser, Georg
University of Innsbruck
Austria

Kitoh, Akio
Japan Meteorological Agency
Japan

Kovats, Sari
London School of Hygiene and Tropical Medicine
UK

Kumar, Pushpam
University of Liverpool
UK

Magadza, Christopher H.D.
University of Zimbabwe
Zimbabwe

Martino, Daniel
Carbosur
Uruguay

Mata, Luis José
Nord-Süd Zentrum für Entwicklungsforschung
Germany/Venezuela

Medany, Mahmoud
The Central Laboratory for Agricultural Climate
Egypt

Miller, Kathleen
National Center for Atmospheric Research
USA

Oki, Taikan
University of Tokyo
Japan

Osman, Balgis
Higher Council for Environment and Natural Resources
Sudan

Palutikof, Jean
Met Office Hadley Centre
UK

Prowse, Terry
Environment Canada and University of Victoria
Canada

Pulwarty, Roger
NOAA/CIRES/Climate Diagnostics Center
USA/Trinidad and Tobago

Räisänen, Jouni
University of Helsinki
Finland

Renwick, James
National Institute of Water and Atmospheric Research
New Zealand

Tubiello, Francesco Nicola
Columbia University
USA/IIASA/Italy

Wood, Richard
Met Office Hadley Centre
UK

Zhao, Zong-Ci
China Meteorological Administration
China
Arblaster, Julie
National Center for Atmospheric Research, USA and Bureau of Meteorology, Australia

Betts, Richard
Met Office Hadley Centre
UK

Dai, Aiguo
National Center for Atmospheric Research
USA

Milly, Christopher
US Geological Survey
USA

Mortsch, Linda
Environment Canada
Canada

Nurse, Leonard
University of the West Indies, Cave Hill Campus
Barbados

Payne, Richard
Department of Agriculture and Food Western Australia
Australia

Pinskwar, Iwona
Polish Academy of Sciences
Poland

Wilbanks, Tom
Oak Ridge National Laboratory
USA

Appendix V: List of Reviewers

Andressen, Rigoberto
Universidad de Los Andes
Venezuela

Asanuma, Jun
University of Tsukuba
Japan

Bandyopadhyay, Jayanta
Indian Institute of Management
India

Bayoumi, Attia
Ministry of Water Resources and Irrigation
Egypt

Bergström, Sten
Swedish Meteorological and Hydrological Institute
Sweden

Bernstein, Leonard
International Petroleum Industry Environmental Conservation Association
UK

Bidegain, Mario
Uruguay

Bojariu, Roxana
National Meteorological Administration
Romania

de Loë, Rob
University of Guelph
Canada

Diaz Morejon, Cristobel Felix
Ministry of Science, Technology and the Environment
Cuba

Elgizouli, Ismail
Higher Council for Environment and Natural Resources
Sudan

Fobil, Julius
University of Ghana, Legon
Ghana

Folland, Chris
Met Office Hadley Centre
UK

Gallart, Francesc
CSIC
Spain

Gerten, Dieter
Potsdam Institute for Climate Impact Research
Germany

Gillett, Nathan
University of East Anglia
UK

Ginzo, Héctor
Ministerio de Relaciones Exteriores
Argentina

Grabs, Wolfgang
World Meteorological Organization
Switzerland

Hatfield, Jerry
US Department of Agriculture
USA

Jacob, Daniela
Max Planck Institute for Meteorology
Germany

Jacobs, Katharine
Arizona Universities
USA

Jeffrey, Paul
Cranfield University
UK

Jouzel, Jean
Institut Pierre-Simon Laplace
France

Jin, Byung-bok
Environmental Management Corporation
Republic of Korea

Kadaja, Jüri
Estonian Research Institute of Agriculture
Estonia

Kaser, Georg
University of Innsbruck
Austria

Kimball, Bruce
US Department of Agriculture
USA

Knutson, Thomas
Princeton University
USA

Komen, Gerbrand
Royal Netherlands Meteorological Institute
The Netherlands

Kotwicki, Vincent
Kuwait Institute for Scientific Research
Kuwait

Lal, Murari
CESDAC
India

Lapin, Milan
Comenius University
Slovakia

Leon, Alejandro
Universidad de Chile
Chile

Liu, Chunzhen
Ministry of Water Resources
China

Mares, Constantin
Romanian Academy of Technical Sciences
Romania

Mares, Ileana
Romanian Academy of Technical Sciences
Romania

Mariotti, Annarita
ENEA
Italy

Morgenschweis, Gerd
Water Resources Management
Germany

Müller, Lars
Climate Strategy
European Union (Germany)

Njie, Momodou
Blue Gold Solutions
The Gambia

Noda, Akira
Frontier Research Centre for Global Change
Japan

Parry, Martin
Co-chair IPCC Working Group II
UK

Ragab, Ragab
Centre for Ecology and Hydrology
UK

Ren, Guoyu
National Climate Centre
China

Robock, Alan
Rutgers University
USA

Roy, Rene
Ouranos, Consortium on Climate Change
Canada

Savard, Martine M.
Natural Resources Canada
Canada

Schipper, Lisa
Chulalongkorn University
Thailand

Şen, Zekai
Istanbul Technical University
Turkey

Sherwood, Steve
Yale University
USA

Shim, Kyo-moon
National Institute of Agricultural Science and Technology
South Korea

Sorooshian, Soroosh
University of California, Irvine
USA

Szolgay, Jan
Slovak University of Technology
Slovakia

Tabet-Aoul, Mahi
Research Centre on Social and Cultural Anthropology (CRASC)
Algeria

Trenberth, Kevin
National Center for Atmospheric Research
USA

van Walsum, Paul
Wageningen University and Research Centre
The Netherlands

Wojciech, Majewski
Institute of Meteorology and Water Management
Poland

Wratt, David
National Institute of Water and Atmospheric Research
New Zealand

Wurzler, Sabine
North Rhine Westphalia State Agency for Nature, Environment and Consumer Protection
Germany

Yabi, Ibouraïma
LECREDE/DGAT/FLASH/UAC
Republic of Benin

Zhao, Zong-Ci
China Meteorological Administration
China

Appendix VI: Permissions to publish

Permissions to publish have been granted by the following copyright holders:

Figure 3.2: Reprinted with kind permission from Petra Döll.

Figure 3.3: Reprinted from Lehner, B. and Co-authors, 2005: Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated assessment. *Climatic Change*, **75**, 273-299, with kind permission from Springer Science and Business Media.

Figure 4.1(a): From Fischer, G. and Co-authors, 2002: Global agro-ecological assessment for agriculture in the 21st century: methodology and results. Research Report RR-02-02. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. Reprinted with kind permission of IIASA.

Figure 5.1: Reprinted by permission from Macmillan Publishers Ltd [*Nature*]: O'Reilly, C.M. and Co-authors, 2003: Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. *Nature*, **424**, 766-768. Copyright 2003.

Figure 5.3: From Hemp, A., 2005: Climate change-driven forest fires marginalize the impact of ice cap wasting on Kilimanjaro. *Glob. Change Biol.*, **11**, 1013-1023. Reprinted with permission from Blackwell Publishing Ltd.

Figure 5.4: From Arnell, N.W., 2006b: Climate change and water resources: a global perspective. *Avoiding Dangerous Climate Change*, H.J. Schellnhuber, W. Cramer, N. Nakićenović, T. Wigley and G. Yohe, Eds., Cambridge University Press, Cambridge, 167-175. Reprinted with permission from Cambridge University Press.

Figure 5.8(a): From Haylock, M.R. and Co-authors, 2006: Trends in total and extreme South American rainfall 1960-2000 and links with sea surface temperature. *J. Climate*, **19**, 1490-1512. Reprinted with permission from American Meteorological Society.

Figure 5.8(b): From Aguilar, E. and Co-authors, 2005: Changes in precipitation and temperature extremes in Central America and northern South America, 1961–2003. *J. Geophys. Res.*, **110**, D23107, doi:10.1029/2005JD006119. Copyright (2005) American Geophysical Union. Reproduced by permission of American Geophysical Union.

Figure 5.12: From Smith, L.C. and Co-authors, 2005: Disappearing Arctic lakes. *Science*, **308**, 1429. Reprinted with permission from AAAS.

Index

Note: Page numbers in bold indicate page spans for entire chapters. Page numbers in italics denote tables, figures and boxed material.

Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems.

The Intergovernmental Panel on Climate Change (IPCC) Technical Paper *Climate Change and Water* draws together and evaluates the information in IPCC Assessment and Special Reports concerning the impacts of climate change on hydrological processes and regimes, and on freshwater resources – their availability, quality, use and management. It takes into account current and projected regional key vulnerabilities, prospects for adaptation, and the relationships between climate change mitigation and water. Its objectives are:

- To improve understanding of the links between both natural and anthropogenically induced climate change, its impacts, and adaptation and mitigation response options, on the one hand, and water-related issues, on the other;
- To communicate this improved understanding to policymakers and stakeholders.

Text in the Technical Paper carefully follows the text of the underlying IPCC Reports, especially the Fourth Assessment. It reflects the balance and objectivity of those Reports and, where the text differs, this is with the purpose of supporting and/or explaining further the conclusions of those Reports. Every substantive paragraph is sourced back to an IPCC Report.

The Intergovernmental Panel on Climate Change (IPCC) was set up jointly by the World Meteorological Organization and the United Nations Environment Programme to provide an authoritative international assessment of scientific information on climate change. *Climate Change and Water* is one of six Technical Papers prepared by the IPCC to date. It was prepared in response to a request from the World Climate Programme – Water and the International Steering Committee of the Dialogue on Water and Climate.