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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]

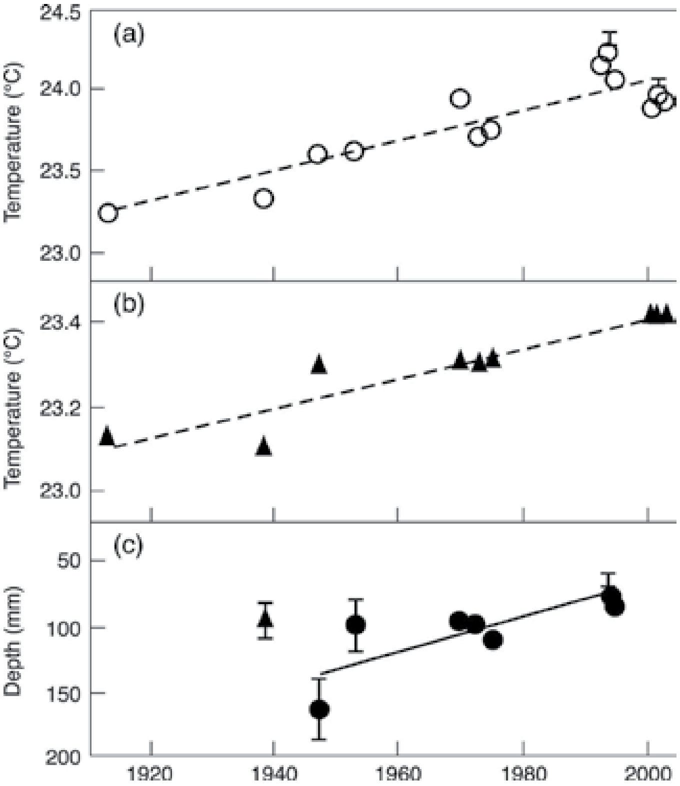

Figure 5.1: *Historical and recent measurements from Lake Tanganyika, East Africa: (a) upper mixed layer (surface water) temperatures; (b) deep-water (600 m) temperatures; (c) depth of the upper mixed layer. Triangles represent data collected by a different method. Error bars represent standard deviations. 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

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[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]

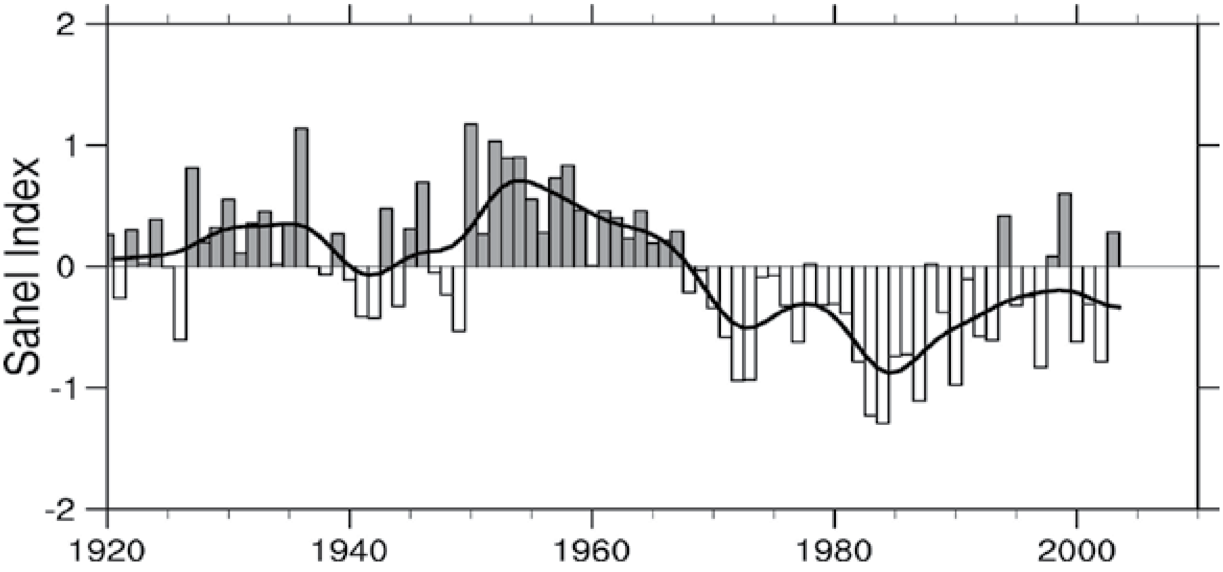

Figure 5.2: *Time-series of Sahel (10°N–20°N, 18°W–20°E) regional rainfall (April–October) from 1920 to 2003 derived from gridding normalised station anomalies and then averaging using area weighting (adapted from Dai et al., 2004a). Positive values (shaded bars) indicate conditions wetter than the long-term 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).

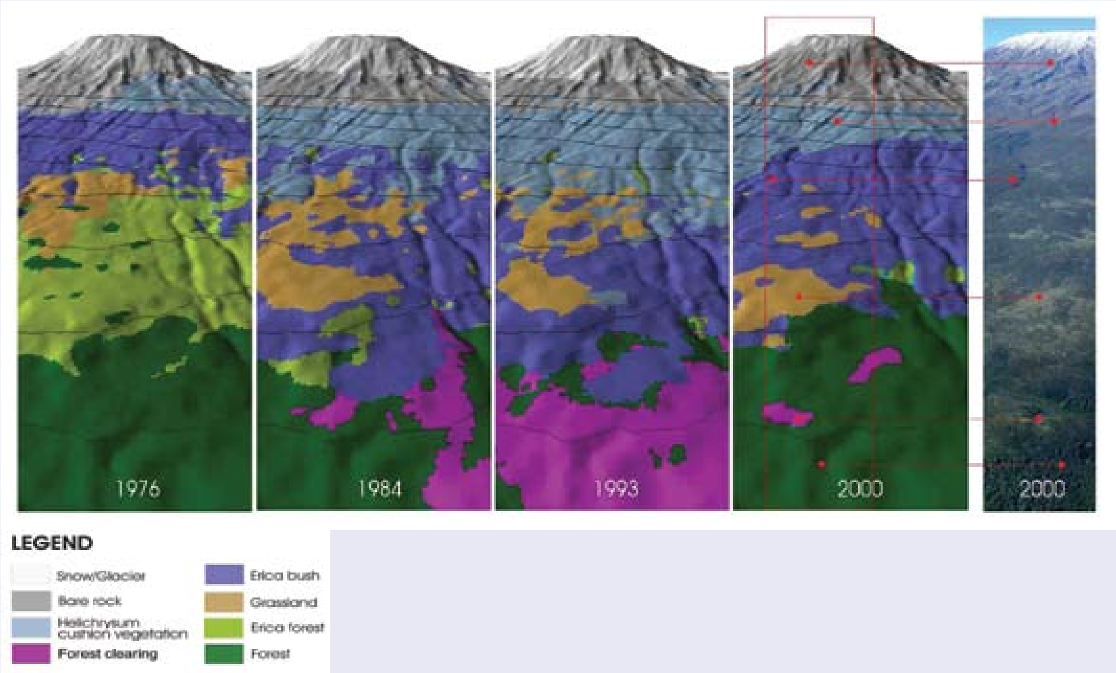

Figure 5.3: *Land cover changes induced by complex land use and climate interactions on Kilimanjaro (Hemp, 2005). Reprinted by permission from Blackwell Publishing Ltd.*

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]

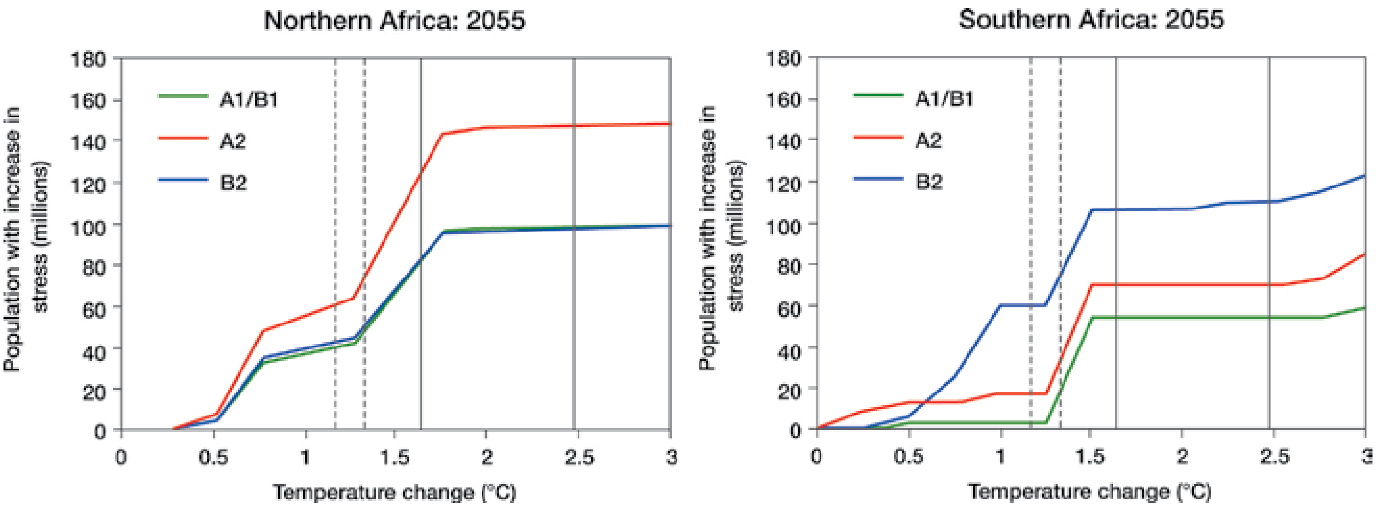

Figure 5.4: *Number of people (millions) living in watersheds exposed to an increase in water stress, compared to 1961–1990 (Arnell, 2006b). Water-stressed watersheds have runoff less than 1,000 m^3/capita/yr, and populations are exposed to an increase in water stress when runoff reduces significantly, 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]

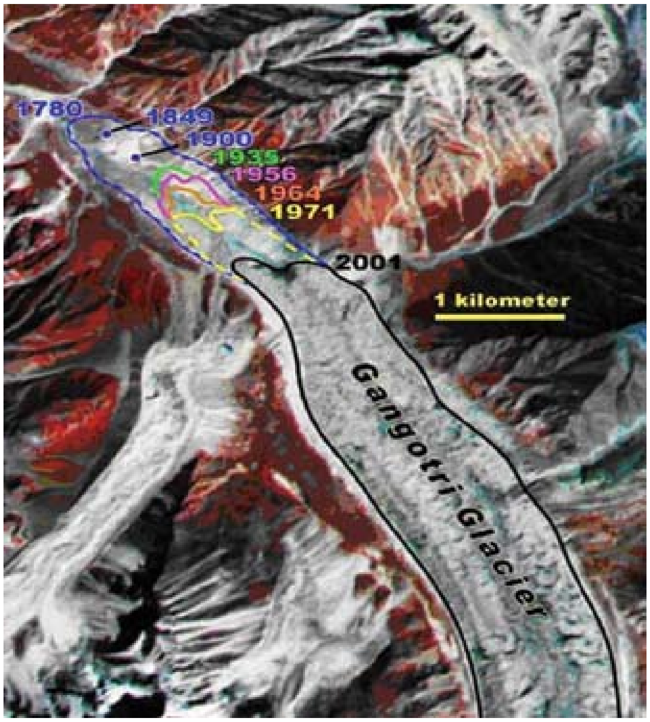

Figure 5.5: *Composite satellite image showing how the Gangotri Glacier (source of the Ganges, located in Uttarakhand, India) terminus has retracted since 1780 (courtesy of NASA EROS Data Center, 9 September, 2001). [WGII Figure 10.6]*

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 subcontinent 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).

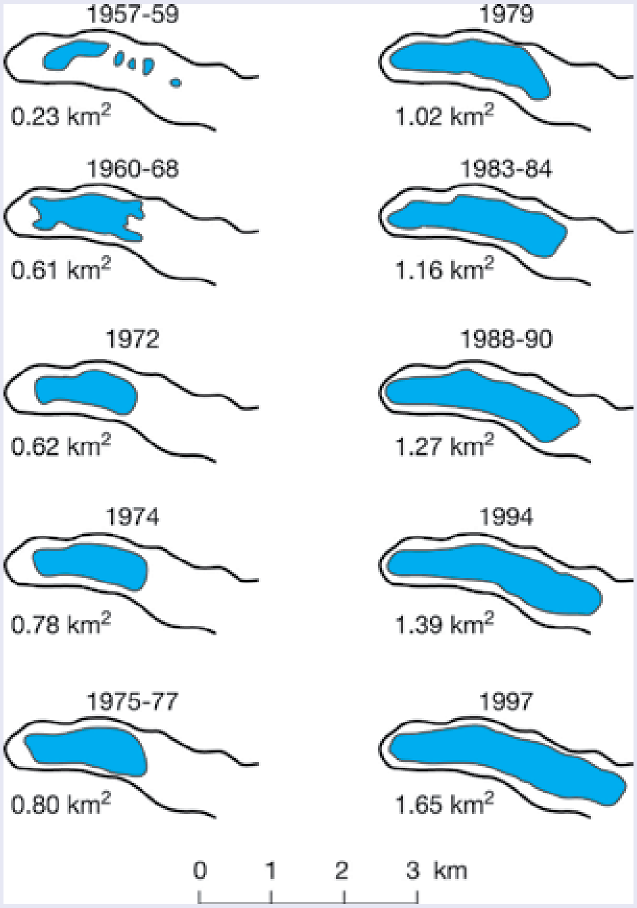

Figure 5.6: *Changes in the area of the Tsho Rolpa over time.*

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

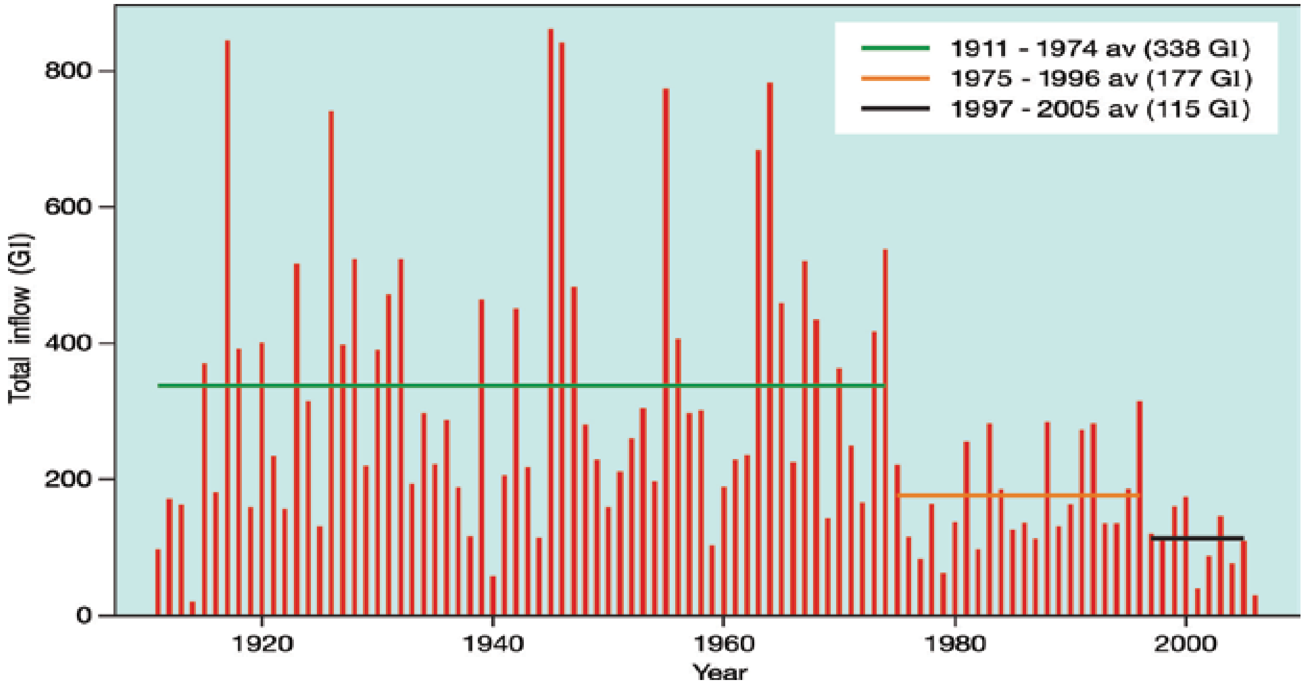

Figure 5.7: *Annual inflow to Perth Water Supply System from 1911 to 2006. Horizontal lines show averages. Source: http://www.watercorporation.com.au/D/dams_streamflow.cfm (courtesy of the Water Corporation of Western Australia). [WGII Figure 11.3]*

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] Decrease in summer flow[d]	Increasing risk of winter flood in northern Europe and of flash flood in all of Europe 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] 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]	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]

[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

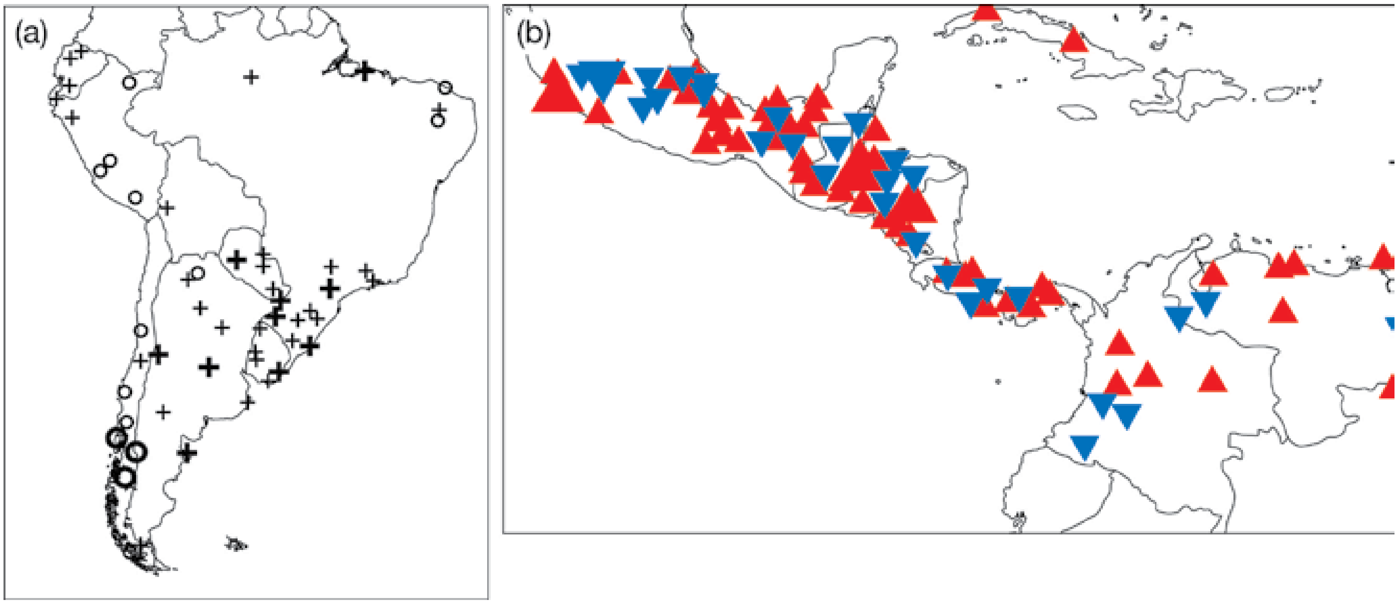

Figure 5.8: *Trends in annual rainfall in (a) South America (1960–2000). An increase is shown by a plus sign, a decrease by a circle; bold values indicate significance at P ≤ 0.05 (reproduced from Haylock et al. (2006) with permission from the American Meteorological Society). (b) Central America and 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).

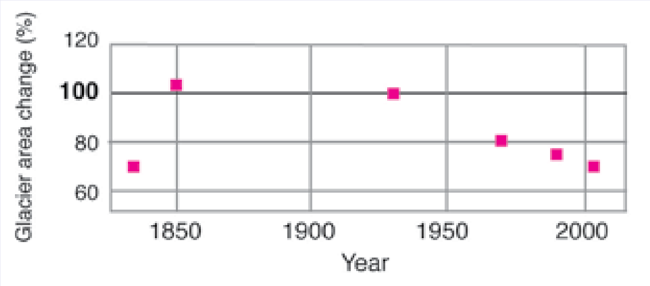

Figure 5.9: *Extent (%) of the total surface area of glaciers of the tropical Cordillera Blanca, Peru, relative to their extent around 1925 (=100) (Georges, 2004). The area of glacier in the Cordillera Blanca in 1990 was 620 km^2. [Extracted from WGI Figure 4.16]*

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 km^2, and this has currently (in 2005) reduced to less than 0.01 km^2 (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).

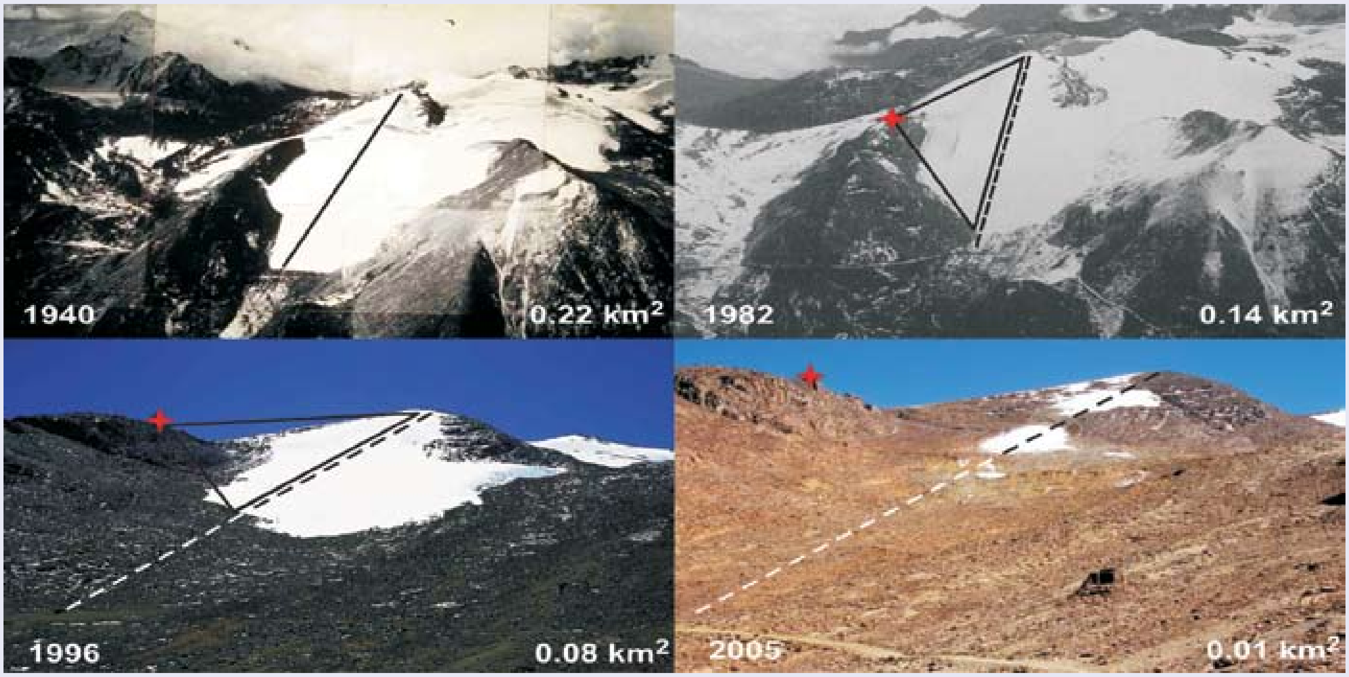

Figure 5.10: *Areal extent of Chacaltaya Glacier, Bolivia, from 1940 to 2005. By 2005, the glacier had separated into three distinct small bodies. The position of the ski hut, which did not exist in 1940, is indicated with a red cross. The ski lift had a length of about 800 m in 1940 and about 600 m 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]

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]

***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]

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

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[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]

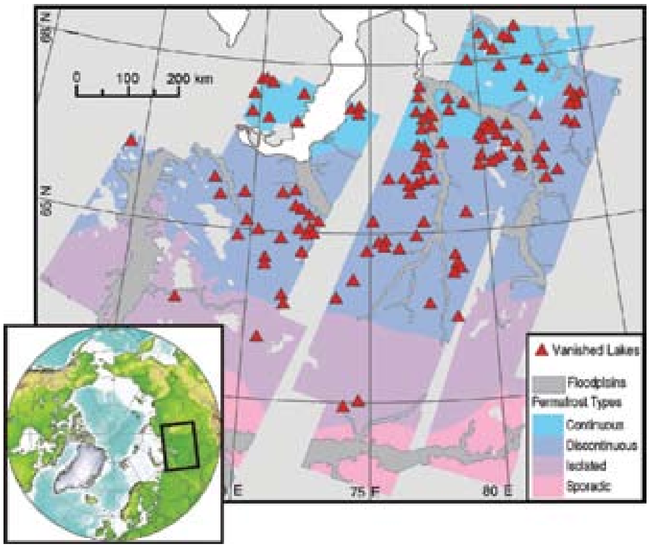

Figure 5.12: *Locations of Siberian lakes that have disappeared after a three-decade period of rising soil and air temperatures (changes registered from satellite imagery from the early 1970s to 1997–2004), overlaid on various permafrost types. The spatial pattern of lake disappearance suggests that 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

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[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]

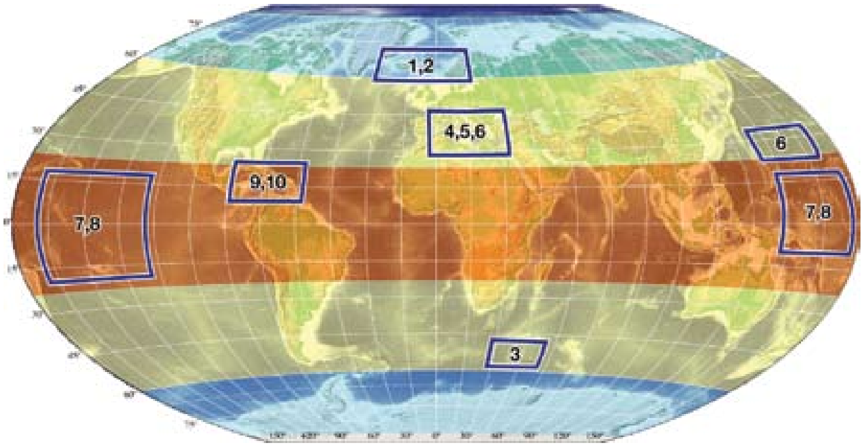
5.8.3 Adaptation, vulnerability and sustainability

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]