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Changes in Impacts of Climate Extremes: Human Systems and Ecosystems

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Executive Summary

Extreme impacts can result from extreme weather and climate events, but can also occur without extreme events. This chapter examines two broad categories of impacts on human and ecological systems, both of which are influenced by changes in climate, vulnerability, and exposure: first, the chapter primarily focuses on impacts that result from extreme weather and climate events, and second, it also considers extreme impacts that are triggered by less-than-extreme weather or climate events. These two categories of impacts are examined across sectors, systems, and regions. Extreme events can have positive as well as negative impacts on ecosystems and human activities.

Economic losses from weather- and climate-related disasters have increased, but with large spatial and interannual variability (*high confidence*, based on *high agreement, medium evidence*). Global weather- and climate-related disaster losses reported over the last few decades reflect mainly monetized direct damages to assets, and are unequally distributed. Estimates of annual losses have ranged since 1980 from a few US\$ billion to above 200 billion (in 2010 dollars), with the highest value for 2005 (the year of Hurricane Katrina). In the period 2000 to 2008, Asia experienced the highest number of weather- and climate-related disasters. The Americas suffered the most economic loss, accounting for the highest proportion (54.6%) of total loss, followed by Asia (27.5%) and Europe (15.9%). Africa accounted for only 0.6% of global economic losses. Loss estimates are lower bound estimates because many impacts, such as loss of human lives, cultural heritage, and ecosystem services, are difficult to value and monetize, and thus they are poorly reflected in estimates of losses. Impacts on the informal or undocumented economy, as well as indirect effects, can be very important in some areas and sectors, but are generally not counted in reported estimates of losses. [4.5.1, 4.5.3.3, 4.5.4.1]

Economic, including insured, disaster losses associated with weather, climate, and geophysical events are higher in developed countries. Fatality rates and economic losses expressed as a proportion of gross domestic product (GDP) are higher in developing countries (*high confidence*). During the period from 1970 to 2008, over 95% of deaths from natural disasters occurred in developing countries. Middle-income countries with rapidly expanding asset bases have borne the largest burden. During the period from 2001 to 2006, losses amounted to about 1% of GDP for middle-income countries, while this ratio has been about 0.3% of GDP for low-income countries and less than 0.1% of GDP for high-income countries, based on *limited evidence*. In small exposed countries, particularly small island developing states, losses expressed as a percentage of GDP have been particularly high, exceeding 1% in many cases and 8% in the most extreme cases, averaged over both disaster and non-disaster years for the period from 1970 to 2010. [4.5.2, 4.5.4.1]

Increasing exposure of people and economic assets has been the major cause of long-term increases in economic losses from weather- and climate-related disasters (*high confidence*). Long-term trends in economic disaster losses adjusted for wealth and population increases have not been attributed to climate change, but a role for climate change has not been excluded (*high agreement, medium evidence*). These conclusions are subject to a number of limitations in studies to date. Vulnerability is a key factor in disaster losses, yet not well accounted. Other limitations are: (i) data availability, as most data are available for standard economic sectors in developed countries; and (ii) type of hazards studied, as most studies focus on cyclones, where confidence in observed trends and attribution of changes to human influence is *low*. The second conclusion is subject to additional limitations: the processes used to adjust loss data over time, and record length. [4.5.3.3]

Settlement patterns, urbanization, and changes in socioeconomic conditions have all influenced observed trends in exposure and vulnerability to climate extremes (*high confidence*). Settlements concentrate the exposure of humans, their assets, and their activities. The most vulnerable populations include urban poor in informal settlements, refugees, internally displaced people, and those living in marginal areas. Population growth is also a driver of changing exposure and vulnerability. [4.2.1, 4.2.2, 4.3.5.1]

In much of the developed world, societies are aging and hence can be more vulnerable to climate extremes, such as heat waves. For example, Europe currently has an aging population, with a higher population

density and lower birth rate than any other continent. Nonetheless, exposure to climate extremes in Europe has increased whereas vulnerability has decreased as a result of implementation of policy, regulations, risk prevention, and risk management. Urban heat islands pose an additional risk to urban inhabitants, most affecting the elderly, ill, and socially isolated. [4.3.5.1, 4.3.6, 4.4.5]

Transportation, infrastructure, water, and tourism are sectors sensitive to climate extremes. Transport infrastructure is vulnerable to extremes in temperature, precipitation/river floods, and storm surges, which can lead to damage in road, rail, airports, and ports, and electricity transmission infrastructure is also vulnerable to extreme storm events. The tourism sector is sensitive to climate, given that climate is the principal driver of global seasonality in tourism demand. [4.3.5.2, 4.3.5.3]

Agriculture is also an economic sector exposed and vulnerable to climate extremes. The economies of many developing countries rely heavily on agriculture, dominated by small-scale and subsistence farming, and livelihoods in this sector are especially exposed to climate extremes. Droughts in Africa, especially since the end of the 1960s, have impacted agriculture, with substantial famine resulting. [4.3.4, 4.4.2]

Coastal settlements in both developed and developing countries are exposed and vulnerable to climate extremes. For example, the major factor increasing the vulnerability and exposure of North America to hurricanes is the growth in population and increase in property values, particularly along the Gulf and Atlantic coasts of the United States. Small island states are particularly vulnerable to climate extremes, especially where urban centers and/or island infrastructure predominate in coastal locations. Asia's mega-deltas are also exposed to extreme events such as flooding and have vulnerable populations in expanding urban areas. Mountain settlements are also exposed and vulnerable to climate extremes. [4.3.5.1, 4.4.3, 4.4.6, 4.4.9, 4.4.10]

In many regions, the main drivers of future increases in economic losses due to some climate extremes will be socioeconomic in nature (*medium confidence*, based on *medium agreement, limited evidence*). The frequency and intensity of extreme weather and climate events are only one factor that affects risks, but few studies have specifically quantified the effects of changes in population, exposure of people and assets, and vulnerability as determinants of loss. However, these studies generally underline the important role of projected changes (increases) in population and capital at risk. Additionally, some researchers argue that poorer developing countries and smaller economies are more likely to suffer more from future disasters than developed countries, especially in relation to extreme impacts. [4.5.2, 4.5.4.2]

Increases in exposure will result in higher direct economic losses from tropical cyclones. Losses will depend on future changes in tropical cyclone frequency and intensity (*high confidence*). Overall losses due to extratropical cyclones will also increase, with possible decreases or no change in some areas (*medium confidence*). Although future flood losses in many locations will increase in the absence of additional protection measures (*high agreement, medium evidence*), the size of the estimated change is highly variable, depending on location, climate scenarios used, and methods used to assess impacts on river flow and flood occurrence. [4.5.4.2]

Extreme events will have greater impacts on sectors with closer links to climate, such as water, agriculture and food security, forestry, health, and tourism. For example, while it is not currently possible to reliably project specific changes at the catchment scale, there is *high confidence* that changes in climate have the potential to seriously affect water management systems. However, climate change is in many instances only one of the drivers of future changes in supply reliability, and is not necessarily the most important driver at the local scale. The impacts of changes in flood characteristics are also highly dependent on how climate changes in the future, and as noted in Section 3.5.2, there is *low confidence* in projected changes in flood magnitude or frequency. However, based on the available literature, there is *high confidence* that, in some places, climate change has the potential to substantially affect flood losses. Climate-related extremes are also expected to produce large impacts on infrastructure, although detailed

analysis of potential and projected damages are limited to a few countries, infrastructure types, and sectors.
[4.3.2, 4.3.5.2]

Estimates of adaptation costs to climate change exhibit a large range and relate to different assessment periods. For 2030, the estimated global cost ranges from US\$ 48 to 171 billion per year (in 2005 US\$) with recent estimates for developing countries broadly amounting to the average of this range with annual costs of up to US\$ 100 billion. Confidence in individual estimates is *low* because the estimates are derived from only three relatively independent studies. These studies have not explicitly separated costs of adapting to changes in climate extremes from other climate change impacts, do not include costs incurred by all sectors, and are based on extrapolations of bottom-up assessments and on top-down analysis lacking site-specificity. [4.5.3, 4.5.5, 4.5.6]

4.1. Introduction

Chapter 3 evaluates observed and projected changes in the frequency, intensity, spatial extent, and duration of extreme weather and climate events. This physical basis provides a picture of climate change and extreme events. But it does not by itself indicate the impacts experienced by humans or ecosystems. For example, for some sectors and groups of people, severe impacts may result from relatively minor weather and climate events. To understand impacts triggered by weather and climate events, the exposure and vulnerability of humans and ecological systems need to be examined. The emphasis of this chapter is on negative impacts, in line with this report's focus on managing the risks of extreme events and disasters. Weather and climate events, however, can and often do have positive impacts for some people and ecosystems.

In this chapter, two different types of impacts on human and ecological systems are examined: (i) impacts of extreme weather and climate events; and (ii) extreme impacts triggered by less-than-extreme weather or climate events (in combination with non-climatic factors, such as high exposure and/or vulnerability). Where data are available, impacts are examined from sectoral and regional perspectives. Throughout this chapter, the term 'climate extremes' will be used to refer in brief to 'extreme weather and extreme climate events,' as defined in the Glossary and discussed more extensively in Section 3.1.2.

Activities undertaken as disaster risk reduction may also act as adaptation to trends in climate extremes resulting from climate change, and they may thereby act to reduce impacts. Strategies to reduce risk from one type of climate extreme may act to increase or decrease the risk from another. In writing this chapter, we have not considered these issues as subsequent chapters are dedicated to adaptation. Here, impacts are assessed without discussion of the specific possible adaptation or disaster risk reduction strategies or policies evaluated in subsequent chapters.

Examination of trends in impacts and disasters highlights the difficulties in attributing trends in weather- and climate-related disasters to climate change. Trends in exposure and vulnerability and their relationship with climate extremes are discussed. The chapter then examines system- and sector-based aspects of vulnerability, exposure, and impacts, both observed and projected. The same issues are examined regionally before the chapter concludes with a section on the costs of weather- and climate-related impacts, disasters, and adaptation.

4.2. Climatic Extremes in Natural and Socioeconomic Systems

4.2.1. How Do Climate Extremes Impact on Humans and Ecosystems?

The impacts of weather and climate extremes are largely determined by exposure and vulnerability. This is occurring in a context where all three components – exposure, vulnerability, and climate – are highly dynamic

and subject to continuous change. Some changes in exposure and vulnerability can be considered as adaptive actions. For example, migration away from high-hazard areas (see Chapter 1 and the Glossary for a definition of the term 'hazard') reduces exposure and the chance of disaster and is also an adaptation to increasing risk from climate extremes (Adger et al., 2001; Dodman and Satterthwaite, 2008; Revi, 2008). Similar adaptive actions are reflected in changes in building regulations and livelihoods, among many other examples.

Extreme impacts on humans and ecosystems can be conceptualized as 'disasters' or 'emergencies.' Many contemporary definitions emphasize either that a disaster results when the impact is such that local capacity to cope is exceeded or such that it severely disrupts normal activities. There is a significant literature on the definitional issues, which include factors of scale and irreversibility (Quarantelli, 1998; Handmer and Dovers, 2007). Disasters result from impacts that require both exposure to the climate event and a susceptibility to harm by what is exposed. Impacts can include major destruction of assets and disruption to economic sectors, loss of human lives, mental health effects, or loss and impacts on plants, animals, and ecosystem services. The Glossary provides the definition of disaster used in this chapter.

Exposure can be conceptualized as the presence of human and ecosystem tangible and intangible assets and activities (including services) in areas affected by climate extremes (see Sections 1.1.2 and 2.2 and the Glossary for definitional discussion). Without exposure there is no impact. Temporal and spatial scales are also important. Exposure can be more or less permanent; for example, exposure can be increased by people visiting an area or decreased by evacuation of people and livestock after a warning. As human activity and settlements expand into an exposed area, more people will be subject to and affected by local climatic hazards. Population growth is predominantly in developing countries (Peduzzi et al., 2011; UNISDR, 2011). Newly occupied areas around or in urban areas were previously left vacant because they are prone to the occurrence of climatic hazards (Handmer and Dovers, 2007; Satterthwaite et al., 2007; Wilbanks et al., 2007), for example with movement of squatters to and development of informal settlements in areas prone to flooding (Huq et al., 2007) and landslides (Anderson et al., 2007). 'Informal settlements' are characterized by an absence of involvement by government in planning, building, or infrastructure and lack of secure tenure. In addition, there are affluent individuals pursuing environmental amenity through coastal canal estates, riverside, and bush locations, which are often at greater risk from floods and fires (Handmer and Dovers, 2007).

Exposure is a necessary but not sufficient condition for impacts. For exposed areas to be subjected to significant impacts from a weather or climate event there must be vulnerability. Vulnerability is composed of (i) susceptibility of what is exposed to harm (loss or damage) from the event, and (ii) its capacity to recover (Cutter and Emrich, 2006; see Sections 1.1.2 and 2.2 and the Glossary). Vulnerability is defined here as in the Glossary as the propensity or predisposition to be adversely affected. For example, those whose livelihoods are weather-dependent

or whose housing offers limited protection from weather events will be particularly susceptible to harm (Dodman and Satterthwaite, 2008). Others with limited capacity to recover include those with limited personal resources for recovery or with no access to external resources such as insurance or aid after an event, and those with limited personal support networks (Handmer and Dovers, 2007). Knowledge, health, and access to services of all kinds including emergency services and political support help reduce both key aspects of vulnerability.

The concept of 'resilience' (developed in an ecological context by Holling, 1978; in a broad social sustainability context by Handmer and Dovers, 2007; and by Adger, 2000; Folke et al., 2002; see also the Glossary) emphasizes the positive components of resistance or adaptability in the face of an event and ability to cope and recover. This concept of 'resilience' is often seen as a positive way of expressing a similar concept to that contained in the term 'vulnerability' (Handmer, 2003).

Refugees, internally displaced people, and those driven into marginal areas as a result of violence can be dramatic examples of people vulnerable to the negative effects of weather and climate events, cut off from coping mechanisms and support networks (Handmer and Dovers, 2007). Reasons for the increase in vulnerability associated with warfare include destruction or abandonment of infrastructure (e.g., transport, communications, health, and education) and shelter, redirection of resources from social to military purposes, collapse of trade and commerce, abandonment of subsistence farmlands, lawlessness, and disruption of social networks (Levy and Sidel, 2000; Collier et al., 2003). The proliferation of weapons and minefields, the absence of basic health and education, and collapse of livelihoods can ensure that the effects of war on vulnerability to disasters are long lasting, although some also benefit (Korf, 2004). These areas are also characterized by an exodus of trained people and an absence of inward investment.

Many ecosystems are dependent on climate extremes for reproduction (e.g., through fire and floods), disease control, and in many cases general ecosystem health (e.g., fires or windstorms allowing new growth to replace old). How such extreme events interact with other trends and circumstances can be critical to the outcome. For example, floods that would normally be essential to river gum reproduction may carry disease and water weeds (Rogers and Ralph, 2010).

Climate extremes can cause substantial mortality of individual species and contribute to determining which species exist in ecosystems (Parmesan et al., 2000). For example, drought plays an important role in forest dynamics, as a major influence on the mortality of trees (Villalba and Veblen, 1997; Breshears and Allen, 2002; Breshears et al., 2005).

4.2.2. Complex Interactions among Climate Events, Exposure, and Vulnerability

There exist complex interactions between different climatic and non-climatic hazards, exposure, and vulnerability that have the potential of

triggering complex, scale-dependent impacts. Anthropogenic changes in atmospheric systems are influencing changes in many climatic variables and the corresponding physical impacts (see Chapter 3). However, the impacts that climatic extremes have on humans and ecosystems (including those altered by humans) depend also on several other non-climatic factors (Adger, 2006). This section will explore these factors, drawing on examples of flooding and drought.

Changes in socioeconomic status are a key component of exposure; in particular, population growth is a major driver behind changing exposure and vulnerability (Downton et al., 2005; Barredo, 2009). In many regions, people have been encroaching into flood-prone areas where effective flood protection is not assured, due to human pressure and lack of more suitable and available land (McGranahan et al., 2007; Douglas et al., 2008). Urbanization, often driven by rural poverty, drives such migration (Douglas et al., 2008). In these areas, both population and wealth are accumulating, thereby increasing the flood damage potential. In many developed countries, population and wealth accumulation also occur in hazard-prone areas for reasons of lifestyle and/or lower cost (e.g., Radeloff et al., 2005). Here, a tension between climate change adaptation and development is seen; living in these areas without appropriate adaptation may be maladaptive from a climate change perspective, but this may be a risk people are willing to take, or a risk over which they have limited choice, considering their economic circumstances (Wisner et al., 2004). Furthermore, there is often a deficient risk perception present, stemming from an unjustified faith in the level of safety provided by flood protection systems and dikes in particular (Grothmann and Patt, 2005) (e.g., 2005 Hurricane Katrina in New Orleans).

Economic development and land use change can also lead to changes in natural systems. Land cover changes induce changes in rainfall-runoff patterns, which can impact on flood intensity and frequency (e.g., Kundzewicz and Schellnhuber, 2004). Deforestation, urbanization, reduction of wetlands, and river regulation (e.g., channel straightening, shortening, and embankments) change the percentage of precipitation becoming runoff by reducing the available water storage capacity (Few, 2003; Douglas et al., 2008). The proportion of impervious areas (e.g., roofs, yards, roads, pavements, parking lots, etc.) and the value of the runoff coefficient are increased. As a result, water runs off faster to rivers or the sea, and the flow hydrograph has a higher peak and a shorter time-to-peak (Cheng and Wang, 2002; Few, 2003; Douglas et al., 2008), reducing the time available for warnings and emergency action. In mountainous areas, developments extending into hilly slopes are potentially endangered by landslides and debris flows triggered by intense rains. These changes have resulted in rain that is less extreme leading to serious impacts (Crozier, 2010).

Similarly, the socioeconomic impacts of droughts may arise from the interaction between natural conditions and human water use, which can be conceptualized as a combination of supply and demand factors. Human activities (such as over-cultivation, overgrazing, deforestation) have exacerbated desertification of vulnerable areas in Africa and Asia,

Box 4-1 | Evolution of Climate, Exposure, and Vulnerability – The Melbourne Fires, 7 February 2009

The fires in the Australian state of Victoria, on 7 February 2009, demonstrate the evolution of risk through the relationships between the weather- and climate-related phenomena of a decade-long drought, record extreme heat, and record low humidity of 5% (Karoly, 2010; Trewin and Vermont, 2010) interacting with rapidly increasing exposure. Together the climate phenomena created the conditions for major uncontrollable wildfires (Victorian Bushfires Royal Commission, 2010).

The long antecedent drought, record heat, and a 35-day period with no rain immediately before the fires turned areas normally seen as low to medium wildfire risk into very dry high-risk locations. A rapidly expanding urban-bush interface and valuable infrastructure (Berry, 2003; Burnley and Murphy, 2004; Costello, 2007, 2009) provided the values exposed and the potential for extreme impacts that was realized with the loss of 173 lives and considerable tangible and intangible damage. There was a mixture of natural and human sources of ignition, showing that human agency can trigger such fires and extreme impacts.

Many people were not well-prepared physically or psychologically for the fires, and this influenced the level of loss and damage they incurred. Levels of physical and mental health also affected people's vulnerability. Many individuals with ongoing medical conditions, special needs because of their age, or other impairments struggled to cope with the extreme heat and were reliant on others to respond safely (Handmer et al., 2010). However, capacity to recover in a general sense was high for humans and human activities through insurance, government support, private donations, and nongovernmental organizations (NGOs) and was variable for the affected bush with some species and ecosystems benefitting (Lindenmayer et al., 2010; Banks et al., 2011; see also Case Study 9.2.2).

Chapter 3 details projected changes in climate extremes for this region that could increase fire risk, in particular warm temperature extremes, heat waves, and dryness (see Table 3-3 for summary).

where soil and bio-productive resources became permanently degraded (Dregne, 1986). An extreme example of a human-made, pronounced hydrological drought comes from the Aral Sea basin in Central Asia. Due to excessive and non-sustainable water withdrawals from the tributaries (Syr Darya and Amu Darya), their inflow into the Aral Sea has shrunk in volume by some 75% (Micklin, 2007; Rodell et al., 2009) resulting in severe economic and ecological impacts.

The changing impacts of climate extremes on sectors, such as water and food, depend not only on changes in the characteristics of climate-related variables relevant to a given sector, but also on sector-relevant non-climatic stressors, management characteristics (including organizational and institutional aspects), and adaptive capacity (Kundzewicz, 2003).

There also may be increasing risks from possible interactions of hazards (Cruz, 2005; see Sections 3.1.3 and 3.1.4 for discussion of interactions and feedbacks). One hazard may influence other hazards or exacerbate their effects, also with dependence on scale (Buzna et al., 2006). For instance, temperature rise can lead to permafrost thaw, reduced slope stability, and damage to buildings. Another example is that intense precipitation can lead to flash flood, landslides, and infrastructure damage, for example, collapse of bridges, roads, and buildings, and interruption of power and water supplies. In the Philippines, two typhoons hitting the south of Luzon Island in 2004 caused a significant flood disaster as well as landslides on the island, leading to 900 fatalities (Pulhin et al., 2010). It is worthwhile to note that cascading system failures (e.g.,

among infrastructure) can happen rapidly and over large areas due to their interdependent nature.

4.3. System- and Sector-Based Aspects of Vulnerability, Exposure, and Impacts

4.3.1. Introduction

In this subsection, studies evaluating impacts and risks of extreme events are surveyed for major affected sectors and systems. Sectors and systems considered here include water; ecosystems; food systems and food security; human settlements, infrastructure, and tourism; and human health, well-being, and security. Impacts of climate extremes are determined by the climate extremes themselves as well as by exposure and vulnerability. Climate extremes, exposure, and vulnerability are characterized by uncertainty and continuous change, and shifts in any of these components of risk will have implications for the impacts of extreme events. Generally, there is limited literature on the potential future impacts of extreme events; most literature analyzes current impacts of extreme events. This focus may result in part from incomplete knowledge and uncertainties regarding future changes in some extreme events (see, for example, Section 3.2.3 and Tables 3-1 and 3-3) as well as from uncertainties regarding future exposure and vulnerabilities. Nonetheless, understanding current impacts can be important for decisionmakers preparing for future risks. Analyses of both observed and projected impacts due to extreme climate and weather events are

Box 4-2 | Observed and Projected Trends in Human Exposure: Tropical Cyclones and Floods

The International loss databases with global coverage such as EM-DAT, NatCat, and Sigma (maintained by the Centre for the Epidemiology of Disasters, Munich Re, and Swiss Re, respectively) present an increase in reported disasters through time. Although the number of reported tropical cyclone disasters, for example, has increased from a yearly average of 21.7 during the 1970s to 63 during the 2000s (see Table 4-1), one should not simply conclude that the number of disasters is increasing due to climate change. There are four factors that may individually or together explain this increase: improved access to information, higher population exposure, higher vulnerability, and higher frequency and/or intensity of hazards (Dao and Peduzzi, 2004; Peduzzi et al., 2009). Due to uncertainties in the significance of the role of each of these four possible factors (especially regarding improved access to information), a vulnerability and risk trend analysis cannot be performed based on reported losses (e.g., from EM-DAT or Munich Re). To better understand this trend, international loss databases would have to be standardized.

Here for both tropical cyclones and floods, we overview a method for better understanding these factors through calculation of past trends and future projections of human exposure at regional and global scales. Changes in population size strongly influence changes in exposure to hazards. It is estimated that currently about 1.15 billion people live in tropical cyclone-prone areas. The physical exposure (yearly average number of people exposed) to tropical cyclones is estimated to have increased from approximately 73 million in 1970 to approximately 123 million in 2010 (Figure 4-1; Peduzzi et al., 2011). The number of times that countries are hit by tropical cyclones per year is relatively steady (between 140 and 155 countries per year¹ on average; see Table 4-1 (UNISDR, 2011).

Table 4-1 | Trend in tropical cyclone disasters reported versus tropical cyclones detected by satellite during the last four decades. The reported disasters as a percentage of the number of countries hit by tropical cyclones increased three-fold. Note that 'best track data' generally comprise four-times daily estimates of tropical cyclone intensity and position; these data are based on post-season reprocessing of data that were collected operationally during each storm's lifetime. Source: UNISDR, 2011.

	1970 - 79	1980 - 89	1990 - 99	2000 - 09
Number of tropical cyclones as identified in best track data (average per year)	88.4	88.2	87.2	86.5
Number of countries hit by tropical cyclones as detected by satellite (average per year)	142.1	144.0	155.0	146.3
Number of disasters triggered by tropical cyclones as reported by EM-DAT (average per year)	21.7	37.5	50.6	63.0
Reported disasters as a percentage of number of countries hit by tropical cyclones	15%	26%	33%	43%

In most oceans, the frequency of tropical cyclones is *likely* to decrease or remain unchanged while mean tropical cyclone

Continued next page →

¹ This is the number of intersections between countries and tropical cyclones. One cyclone can affect several countries, but also many tropical cyclones occur only over the oceans.

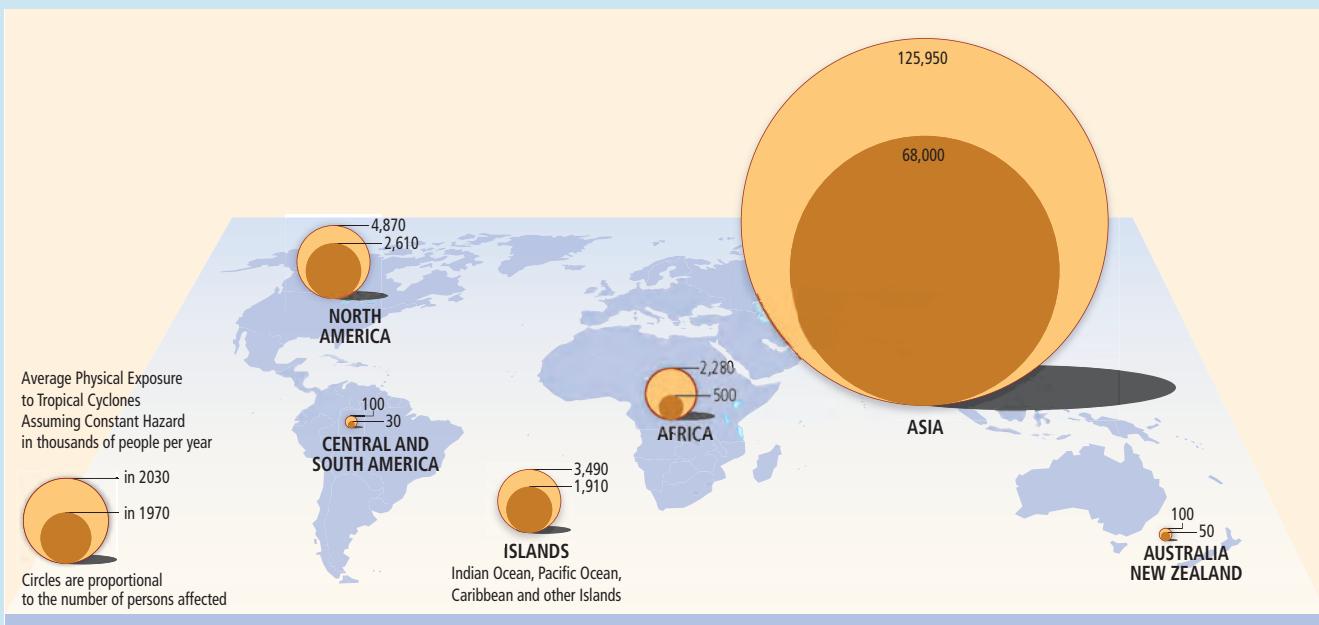


Figure 4-1 | Average physical exposure to tropical cyclones assuming constant hazard (in thousands of people per year). Data from Peduzzi et al., 2011.

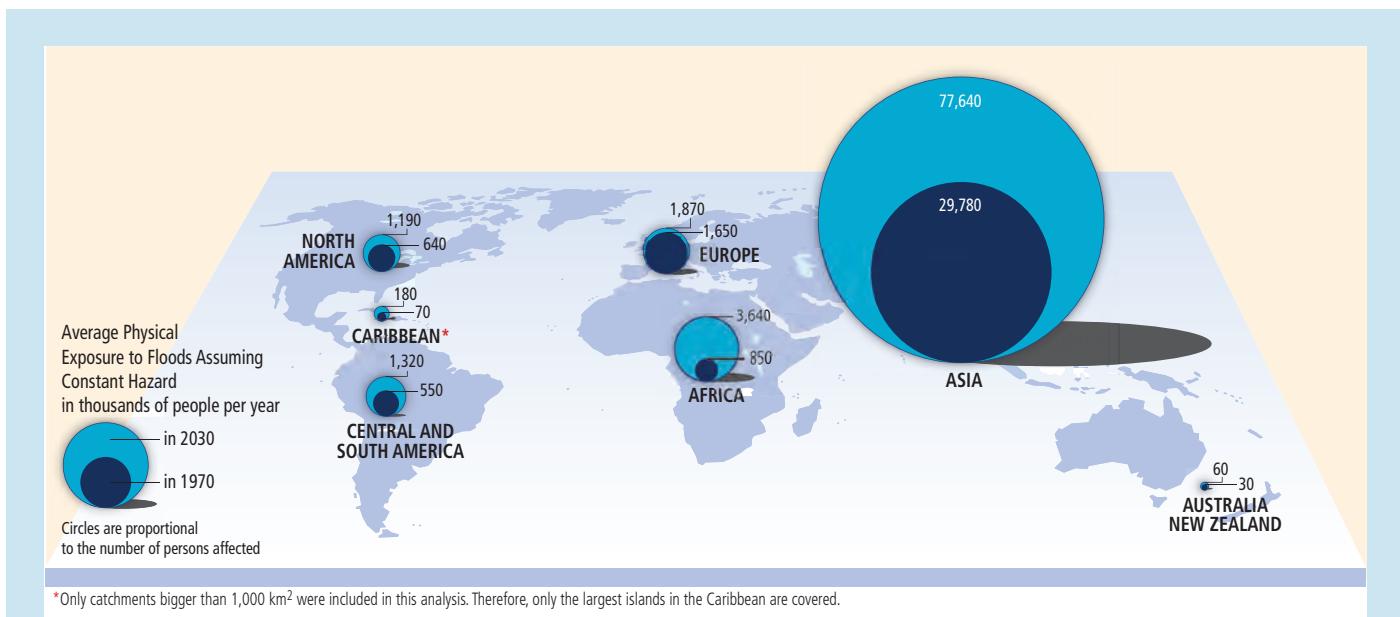


Figure 4-2 | Average physical exposure to floods assuming constant hazard (in thousands of people per year). Data from Peduzzi et al., 2011.

maximum wind speed is *likely* to increase (see Section 3.4.4). Figure 4-1 provides the modeled change in human exposure at constant hazard (without forecast of the influence of climate change on the hazard). It shows that the average number of people exposed to tropical cyclones per year globally would increase by 11.6% from 2010 to 2030 from population growth only. In relative terms, Africa has the largest percentage increase in physical exposure to tropical cyclones. In absolute terms, Asia has more than 90% of the global population exposed to tropical cyclones.

In terms of exposure to flooding, about 800 million people are currently living in flood-prone areas, and about 70 million people currently living in flood-prone areas are, on average, exposed to floods each year (UNISDR, 2011). Given the lack of complete datasets on past flood events, and the uncertainty associated with projected trends in future flood frequencies and magnitudes (see Section 3.5.2), it is difficult to estimate future flood hazards. However, using population increase in the flood-prone area, it is possible to look at trends in the number of people exposed per year on average at constant hazard (UNISDR, 2011). Figure 4-2 shows that population growth will continue to increase exposure to floods. Due to model constraints, areas north of 60°N and south of 60°S, as well as catchments smaller than 1,000 km² (typically small islands) are not modeled. The data provided in Figure 4-2 correspond to river flooding.

A number of factors underlie increases in impacts from floods and cyclones. However, trends in the population exposed to these hazards are an important factor. Population projections in tropical cyclone areas and flood-prone areas imply that impacts will almost certainly continue to increase based on this factor alone.

thus assessed. Sections 4.3.2 to 4.3.6, building on an understanding of exposure and vulnerability, evaluate knowledge of current and future risks of extreme events by sectors and systems.

4.3.2. Water

Past and future changes in exposure and vulnerability to climate extremes in the water sector are driven by both changes in the volume, timing, and quality of available water and changes in the property, lives, and systems that use the water resource or that are exposed to water-related hazards (Aggarwal and Singh, 2010). With a constant resource or physical hazard, there are two opposing drivers of change in exposure

and vulnerability. On the one hand, vulnerability increases as more demands are placed on the resource (due to increased water consumption, for example, or increased discharge of polluting effluent) or exposure increases as more property, assets, and lives encounter flooding. On the other hand, vulnerability is reduced as measures are implemented to improve the management of resources and hazards and to enhance the ability to recover from extreme events. For example, enhancing water supplies, improving effluent treatment, and employing flood management measures (including the provision of insurance or disaster relief) would all lead to reductions in vulnerability in the water sector. Such measures have been widely implemented, and the runoff regime of many rivers has been considerably altered (Vörösmarty, 2002). The change in exposure and vulnerability in any place is a function of the relationship between

these two opposing drivers, which also interact. Flood or water management measures may reduce vulnerability in the short term, but increased security may generate more development and ultimately lead to increased exposure and vulnerability.

Extreme events considered in this section can threaten the ability of the water supply 'system' (from highly managed systems with multiple sources to a single rural well) to supply water to users. This may be because a surplus of water affects the operation of systems, but more typically results from a shortage of water relative to demands – a drought. Water supply shortages may be triggered by a shortage of river flows and groundwater, deterioration in water quality, an increase in demand, or an increase in vulnerability to water shortage. There is *medium confidence* that since the 1950s some regions of the world have experienced more intense and longer droughts, in particular in southern Europe and West Africa (see Section 3.5.1), but it is not possible to attribute trends in the human impact of drought directly or just to these climatic trends because of the simultaneous change in the other drivers of drought impact.

There is *medium confidence* that the projected duration and intensity of hydrological drought will increase in some regions with climate change (Section 3.5.1), but other factors leading to a reduction in river flows or groundwater recharge are changes in agricultural land cover and upstream interventions. A deterioration in water quality may be driven by climate change (as shown for example by Delpla et al., 2009; Whitehead et al., 2009; Park et al., 2010), change in land cover, or upstream human interventions. An increase in demand may be driven by demographic, economic, technological, or cultural drivers as well as by climate change (see Section 2.5). An increase in vulnerability to water shortage may be caused, for example, by increasing reliance on specific sources or volumes of supply, or changes in the availability of alternatives. Indicators of hydrological and water resources drought impact include lost production (of irrigated crops, industrial products, and energy), the cost of alternative or replacement water sources, and altered human well-being, alongside consequences for freshwater ecosystems (impacts of meteorological and agricultural droughts on production of rain-fed crops are summarized in Section 4.3.4).

Few studies have so far been published on the effect of climate change on the impacts of drought in water resources terms at the local catchment scale. Virtually all of these have looked at water system supply reliability during a drought, or the change in the yield expected with a given reliability, rather than indicators such as lost production, cost, or well-being. Changes in the reliability of a given yield, or yield with a given reliability, of course vary with local hydrological and water management circumstances, the details of the climate scenarios used, and other drivers of drought risk. Some studies show large potential reductions in supply reliability due to climate change that challenge existing water management systems (e.g., Fowler et al., 2003; Kim et al., 2009; Takara et al., 2009; Vanham et al., 2009); some show relatively small reductions that can be managed – albeit at increased cost – by existing systems (e.g., Fowler et al., 2007), and some show that under some scenarios the

reliability of supply increases (e.g., Kim and Kaluarachchi, 2009; Li et al., 2010). While it is not currently possible to reliably project specific changes at the catchment scale, there is *high confidence* that changes in climate have the potential to seriously affect water management systems. However, climate change is in many instances only one of the drivers of future changes in supply reliability, and is not necessarily the most important driver at the local scale. MacDonald et al. (2009), for example, demonstrate that the future reliability of small-scale rural water sources in Africa is largely determined by local demands, biological aspects of water quality, or access constraints, rather than changes in regional recharge, because domestic supply requires only 3–10 mm of recharge per year. However, they noted that up to 90 million people in low rainfall areas (200–500 mm) would be at risk if rainfall reduces to the point at which groundwater resources become nonrenewable.

There have been several continental- or global-scale assessments of potential change in hydrometeorological drought indicators (see Section 3.5.1), but relatively few on measures of water resources drought or drought impacts. This is because these impacts are very dependent on context. One published large-scale assessment (Lehner et al., 2006) used a generalized drought deficit volume indicator, calculated by comparing simulated river flows with estimated withdrawals for municipal, industrial, and agricultural uses. The indicator was calculated across Europe, using climate change projections from two climate models and assuming changes in withdrawals over time. They showed substantial changes in the return period of the drought deficit volume, comparing the 100-year return period for the 1961–1990 period with projections for the 2070s (Figure 4–3). Across large parts of Europe, the 1961–1990 100-year drought deficit volume is projected to have a return period of less than 10 years by the 2070s. Lehner et al. (2006) also demonstrated that this projected pattern of change was generally driven by changes in climate, rather than the projected changes in withdrawals of water (Figure 4–3). In southern and western Europe, changing withdrawals alone only are projected to increase deficit volumes by less than 5%, whereas the combined effect of changing withdrawals and climate change is projected to increase deficit volumes by at least 10%, and frequently by more than 25%. In eastern Europe, increasing withdrawals are projected to increase drought deficit volumes by over 5%, and more than 10% across large areas, but this is offset under both climate scenarios by increasing runoff.

Climate change has the potential to change river flood characteristics through changing the volume and timing of precipitation, by altering the proportions of precipitation falling as snow and rain, and to a lesser extent, by changing evaporation and hence accumulated soil moisture deficits. However, there is considerable uncertainty in the magnitude, frequency, and direction of change in flood characteristics (Section 3.5.2). Changes in catchment surface characteristics (such as land cover), floodplain storage, and the river network can also lead to changes in the physical characteristics of river floods (e.g., along the Rhine: Bronstert et al., 2007). The impacts of extreme flood events include direct effects on livelihoods, property, health, production, and communication, together with indirect effects of these consequences

through the wider economy. There have, however, been very few studies that have looked explicitly at the human impacts of changes in flood frequency, rather than at changes in flood frequencies and magnitudes. One study has so far looked at changes in the area inundated by floods with defined return periods (Veijalainen et al., 2010), showing that the relationship between change in flood magnitude and flood extent depended strongly on local topographic conditions.

An early study in the United States (Choi and Fisher, 2003) constructed regression relationships between annual flood loss and socioeconomic

and climate drivers, concluding that a 1% increase in average annual precipitation would, other things being equal, lead to an increase in annual national flood loss of around 6.5%. However, the conclusions are highly dependent on the regression methodology used, and the spatial scale of analysis. More sophisticated analyses combine estimates of current and future damage potential (as represented by a damage-magnitude relationship) with estimates of current and future flood frequency curves to estimate event damages and average annual damages (sometimes termed expected annual damage). For example, Mokrech et al. (2008) estimated damages caused by the current 10- and 75-year

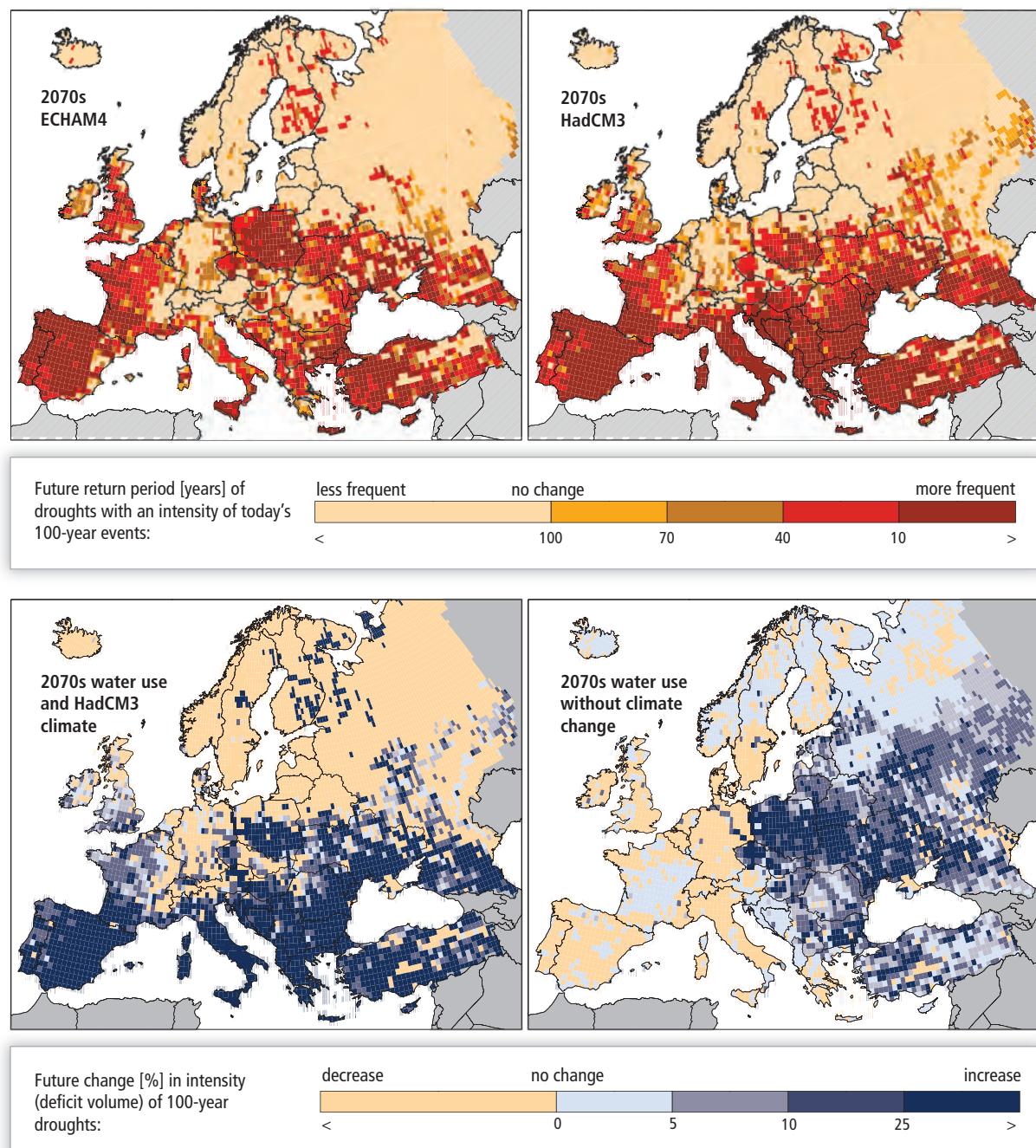


Figure 4-3 | Change in indicators of water resources drought across Europe by the 2070s. (top): projected changes in the return period of the 1961–1990 100-year drought deficit volume for the 2070s, with change in river flows and withdrawals for two climate models, ECHAM4 and HadCM3; (bottom): projected changes in the intensity (deficit volume) of 100-year droughts with changing withdrawals for the 2070s, with climate change (left, with HadCM3 climate projections) and without climate change (right). Source: Lehner et al., 2006.

events in two regions of England, combining fluvial and coastal flooding. The two main conclusions from their work were as follows. First, the percentage change in cost was greater for the rarer event than the more frequent event. Second, the absolute value of impacts, and therefore the percentage change from current impacts, was found to be highly dependent on the assumed socioeconomic change. In one region, event damage varied, in monetary terms, between four and five times across socioeconomic scenarios. An even wider range in estimated average annual damage was found in the UK Foresight Future Flooding and Coastal Defence project (Evans et al., 2004; Hall et al., 2005), which calculated average annual damage in 2080 of £1.5 billion, £5 billion, and £21 billion under similar climate scenarios but different socioeconomic futures (current average annual damage was estimated at £1 billion). The Foresight project represented the effect of climate change on flood frequency by altering the shape of the flood frequency curve using precipitation outputs from climate models and rainfall-runoff models for a sample of UK catchments. The EU-funded Projection of Economic impacts of climate change in Sectors of the European Union based on boTtom-up Analysis (PESETA) project (Ciscar, 2009; Feyen et al., 2009) used a hydrological model to simulate river flows, flooded areas, and flood frequency curves from climate scenarios derived from regional climate models, but – in contrast to the UK Foresight project – assumed no change in economic development in flood-prone areas. Figure 4-4 summarizes estimated changes in the average annual number of people flooded and average annual damage, by European region (Ciscar, 2009). There are strong regional variations in impact, with particularly large projected increases in both number of people flooded and economic damage (over 200%) in central and Eastern Europe, while in parts of North Eastern Europe, average annual flood damages decrease.

At the global scale, two studies have estimated the numbers of people affected by increases (or decreases) in flood hazard. Kleinen and Petschel-Held (2007) calculated the percentage of population living in river basins where the return period of the current 50-year event becomes shorter, for three climate models and a range of increases in global mean temperature. With an increase in global mean temperature of 2°C (above late 20th-century temperatures), between (approximately) 5 and 27% of the world's population would live in river basins where the current 50-year return period flood occurs at least twice as frequently. Hirabayashi and Kanae (2009) used a different metric, counting each year the number of people living in grid cells where the flood peak exceeded the (current) 100-year magnitude, using runoff as simulated by a high-resolution climate model fed through a river routing model. Beyond 2060, they found that at least 300 million people could be affected by substantial flooding even in years with relatively low flooding, with of the order of twice as many being flooded in flood-rich years (note that they used only one climate scenario with one climate model). This compares with a current range (using the same index) of between 20 and 300 million people. The largest part of the projected increase is due to increases in the occurrence of floods, rather than increases in population.

The impacts of changes in flood characteristics are highly dependent on how climate changes in the future, and as noted in Section 3.5.2, there

is *low confidence* in projections of changes in flood magnitude or frequency. However, based on the available literature, there is *high confidence* that, in some places, climate change has the potential to substantially affect flood losses.

4.3.3. Ecosystems

Available information shows that high temperature extremes (i.e., heat wave), drought, and floods substantially affect ecosystems. Increasing gaps and overall contraction of the distribution range for species habitat could result from increases in the frequency of large-scale disturbances due to extreme weather and climate events (Opdam and Wascher, 2004). Fischlin et al. (2007), from assessment of 19 studies, found that 20 to 30% of studied plant and animal species may be at an increased risk of extinction if warming exceeds 2 to 3°C above the preindustrial level. Changes due to climate extremes could also entail shifts of ecosystems to less-desired states (Scheffer et al., 2001; Chapin et al., 2004; Folke et al., 2004) through, for example, the exceedance of critical temperature thresholds, with potential loss of ecosystem services dependent on the previous state (Reid et al., 2005; see also Fischlin et al., 2007).

4.3.3.1. Heat Waves

Heat waves can directly impact ecosystems by, for example, constraining carbon and nitrogen cycling and reducing water availability, with the result of potentially decreasing production or even causing species mortality.

Warming can decrease net ecosystem carbon dioxide (CO₂) exchange by inducing drought that suppresses net primary productivity. More frequent warm years may lead to a sustained decrease in CO₂ uptake by terrestrial ecosystems (Arnone et al., 2008). Extreme temperature conditions can shift forest ecosystems from being a net carbon sink to being a net carbon source. For example, tall-grass prairie net ecosystem CO₂ exchange levels decreased in both an extreme warming year (2003) and the following year in grassland monoliths from central Oklahoma, United States (Arnone et al., 2008). A 30% reduction in gross primary productivity together with decreased ecosystem respiration over Europe during the heat wave in 2003 resulted in a strong net source of CO₂ (0.5 Pg C yr⁻¹) to the atmosphere and reversed the effect of four years of net ecosystem carbon sequestration. Such a reduction in Europe's primary productivity is unprecedented during the last century (Ciais et al., 2005).

Impacts are determined not only by the magnitude of warming but also by organisms' physiological sensitivity to that warming and by their ability to compensate behaviorally and physiologically. For example, warming may affect tropical forest lizards' physiological performance in summer, as well as their ability to compete with warm-adapted, open-habitat competitors (Huey et al., 2009). Projected increases in maximum

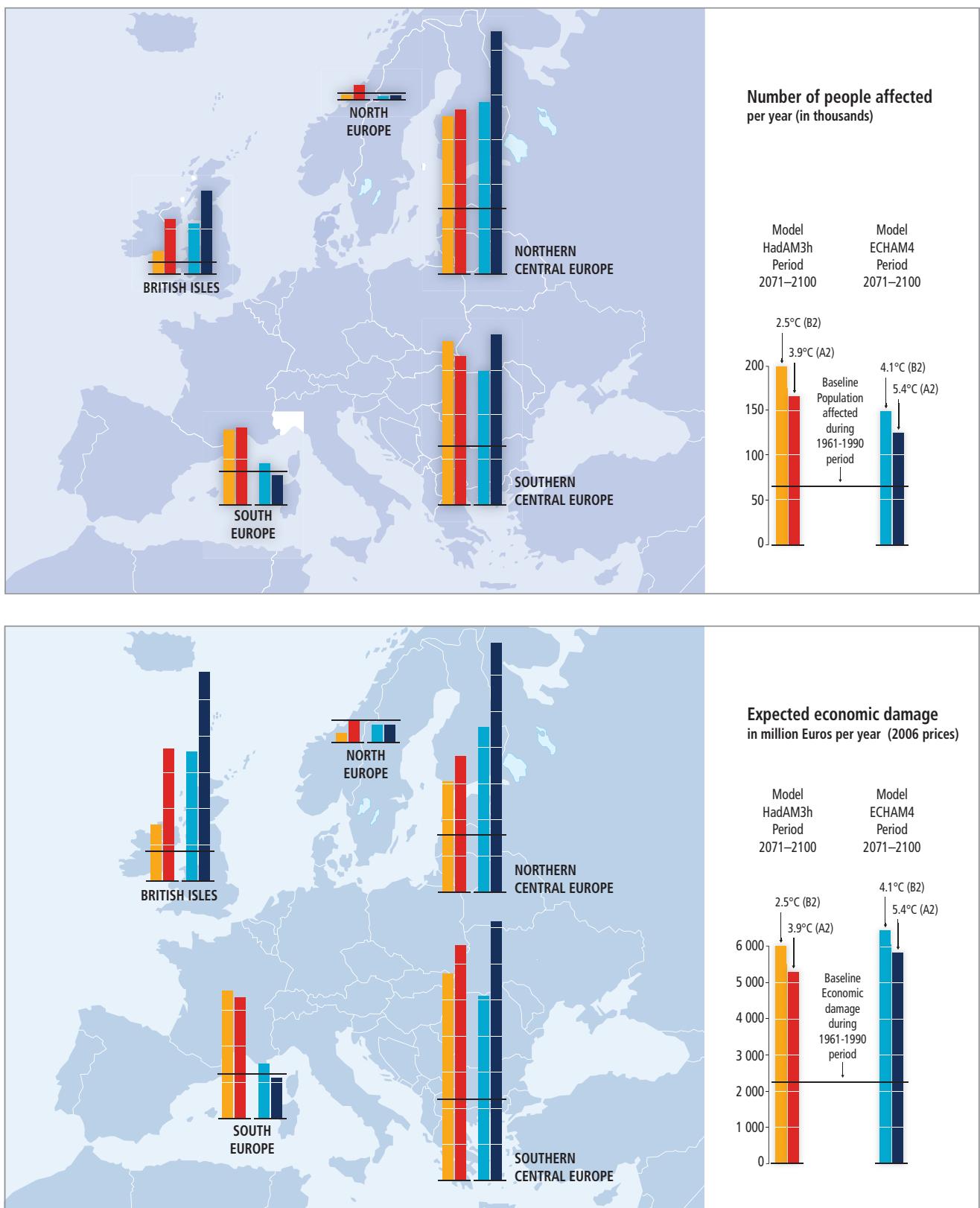


Figure 4-4 | Impact of climate change by 2071–2100 on flood risk in Europe. Note that the numbers assume no change in population or development in flood-prone areas. As illustrated in the legend on the right of each panel, projections are given for two Special Report on Emissions Scenarios (SRES) scenarios (A2 and B2) and for two global climate models (HadAM3h and ECHAM4). Projected mean temperature increase in the European region for the period 2071–2100 compared with 1961–1990 is indicated for each scenario and model combination. (top): For each region, baseline simulated population affected over 1961–1990 (thousands per year) and expected population affected (thousands per year) for 2071–2100 for each scenario and model combination. (bottom): For each region, baseline simulated economic damage over 1961–1990 (million € per year, 2006 prices) and expected economic damage (million € per year, 2006 prices) for 2071–2100 for each scenario and model combination. Data from Ciscar, 2009.

air temperatures may increase evaporative water requirements in birds, thus influencing survival during extreme heat events (McKeechnie and Wolf, 2010). Heat waves could also cause increased likelihood of catastrophic avian mortality events (McKeechnie and Wolf, 2010).

4.3.3.2. Drought

A rapid, drought-induced die-off of overstory woody plants at a subcontinental scale was triggered by the 2000–2003 drought in southwestern North America. Following 15 months of diminished soil water content, more than 90% of the dominant tree species, *Pinus edulis*, died. Limited observations indicate that die-off was more extensive than during the previous drought of the 1950s, also affecting wetter sites within the tree species' distribution (Breshears et al., 2005). Regional-scale piñon pine mortality was observed following an extended drought (2000–2004) in northern New Mexico (Rich et al., 2008). Dominant plant species from diverse habitat types (i.e., riparian, chaparral, and low-to high-elevation forests) exhibited significant mortality during a drought in the southwestern United States; average mortality among dominant species was 3.3 to 41.4% (Gitlin et al., 2006).

Evergreen coniferous species mortality caused by the coupling of drought and higher temperatures from winter to spring has been observed in the Republic of Korea (Lim et al., 2010). In 1998, 2002, 2007, and 2009, years of high winter-spring temperatures and lower precipitation, *P. densiflora* and *P. koraiensis* were affected by droughts, with many dying in the crown layer, while deciduous species survived. Similarly, *Abies koreana*, an endemic species in Korea, at high elevation has declined following a rise in winter temperatures since the late 1990s (Lim et al., 2010). Beech crown condition was observed to decline following severe drought in 1976 (Power, 1994), 1989 (Innes, 1992), and 1990 (Stribley and Ashmore, 2002). Similarly, the percentage of moderately or severely damaged trees displayed an upward trend after the 1989 drought in Central Italy, especially for *P. pinea* and *Fagus sylvatica* (Bussotti et al., 1995). As final examples, defoliation and mortality in Scots pine observed in each year during 1996 to 2002 was related to the precipitation deficit and hot conditions of the previous year in the largest inner-alpine valley of Switzerland (Valais) (Rebetz and Dobbertin, 2004), and both gross primary production and total ecosystem respiration decreased in 2003 in many regions of Europe (Granier et al., 2007).

In a shallow temperate southern European estuary, the Mondego Estuary in Portugal, the severe drought in 2004–2005 was responsible for spatial shifts in the estuary's zooplankton community, with an increase in abundance and diversity during the period of low freshwater flow (Marques et al., 2007).

4.3.3.3. Floods

Floods also impact ecosystems. Floods can cause population- and community-level changes superimposed on a background of more

gradual trends (Thibault and Brown, 2008). As an example, an extreme flood event affected a desert rodent community (that had been monitored for 30 years) by inducing a large mortality rate, eliminating the advantage of previously dominant species, resetting long-term population and community trends, altering competitive and meta-population dynamics, and reorganizing the community (Thibault and Brown, 2008).

4.3.3.4. Other Events

Other events, such as hurricanes and storms, can also impact ecosystems. Hurricanes can cause widespread mortality of wild birds, and their aftermath may cause declines due to the birds' loss of resources required for foraging and breeding (Wiley and Wunderle, 1994). Winter storms can also impact forest ecosystems, particularly in pre-alpine and alpine areas (Faccio, 2003; Schelhaas et al., 2003; Fuhrer et al., 2006). In addition, saltmarshes, mangroves, and coral reefs can be vulnerable to climate extremes (e.g., Bertness and Ewanchuk, 2002; Hughes et al., 2003; Fischlin et al., 2007).

4.3.4. Food Systems and Food Security

Food systems and food security can be affected by extreme events that impair food production and food storage and delivery systems (food logistics). Impacts transmitted through an increase in the price of food can be especially challenging for the urban poor in developing countries (FAO, 2008). Global food price increases are borne disproportionately by low-income countries, where people spend more of their income on food (OECD-FAO, 2008).

When agricultural production is not consumed where it is produced, it must be transported and often processed and stored. This process involves complex interdependent supply chains exposed to multiple hazards. At every step of the process, transport and associated infrastructure such as roads, railways, bridges, warehouses, airports, ports, and tunnels can be at risk of direct damage from climate events, making the processing and delivery chain as a whole at risk of disruption resulting from damage or blockages at any point in the chain.

The economies of many developing countries rely heavily on agriculture, dominated by small-scale and subsistence farming. People's livelihoods in this sector are especially exposed to weather extremes (Easterling and Apps, 2005; Easterling et al., 2007). Subsistence farmers can be severely impacted by climate and weather events. For example, the majority of households produce maize in many African countries, but only a modest proportion sells it – the great majority eat all they produce. In Kenya for example, nearly all households grow maize, but only 36% sell it, with 20% accounting for the majority of sales (FAO, 2009). Both such famers and their governments have limited capacity for recovery (Easterling and Apps, 2005).

Evidence that the current warming trends around the world have already begun to impact agriculture is reported by Lobell et al. (2011). They show that crop yields have already declined due to warmer conditions compared to the expected yields without warming. Both Schlenker and Roberts (2009) and Muller et al. (2011), after their evaluation of projected temperature effects on crops in the United States and Africa, concluded that climate change would have negative impacts on crop yields. These effects were based on temperature trends and an expected increase in the probability of extremes during the growing season; however, there is also the potential occurrence of extreme events after the crop is grown, which could affect harvest and grain quality. Fallon and Betts (2010) stated that increasing flooding and drought risks could affect agricultural production and require the adoption of robust management practices to offset these negative impacts. Their analysis for Europe showed a probable increase in crop productivity in northern regions but a decrease in the southern regions, leading to a greater disparity in production.

In a recent evaluation of high temperature as a component of climate trends, Battisti and Naylor (2009) concluded that future growing season temperatures are *very likely* to exceed the most extreme temperatures observed from 1900 to 2006, for both tropical and subtropical regions, with substantial potential implications for food systems around the world.

The effects of temperature extremes on a number of different crop species have been summarized in Hatfield et al. (2011). Many crops are especially sensitive to extreme temperatures that occur just prior to or during the critical pollination phase of crop growth (Wheeler et al., 2000; Hatfield et al., 2008, 2011). Crop sensitivity and ability to compensate during later improved weather will depend on the length of time for anthesis in each crop.

Extreme temperatures can negatively impact grain yield (Kim et al., 1996; Prasad et al., 2006). For example, Tian et al. (2010) observed in rice that high temperatures ($>35^{\circ}\text{C}$) coupled with high humidity and low wind speed caused panicle temperatures to be as much as 4°C higher than air temperature, inducing floret sterility. Impacts of temperature extremes may not be limited to daytime events. Mohammed and Tarey (2009) observed that rice yields were reduced by 90% when night temperatures were increased from 27 to 32°C . An additional impact of extremes has been found in the quality of the grain. Kettlewell et al. (1999) found that wheat quality in the United Kingdom was related to the North Atlantic Oscillation and probably caused by variation in rainfall during the grain-filling period. In a more recent study, Hurkman et al. (2009) observed that high-temperature events during grain-filling of wheat altered the protein content of the grain, and these responses were dependent upon whether the exposure was imposed early or midway through the grain-filling period. Skylas et al. (2002) observed that high temperature during grain-filling was one of the most significant factors affecting both yield and flour quality in wheat.

Drought causes yield variation, and an example from Europe demonstrates that historical yield records show that drought has been a primary cause

of interannual yield variation (Hlavinka et al., 2009; Hatfield, 2010). Water supply for agricultural production will be critical to sustain production and even more important to provide the increase in food production required to sustain the world's growing population. With glaciers retreating due to global warming and El Niño episodes, the Andean region faces increasing threats to its water supply (Mark and Seltzer, 2003; Cadier et al., 2007). With precipitation limited to only a few months of the year, melt from glaciers is the only significant source of water during the dry season (Mark and Seltzer, 2003). Glacier recession reduces the buffering role of glaciers, hence inducing more floods during the rainy season and more water shortages during the dry season. Cadier et al. (2007) found that warm anomalies of the El Niño-Southern Oscillation (ENSO) corresponded to an increase in melting four months later.

Food security is linked to our ability to adapt agricultural systems to extreme events using our understanding of the complex system of production, logistics, utilization of the produce, and the socioeconomic structure of the community. The spatial variability and context sensitivity of each of these factors points to the value of downscaled scenarios of climate change and extreme events.

4.3.5. Human Settlements, Infrastructure, and Tourism

4.3.5.1. Human Settlements

Settlements concentrate the exposure of humans, their assets, and their activities. In the case of very large cities, these concentrations can represent a significant proportion of national wealth and may result in additional forms of vulnerability (Mitchell, 1998). Flooding, landslides, storms, heat waves, and wildfires have produced historically important damages in human settlements, and the characteristics of these events and their underlying climate drivers are projected to change (see Chapter 3; Kovats and Akhtar, 2008; Satterthwaite, 2008). The concentration of economic assets and people creates the possibility of large impacts, but also the capacity for recovery (Cutter et al., 2008). Coastal settlements are especially at risk with sea level rise and changes in coastal storm activity (see Sections 3.4.4 and 3.4.5 and Case Study 9.2.8).

At very high risk of impacts are the urban poor in informal settlements (Satterthwaite, 2008; Douglas, 2009). Worldwide, about one billion people live in informal settlements, and informal settlements are growing faster than formal settlements (UN-HABITAT, 2008; UNISDR, 2011). Informal settlements are also found in developed countries; for example, there are about 50 million people in such areas in Europe (UNECE, 2009). Occupants of informal settlements are typically more exposed to climate events with no or limited hazard-reducing infrastructure. The vulnerability is high due to very low-quality housing and limited capacity to cope due to a lack of assets, insurance, and marginal livelihoods, with less state support and limited legal protection (Dodman and Satterthwaite, 2008).

The number and size of coastal settlements and their associated infrastructure have increased significantly over recent decades (McGranahan et al., 2007; Hanson et al., 2011; see also Case Study 9.2.8). In many cases these settlements have affected the ability of natural coastal systems to respond effectively to extreme climate events by, for example, removing the protection provided by sand dunes and mangroves. Small island states, particularly small island developing states (see Case Study 9.2.9), may face substantial impacts from climate change-related extremes.

Urbanization exacerbates the negative effects of flooding through greatly increased runoff concentration, peak, and volume, the increased occupation of flood plains, and often inadequate drainage planning (McGranahan et al., 2007; Douglas et al., 2008). These urbanization issues are universal but often at their worst in informal settlements, which are generally the most exposed to flooding and usually do not have the capacity to deal with the issues (Hardoy et al., 2001). Flooding regularly disrupts cities, and urban food production can be severely affected by flooding, undermining local food security in poor communities (Douglas, 2009; Aggarwal and Singh, 2010). A further concern for low- and middle-income cities as a result of flooding, particularly in developing countries, is human waste, as most of these cities are not served by proper water services such as sewers, drains, or solid waste collection services (Hardoy et al., 2001).

Slope failure can affect settlements in tropical mountainous areas, particularly in deforested areas (e.g., Vanacker et al., 2003) and hilly areas (Loveridge et al., 2010), and especially following heavy prolonged rain (e.g., see Case Study 9.2.5). Informal settlements are often exposed to potential slope failure as they are often located on unstable land with no engineering or drainage works (Alexander, 2005; Anderson et al., 2007). Informal settlements have been disproportionately badly impacted by landslides in Colombia and Venezuela in the past (e.g., Takahashi et al., 2001; Ojeda and Donnelly, 2006) and were similarly affected in 2010 during unusual heavy rains associated with the La Niña weather phenomenon (NCDC, 2011). Densely settled regions in the Alps (Crosta et al., 2004) and Himalayas have been similarly impacted (Petley et al., 2007).

Cities can substantially increase local temperatures and reduce temperature drop at night (e.g., see Case Study 9.2.1). This is the urban heat island effect resulting from the large amount of heat-absorbing material, building characteristics, and emissions of anthropogenic heat from air conditioning units and vehicles (e.g., Rizwan et al., 2008; for a critical review of heat island research, see Stewart, 2011). Heat waves combined with urban heat islands (Basara et al., 2010; Tan et al., 2010) can result in large death tolls with the elderly, the unwell, the socially isolated, and outdoor workers (Maloney and Forbes, 2011) being especially vulnerable, although acclimatization and heat health-warning systems can substantially reduce excess deaths (Fouillet et al., 2008). Heat waves thus pose a future challenge for major cities (e.g., Endlicher et al., 2008; Bacciniet al., 2011; for London, Wilby, 2003). In urban areas, heat waves also have negative effects on air quality and the number of

days with high pollutants, ground level ozone, and suspended particle concentrations (Casimiro and Calheiros, 2002; Sanderson et al., 2003; Langner et al., 2005).

The largest impacts from coastal inundation due to sea level rise (and/or relative sea level rise) in low-elevation coastal zones (i.e., coastal areas with an elevation less than 10 m above present mean sea level; see McGranahan et al., 2007) are thought to be associated with extreme sea levels due to tropical and extratropical storms (e.g., Ebersole et al., 2010; Mozumder et al., 2011) that will be superimposed upon the long-term sea level rise (e.g., Frazier et al., 2010). An increase in the mean maximum wind speed of tropical cyclones is *likely* over the 21st century, but possibly not in all ocean basins (see Table 3-1). The destructive potential of tropical cyclones may increase in some regions as a result of this projected increase in intensity of mean maximum wind speed and tropical cyclone-related rainfall rates (see Section 3.4.4). Storms generally result in considerable disruption and local destruction, but cyclones and their associated storm surges have in some cases caused very substantial destruction in modern cities (e.g., New Orleans and Darwin; see also Case Study 9.2.5). The impacts are considered to be more severe for large urban centers built on deltas and small island states (McGranahan et al., 2007; Love et al., 2010; Wardekker et al., 2010), particularly for those at the low end of the international income distribution (Dasgupta et al., 2009). The details of exposure will be controlled by the natural or human-induced characteristics of the system, for example, the occurrence/distribution of protecting barrier islands and/or coastal wetlands that may attenuate surges (see, e.g., Irish et al., 2010; Wamsley et al., 2010) or changes such as land reclamation (Guo et al., 2009). Recent studies (Nicholls et al., 2008; Hanson et al., 2011) have assessed the asset exposure of port cities with more than one million inhabitants (in 2005). They demonstrated that large populations are already exposed to coastal inundation (~40 million people or 0.6% of the global population) by a 1-in-100-year extreme event, while the total value of exposed assets was estimated at US\$ 3,000 billion (~ 5% of the global GDP in 2005). By the 2070s, population exposure was estimated to triple, whereas asset exposure could grow tenfold to some US\$ 35,000 billion; these estimates, however, do not account for the potential construction of effective coastal protection schemes (see also Dawson et al., 2005), with the exposure growth rate being more rapid in developing countries (e.g., Adamo, 2010). Lenton et al. (2009) estimated a substantial increase in the exposure of coastal populations to inundation (see Figure 4-5).

4.3.5.2. Infrastructure

Weather- and climate-related extremes are expected to produce large impacts on infrastructure, although detailed analyses of potential and projected damages are limited to a few countries (e.g., Australia, Canada, the United States; Holper et al., 2007), infrastructure types (e.g., power lines), and sectors (e.g., transport, tourism). Inadequate infrastructure design may increase the impacts of climate and weather extremes, and some infrastructure may become inadequate where climate

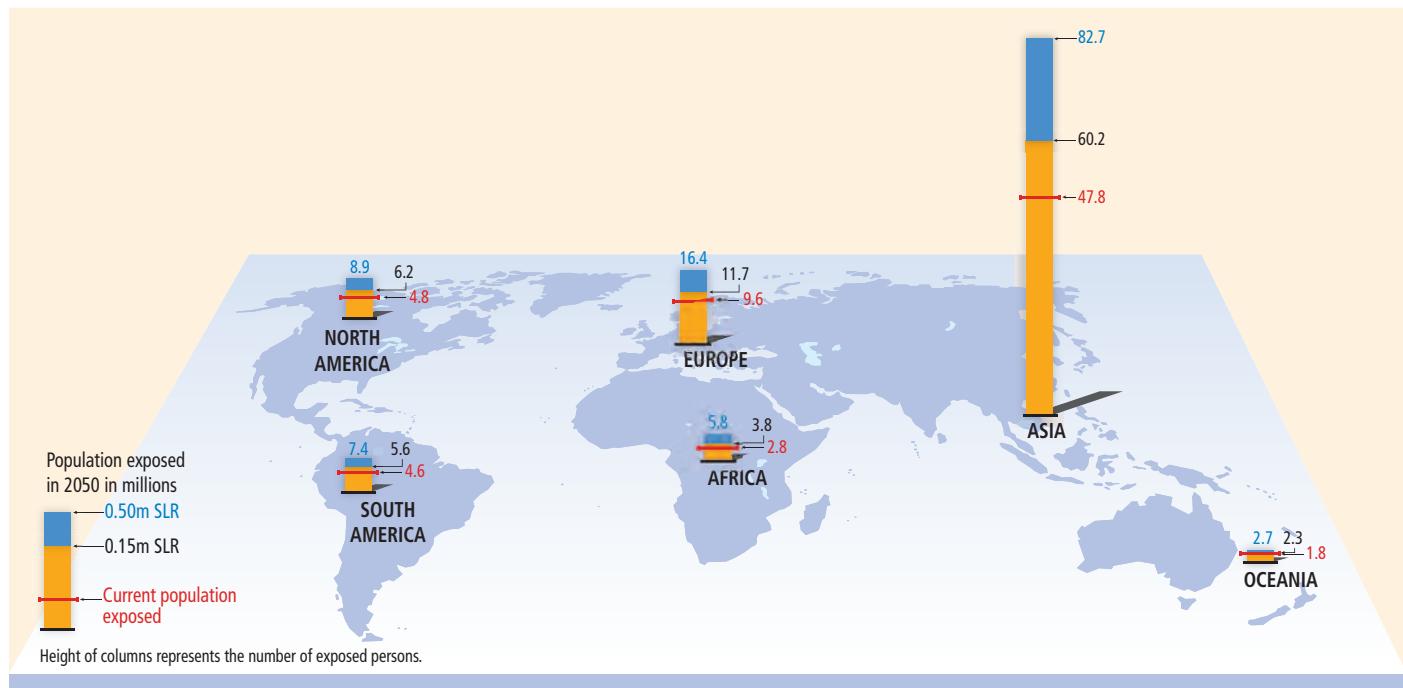


Figure 4-5 | For low-elevation coastal areas, current and future (2050) population exposure to inundation in the case of the 1-in-100-year extreme storm for sea level rise of 0.15 m and for sea level rise of 0.50 m due to the partial melting of the Greenland and West Antarctic Ice Sheets. Data from Lenton et al., 2009.

change alters the frequency and severity of extremes, for example, an increase in heavy rainfalls may affect the capacity and maintenance of storm water, drainage, and sewerage infrastructure (Douglas et al., 2008). In some infrastructure, secondary risks in case of extreme weather may cause additional hazards (e.g., extreme rainfall can damage dams). The same is true for industrial and mining installations containing hazardous substances (e.g., heavy rainfall is the main cause of tailings dam failure, accounting for 25% of incidents worldwide and 35% in Europe; Rico et al., 2008).

In many parts of the world, including Central Asia and parts of Europe, aging infrastructure, high operating costs, low responsiveness to customers, and poor access to capital markets may limit the operability of sewerage systems (Evans and Webster, 2008). Moreover, most urban centers in sub-Saharan Africa and in Asia have no sewers (Hardoy et al., 2001). Current problems of pollution and flooding will be exacerbated by an increase in climatic and weather extremes (e.g., intense rainfall; see Table 3-3 for projected regional changes).

Major settlements are dependent on lengthy infrastructure networks for water, power, telecommunications, transport, and trade, which are exposed to a wide range of extreme events (e.g., heavy precipitation and snow, gale winds). Modern logistics systems are intended to minimize slack and redundancies and as a result are particularly vulnerable to disruption by extreme events (Love et al., 2010).

Transport infrastructure is vulnerable to extremes in temperature, precipitation/river floods, and storm surges, which can lead to damage in roads, rail, airports, and ports. Impacts on coastal infrastructure, on

services, and particularly on ports, key nodes of international supply chains, are expected (e.g., Oh and Reuveny, 2010). This may have far-reaching implications for international trade, as more than 80% of global trade in goods (by volume) is carried by sea (UNCTAD, 2009). All coastal modes of transportation are considered vulnerable, but exposure and impacts will vary, for example, by region, mode of transportation, location/elevation, and condition of transport infrastructure (NRC, 2008; UNCTAD, 2009). Coastal inundation due to storm surges and river floods can affect terminals, intermodal facilities, freight villages, storage areas, and cargo and disrupt intermodal supply chains and transport connectivity (see Figure 4-6). These effects would be of particular concern to small island states, whose transportation facilities are mostly located in low-elevation coastal zones (UNCTAD, 2009; for further examples, see Love et al., 2010).

Regarding road infrastructure, Meyer (2008) pointed to bridges and culverts as vulnerable elements in areas with projected increases in heavy precipitation. Moreover, the lifetime of these rigid structures is longer than average road surfaces and they are costly to repair or replace. Increased temperatures could reduce the lifetime of asphalt on road surfaces (Meizhu et al., 2010). Extreme temperature may cause expansion and increased movement of concrete joints, protective cladding, coatings, and sealants on bridges and airport infrastructure, impose stresses in the steel in bridges, and disrupt rail travel (e.g., Arkell and Darch, 2006). Nevertheless, roads and railways are typically replaced every 20 years and can accommodate climate change at the time of replacement (Meyer, 2008).

Electricity transmission infrastructure is also vulnerable to extreme storm events, particularly wind and lightning, and in some cases heat

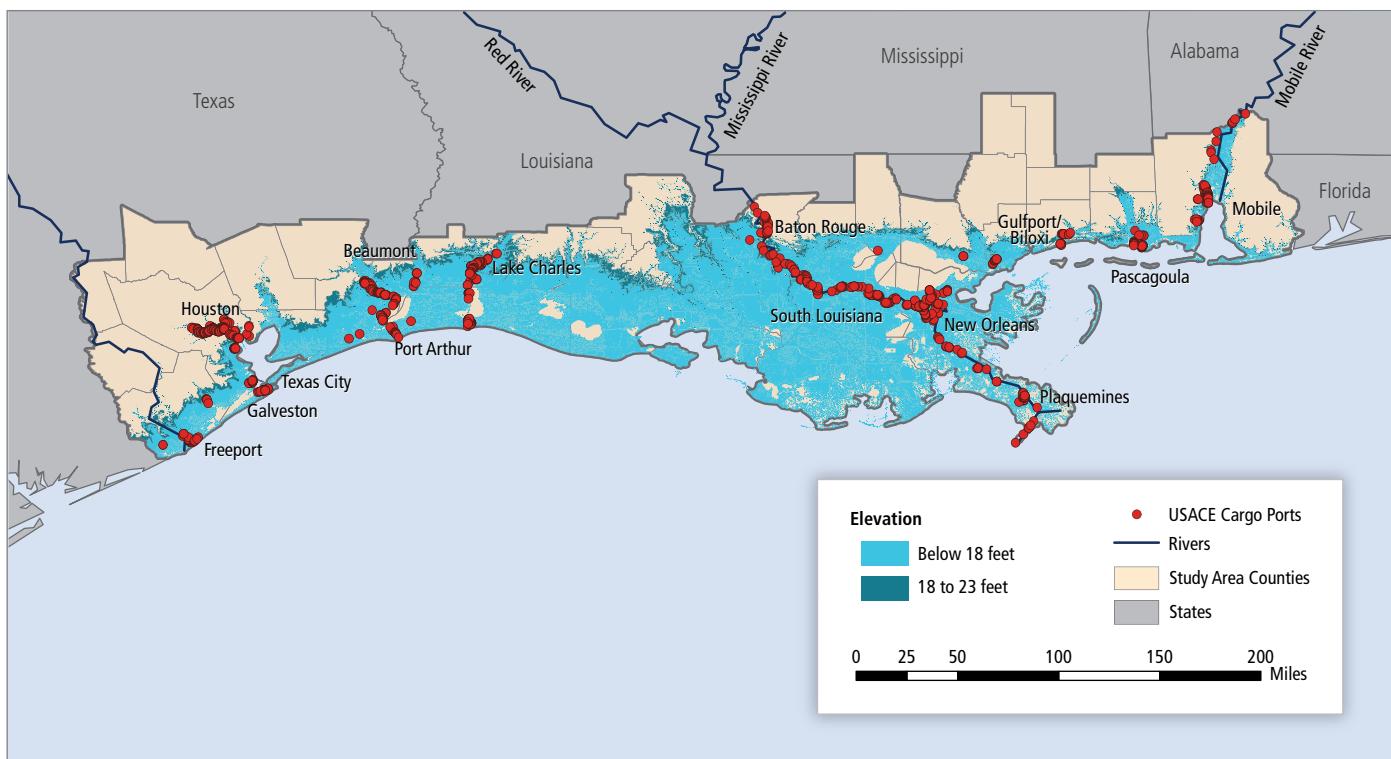


Figure 4-6 | Freight-handling port facilities at risk from storm surge of 5.5 and 7 m on the US Gulf Coast. Adapted from CCSP, 2008.

waves (McGregor et al., 2007). The passage of the Lothar and Martin storms across France in 1999 caused the greatest devastation to an electricity supply network ever seen in a developed country, as 120 high-voltage transmission pylons were toppled, and 36 high-tension transmission lines (one-quarter of the total lines in France) were lost (Abraham et al., 2000). Severe droughts may also affect the supply of cooling water to power plants, disrupting the ongoing supply of power (see Box 4-4; Rübelke and Vögele, 2011).

Buildings and urban facilities may be vulnerable to increasing frequency of heavy precipitation events (see Section 3.3.2). Those close to the coast are particularly at risk when storm surges are combined with sea level rise. In commercial buildings, vulnerable elements are lightweight roofs commonly used for warehouses, causing water spoilage to stored goods and equipment. During the Lothar and Martin storms, the most vulnerable public facilities were schools, particularly those built in the 1960s and 1970s and during the 1990s with the use of lightweight architectural elements of metal, plastic, and glass in walls and roofs (Abraham et al., 2000).

4.3.5.3. Tourism

The tourism sector is highly sensitive to climate, since climate is the principal driver of global seasonality in tourism demand (Lise and Tol, 2002; Becken and Hay, 2007). Approximately 10% of global GDP is spent on recreation and tourism, constituting a major source of income and foreign currency in many developing countries (Berrittella et al.,

2006). Extreme events may play an important role in tourist decisions (e.g., Hein et al., 2009; Yu et al., 2009).

There are three broad categories of impacts of climate extremes that can affect tourism destinations, competitiveness, and sustainability (Scott et al., 2008): (1) direct impacts on tourist infrastructure (hotels, access roads, etc.), on operating costs (heating/cooling, snowmaking, irrigation, food and water supply, evacuation, and insurance costs), on emergency preparedness requirements, and on business disruption (e.g., sun-and-sea or winter sports holidays); (2) indirect environmental change impacts of extreme events on biodiversity and landscape change (e.g., coastal erosion), which may negatively affect the quality and attractiveness of tourism destinations; and (3) tourism-adverse perception of particular touristic regions after occurrence of the extreme event itself. For example, adverse weather conditions or the occurrence of an extreme event can reduce a touristic region's popularity among tourists during the following season.

Apart from extreme events, large impacts on some tourist destinations may be produced by medium-term projected climate change effects (e.g., Bigano et al., 2008). Salinization of the groundwater resources due to sea level rise, land reclamation, and overexploitation of coastal aquifers (e.g., Alpa, 2009) as well as changing weather extreme patterns (Hein et al., 2009) will pose additional stresses for the industry. Nevertheless, the potential impacts on the tourist industry will depend also on tourists' perceptions of the coastal destinations (e.g., of destinations experiencing beach erosion) that, however, cannot be easily predicted (Buzinde et al., 2009). Capacity to recover is related to the degree of

dependence on tourism, with diversified economies being more robust (Ehmer and Heymann, 2008). However, low-lying coastal areas and areas currently on the edge of the snow limit may have limited alternatives. Some ski resorts will be able to adapt using snowmaking, which has become an integral component of the ski industry in Europe (Elsasser and Bürki, 2002), although at the expense of high water and energy consumption.

In some regions, the main impact of extreme events on tourism is decline in revenue, with loss of livelihoods for those working in the sector (Hamilton et al., 2005; Scott et al., 2008; Hein et al., 2009). Quantitative regional climate projections of the frequency or magnitude of certain weather and climate extremes (e.g., heat waves and droughts; see, for example, Table 3-3) inform qualitative understanding of regional impacts on tourism activities (see Box 4-3). The vulnerable hotspot regions in terms of extreme impacts of climate change on tourism include the

Mediterranean, Caribbean, small islands of the Indian and Pacific Oceans, and Australia and New Zealand (Scott et al., 2008). Direct and indirect effects of extremes in these regions will vary greatly with location (Gössling and Hall, 2006a,b; Wilbanks et al., 2007).

Box 4-3 points out a number of potential climate extreme impacts on tourism regions and activities.

4.3.6. Human Health, Well-Being, and Security

Climate extremes, such as heat waves, floods, droughts, and cyclones, influence human health, well-being, and security.

Heat waves have affected developed countries, as exemplified by the 2003 European heat wave (see Case Study 9.2.1 and Box 4-4). In much

Box 4-3 | Regional Examples of Potential Impacts of Climate Extremes on Tourism

Tropics

Projections indicate a *likely* increase in mean maximum wind speed (but not in all basins) and in tropical cyclone-related rainfall rates (see Table 3-1). In the Caribbean, tourist activities may be reduced where beaches erode with sea level rise and where coral is bleached, impacting snorkelers and divers (Uyarra et al., 2005).

Small island states are dependent on tourism, and the tourism infrastructure that lies on the coast is threatened by climate change (Berrittella et al., 2006). Sea level rise in the 20th century – with an average rate of 1.7 mm yr^{-1} and a significantly higher rate (3.1 mm yr^{-1}) for the period 1993–2003 (Bindoff et al., 2007) – poses risks for many touristic resorts of small islands in the Pacific and Indian Oceans (Becken and Hay, 2007; Scott et al., 2008).

Alpine Regions

Warming temperatures will raise the snowline elevation (Elsasser and Bürki, 2002; Scott et al., 2006). In Switzerland, only 44% of ski resorts are projected to be above the ‘snow-reliable’ altitude (snow for 100 days per season) by approximately 2030, as opposed to 85% today (Elsasser and Bürki, 2002). In Austria, 83% of ski resorts are currently snow-reliable but an increase in temperature of 1 and 2°C is projected to reduce this number to 67 and 50%, respectively (Abegg et al., 2007). Ski season simulations show that snowmaking technology can maintain snow-reliable conditions in Austria until the 2040s (A1B) to the 2050s (B1), but by the end of the century the required production in snow volume is projected to increase by up to 330% (Steiger, 2010). This artificial snow production will increase vulnerability to water shortage and local water conflicts, in particular in the French Alps (EEA, 2009).

Mediterranean Countries

More frequent heat waves and tropical nights ($>20^\circ\text{C}$) in summer (see Table 3-3) may lead to exceedance of comfortable temperature levels and reduce the touristic flow by 2060 (Hein et al., 2009). Tourism occupancy may increase during spring and autumn and decrease in summer (Perry, 2003; Esteban-Talaya et al., 2005). Northern European countries are expected to become relatively more attractive, closing their gap with the currently popular southern European countries (Hamilton et al., 2005).

There are major regional gaps in understanding how climate change may affect the natural and cultural resources in Africa and South America, preventing further insight on corresponding impacts for tourism activities (Scott et al., 2008).

In many regions, some types of tourism will benefit from, or be unaffected by, climate extremes (Scott et al., 2008). When an area is impacted directly by an extreme event, tourists will often go to another destination with the result that one area’s loss becomes another’s gain. The impacted area may also gain in the longer term through the provision of new infrastructure. City and cultural tourism is generally seen as relatively unaffected by climate and weather events (Scott et al., 2008).

of the developed world, societies are aging and hence can be more sensitive to climate extremes, such as heat waves (Hennessy et al., 2007). Heat extremes can claim casualties even in tropical countries, where people are acclimatized to the hot climate; McMichael et al. (2008) evaluated the relation between daily temperature and mortality in middle- and low-income countries, and reported that higher mortality was observed on very hot days in most of the cities, including tropical cities, such as Bangkok, Thailand; Delhi, India; and Salvador, Brazil.

Floods can cause deaths and injuries and can be followed by infectious diseases (such as diarrhea) and malnutrition due to crop damage (see Section 4.4.2.3). In Dhaka, Bangladesh, the severe flood in 1998 was associated with an increase in diarrhea during and after the flood, and the risk of non-cholera diarrhea was higher among those from a lower socioeconomic group and not using tap water (Hashizume et al., 2008). Floods may also lead to a geographical shift of malaria epidemic regions by changing breeding sites for vector mosquitoes. Outbreaks of malaria were associated with changes in habitat after the 1991 floods in Costa Rica's Atlantic region (Saenz et al., 1995; for another example, see Case Study 9.2.6). Malaria epidemics can also occur when people with little immunity move into endemic regions, although the displacement of large populations has rarely occurred as a result of acute natural disasters (Toole, 1997).

Drought can affect water security, as well as food security through reduction of agricultural production (MacDonald, 2010), and it can be a factor contributing to human-ignited forest fires, which can lead to widespread deforestation and carbon emissions (D'Almeida et al., 2007; van der Werf et al., 2008; Field et al., 2009; Phillips et al., 2009; Costa and Pires, 2010). Also, drought can increase or decrease the prevalence of mosquito-borne infectious diseases such as malaria, depending on the local conditions (Githcko et al., 2000), and is associated with meningitis (Molesworth et al., 2003). Studies indicate that there is a climate signal in forest fires throughout the American West and Canada and that there is a projected increase in severe wildfires in many areas (Gillett et al., 2004; Westerling et al., 2006; Westerling and Bryant, 2008). As described by McMichael et al. (2003a), the direct effects of fire on human health can include burns and smoke inhalation, with indirect health impacts potentially resulting from loss of vegetation on slopes, increased soil erosion, and resulting increased risk of landslides.

Evaluation of how impacts of climate extremes affect human health tend to focus on the direct, immediate effects of the event, using parameters that are often easier to obtain and quantify like death statistics or hospitalizations. These direct observable outcomes are used to demonstrate the extremity of an event and as a comparison metric to measure against other extreme events. However, indirect health impacts are not often reported, because they are one step removed from the event. Because indirect impacts are hard to monitor and are often temporally separated from the event, they are effectively removed from the cause-and-effect linkage to that event. Examples of indirect health impacts from extreme weather events include illnesses or injury resulting from disruption of human infrastructure built to deal with basic needs like

medical services; exposure to infectious or toxic agents after an extreme event like cyclones or flooding (Schmid et al., 2005); stress, anxiety, and mental illness after evacuation or geographical displacement (Fritze et al., 2008) as well as increased susceptibility to infection (Yee et al., 2007); and disruption of socioeconomic structures and food production that leads to increases of malnutrition that might not manifest until months after an extreme event (Haines et al., 2006; McMichael et al., 2006). Indirect health impacts are therefore a potentially large but under-examined outcome of extreme weather events that lead to a substantial underestimation of the total health burden.

There is a growing body of evidence that the mental health impact from extreme events is substantial (Neria et al., 2008; Berry et al., 2010). Often overshadowed by the physical health outcomes of an event, the psychological effects can be long lasting and can affect a large portion of a population (Morrissey and Reser, 2007). An extreme event may affect mental health directly from acute traumatic stress from an event, with common outcomes of anxiety and depression. It can also have indirect impacts during the recovery period associated with the stress and challenges of loss, disruption, and displacement. Furthermore, indirect mental health impacts could even affect individuals not directly associated with an event, like grieving friends and family of those who die from an event or the rescue and aid workers who suffer post-traumatic stress disorder (PTSD) after their aid efforts. Long-term mental health impacts are not often adequately monitored, but the body of research conducted after natural disasters in the past three decades suggests that the burden of PTSD among persons exposed to disasters is substantial (Neria et al., 2008). A range of other stress-related problems such as grief, depression, anxiety disorders, somatoform disorders, and drug and alcohol abuse (Fritze et al., 2008) have lasting effects, long after the causative event.

There remain large limitations in evaluating health impacts of climate change. The largest research gap is a lack of information on impact outcomes themselves in developing countries in general. This includes the mortality/morbidity data and information on other contributing factors such as nutritional status or access to safe water and medical facilities.

4.4. Regionally Based Aspects of Vulnerability, Exposure, and Impacts

4.4.1. Introduction

The regional subsections presented here discuss the impacts of extreme weather and climate events within the context of other issues and trends. Regional perspective, in social and economic dimensions, is important especially since decisionmaking often has a strong regional context. For a comprehensive assessment of observed and projected regional changes in climate extremes, see Sections 3.3 to 3.5 and Tables 3-2 and 3-3.

For various climate extremes, the following aspects are considered on a regional basis: exposure of humans and their activities to given climate

extremes; the vulnerability of what is exposed to the climate extreme; and the resulting impacts. The individual sections below are structured as is most logical for the trends relevant to each region.

4.4.2. Africa

4.4.2.1. Introduction

Climate extremes exert a significant control on the day-to-day economic development of Africa, particularly in traditional rain-fed agriculture and pastoralism, and water resources, at all scales. Floods and droughts can cause major human and environmental impacts on and disruptions to the economies of African countries, thus exacerbating vulnerability (AMCEN/UNEP, 2002; Scholes and Biggs, 2004; Washington et al., 2004; Thornton et al., 2006). There is still limited scientific information available on observed frequency and projections of many extreme events in Africa (e.g., see Tables 3-2 and 3-3), despite frequent reporting of such events, including their impacts.

Agriculture as an economic sector is most vulnerable and most exposed to climate extremes in Africa. It contributes approximately 50% to Africa's total export value and approximately 21% of its total GDP (Mendelsohn et al., 2000; PACJA, 2009). In particular, with an inefficient agriculture industry, sub-Saharan Africa is extremely vulnerable to climate extremes. This vulnerability is exacerbated by poor health, education, and governance standards (Brooks et al., 2005). Reid et al. (2007) project climate impacts on Namibia's natural resources that would cause annual losses of 1 to 6% of GDP, of which livestock production, traditional agriculture, and fishing are expected to be hardest hit, with a combined loss of US\$ 461 to 2,045 million per year by 2050.

4.4.2.2. Droughts and Heat Waves

An overall increase in dryness in Africa has been observed (*medium confidence*), with prolonged Sahel drought, but regional variability is observed (see Table 3-2). Droughts have affected the Sahel, the Horn of Africa, and Southern Africa particularly since the end of the 1960s (Richard et al., 2001; L'Hôte et al., 2002; Brooks, 2004; Christensen et al., 2007; Trenberth et al., 2007). One of the main consequences of multi-year drought periods is severe famine, such as the one associated with the drought in the Sahel in the 1980s, causing many casualties and important socioeconomic losses. The people in Africa who live in drought-prone areas are vulnerable to the direct impacts of droughts (e.g., famine, death of cattle, soil salinization), as well as indirect impacts (e.g., illnesses such as cholera and malaria) (Few et al., 2004).

The water sector is strongly influenced by, and sensitive to, periods of prolonged drought conditions in a continent with limited water storage infrastructure. Natural water reservoirs such as lakes experience a marked interannual water level fluctuation related to rainfall interannual variability (Nicholson et al., 2000; Verschuren et al., 2000).

Large changes in hydrology and water resources linked to climate variability have led to water stress conditions in human and ecological systems in a number of African countries (Schulze et al., 2001; New, 2002; Legesse et al., 2003; Eriksen et al., 2005; de Wit and Stankiewicz, 2006; Nkomo and Bernard, 2006). Twenty-five percent of the contemporary African population has limited water availability and thus constitutes a drought-sensitive population, whereas 69% of the population experiences relative water abundance (Vörösmarty et al., 2005). Even for this latter part of the population, however, relative abundance does not necessarily correspond to access to safe drinking water and sanitation, and this effective reduction of the quantity of freshwater available for human use negatively affects vulnerability. Despite the considerable improvements in access to freshwater in the 1990s, only about 62% of the African population had access to improved water supplies in 2000 (WHO/UNICEF, 2000). As water demand increases, the population exposed to different drought conditions (agricultural, climate, urban) is expected to increase as well.

Increasing drought risk may cause a decline in tourism, fisheries, and cropping (UNWTO, 2003). This could reduce the revenue available to governments, enterprises, and individuals, and hence further deteriorate the capacity for adaptation investment. For example, the 2003-2004 drought cost the Namibian Government N\$ 275 million (US\$ 43-48 million) in provision of emergency relief (Reid et al., 2007). Cameroon's economy is highly dependent on rain-fed agriculture; a 14% reduction in rainfall is projected to cause significant losses, of up to US\$ 4.56 billion (Molua and Lambi, 2006).

4.4.2.3. Extreme Rainfall Events and Floods

There are inconsistent patterns of change in heavy precipitation in Africa and partial lack of data; hence there is *low confidence* in observed precipitation trends (see Table 3-2). Heavy precipitation may induce landslides and debris flows in tropical mountain regions (Thomas and Thorp, 2003) with potential impacts for human settlements. In the arid and semi-arid areas of countries of the Horn of Africa, extreme rainfall events are often associated with a higher risk of the vector and epidemic diseases of malaria, dengue fever, cholera, Rift Valley fever, and hantavirus pulmonary syndrome (Anyamba et al., 2006; McMichael et al., 2006).

The periods of extreme rainfall and recurrent floods seem to correlate with the El Niño phase (Reason and Kiebel, 2004; Reason et al., 2005; Washington and Preston, 2006; Christensen et al., 2007) of ENSO events (e.g., 1982-1983, 1997-1998, 2006-2007). When such events occur, important economic and human losses result. In 2000, floods in Mozambique (see Case Study 9.2.6), particularly along the valleys of the rivers Limpopo, Save, and Zambezi, resulted in 700 reported deaths and about half a million homeless. The floods had a devastating effect on livelihoods, destroying agricultural crops, disrupting electricity supplies, and demolishing basic infrastructure (Osman-Elasha et al., 2006). However, floods can be highly beneficial in African drylands (e.g.,

Sahara and Namib Deserts) since the floodwaters infiltrate and recharge alluvial aquifers along ephemeral river pathways, extending water availability to dry seasons and drought years (Morin et al., 2009; Benito et al., 2010), and supporting riparian systems and human communities (e.g., Walvis Bay in Namibia).

Damage to African port cities from flooding, storm surge, and high winds might increase due to climate change. For instance, it is indicated that in Alexandria, US\$ 563.28 billion worth of assets could suffer damage or be lost because of coastal flooding alone by 2070 (Nicholls et al., 2008).

4.4.2.4. Dust Storms

Atmospheric dust is a major element of the Saharan and Sahelian environments. The Sahara Desert is the world's largest source of airborne mineral dust, which is transported over large distances, traversing northern Africa and adjacent regions and depositing dust on other continents (Osman-Elasha et al., 2006; Moulin et al., 1997). Dust storms have negative impacts on agriculture, health, and structures. They erode fertile soil; uproot young plants; bury water canals, homes, and properties; and cause respiratory problems. Meningitis transmission is associated with dust in semi-arid conditions and overcrowded living conditions. The frequency of dust events has increased in the Sahel zone, but studies of observations and in particular studies of projections of dust activity are limited (see Section 3.5.8).

4.4.3. Asia

Asia includes mega-deltas, which are susceptible to extreme impacts due to a combination of the following factors: high-hazard rivers, coastal flooding, and increased population exposure from expanding urban areas with large proportions of high vulnerability groups (Nicholls et al., 2007). Asia can also expect changes in the frequency and magnitude of extreme weather and climate events, such as heat waves and heavy precipitation (see, e.g., Table 3-3). Such changes may have ramifications not only for physical and natural systems but also for human systems.

4.4.3.1. Tropical Cyclones (Typhoons or Hurricanes)

Damage due to storm surge is sensitive to any changes in the magnitude of tropical cyclones (Xiao and Xiao, 2010). For example, changes in storm surge and associated damage were projected for the inner parts of three major bays (Tokyo, Ise, and Osaka) in Japan (Suzuki, 2009). The projections were based on calculations of inundations for different sea levels and different strengths of typhoons, using a spatial model with information on topography and levees. The research indicated that a typhoon that is 1.3 times as strong as the design standard with a sea level rise of 60 cm would cause damage costs of about US\$ 3,40, and 27 billion, respectively, in the investigated bays.

Awareness, improved governance, and development are essential in coping with extreme tropical cyclone and typhoon events in developing Asian countries (Cruz et al., 2007). For example, two cyclones in the Indian Ocean (Sidr and Nargis) of similar magnitude and strength caused a significantly different number of fatalities. A comparison is presented in Case Study 9.2.5.

For the period from 1983 to 2006, the direct economic losses in China increased, but there is no trend if the losses are normalized by annual total GDP and GDP per capita, suggesting Chinese economic development contributed to the upward trend. This hypothesis is consistent with data on tropical cyclone casualties, which showed no significant trend over the 24 years (Zhang et al., 2009). Similarly, normalized losses from typhoons on the Indian southeast coast since 1977 show no increases (Raghavan and Rajesh, 2003).

4.4.3.2. Flooding

The geographical distribution of flood risk is heavily concentrated in India, Bangladesh, and China, causing high human and material losses (Brouwer et al., 2007; Dash et al., 2007; Shen et al., 2008). Regarding the occurrence of the extreme events themselves, different flooding trends have been detected and projected in various catchments, but the evidence for broader regional trends is limited (see Section 3.5.2).

In July 2005, severe flooding occurred in Mumbai, India, after 944 mm of rain fell in a 24-hour period (Kshirsagar et al., 2006). The consequent flooding affected households, even in more affluent neighborhoods. Poor urban drainage systems in many parts of India can be easily blocked. Ranger et al. (2011) analyzed risk from heavy rainfall in the city of Mumbai, concluding that total losses (direct plus indirect) for a 1-in-100 year event could triple by the 2080s compared with the present (increasing from US\$ 700 to 2,305 million), and that adaptation could help reduce future damages.

As noted in the final report for the Ministry of Environment and Forest (2005) of the People's Republic of Bangladesh, flooding in Bangladesh is a normal, frequently recurrent, phenomenon. Bangladesh experiences four types of floods: flash floods from the overflowing of hilly rivers; rain floods due to poor drainage; monsoon floods in the flood plains of major rivers; and coastal floods following storm surge. In a normal year, river spills and drainage congestions cause inundation of 20 to 25% of the country's area. Inundation areas for 10-, 50-, and 100-year floods constitute 37, 52, and 60% of the country's area, respectively. In 1987, 1988, and 1998, floods inundated more than 60% of the country. The 1998 flood alone led to 1,100 deaths, caused inundation of nearly 100,000 km², left 30 million people homeless, and substantially damaged infrastructure.

There have been increases in flood impacts associated with changes in surrounding environments. Flooding has increased over the past few decades in the Poyang Lake, South China, due to levee construction

protecting a large rural population (Shankman et al., 2006). Such levees reduce the area for floodwater storage, leading to higher lake stages during the summer flood season and then levee failures. The most extreme floods occurred during or immediately following El Niño events (Shankman et al., 2006). Fengqing et al. (2005) analyzed losses from flooding in the Xinjiang autonomous region of China, and found an increase that seems to be linked to changes in rainfall and flash floods since 1987.

Heavy rainfall and flooding also affect environmental health in urban areas because surface water can be quickly contaminated. Urban poor populations in low- and middle-income countries can experience higher rates of infectious disease after floods, such as cholera, cryptosporidiosis, and typhoid fever (Kovats and Akhtar, 2008).

4.4.3.3. Temperature Extremes

Increases in warm days/nights and heat wave duration, frequency, and/or intensity are observed and projected in Asia (see Tables 3-2 and 3-3), with adverse impacts on both human and natural systems. In 2002, a heat wave was reported to have killed 622 people in the southern Indian state of Andhra Pradesh. Persons living in informal settlements and structures are more exposed to high temperatures (Kovats and Akhtar, 2008).

Agriculture is also affected directly by temperature extremes. For example, rice, the staple food in many parts of Asia, is adversely affected by extremely high temperature, especially prior to or during critical pollination phases (see Section 4.3.4).

4.4.3.4. Droughts

Asia has a long history of drought, which has been linked with other climate extremes. Spatially varying trends have been observed during the second half of the 20th century, with increasing dryness noted in some areas, particularly in East Asia (see Table 3-2), adversely affecting socioeconomic, agricultural, and environmental conditions. Drought causes water shortages, crop failures, starvation, and wildfire.

In Southeast Asia, El Niño is associated with comparatively dry conditions: 93% of droughts in Indonesia between 1830 and 1953 occurred during El Niño years (Quinn et al., 1978). In four El Niño years between 1973 and 1992, the average annual rainfall amounted to only around 67% of the 20-year average in two major rice growing areas in Java, Indonesia, causing a yield decline of approximately 50% (Amien et al., 1996).

During drought, severe water scarcity results from one of, or a combination of, the following mechanisms: insufficient precipitation; high evapotranspiration; and over-exploitation of water resources (Bhuiyan et al., 2006).

About 15% (23 million ha) of Asian rice areas experience frequent yield loss due to drought (Widawsky and O'Toole, 1990). The problem is particularly pertinent to eastern India, where the area of drought-prone fields exceeds more than 10 million ha (Pandey et al., 2000). Even when the total rainfall is adequate, shortages during critical periods reduce yield (Kumar et al., 2007). Lowland rice production in the Mekong region is generally reduced because crops are cultivated under rain-fed conditions, rather than irrigated, and often exposed to drought. In Cambodia, severe drought that affects grain yield mostly occurs late in the growing season, and longer-duration genotypes are more likely to encounter drought during grain filling (Tsubo et al., 2009).

Asian wetlands provide resources to people in inundation areas, who are susceptible to droughts. For achieving the benefits from fertilization for inundation agriculture in Cambodia, wide areas along the rivers need to be flooded (Kazama et al., 2009). Flood protection in this area needs to consider this benefit of inundation.

4.4.3.5. Wildfires

Grassland fire disaster is a critical problem in China (Su and Liu, 2004; Zhang et al., 2006), especially in northwestern and northeastern China due to expansive territory and complex physiognomy. Statistical analysis of historical grassland fire disaster data has suggested a gradual increase in grassland fire disasters with economic development and population growth in 12 northern provinces of China between 1991 and 2006 (Liu et al., 2006).

In tropical Asia, although humans are igniting the fires, droughts are predisposing factors for fire occurrence (Field et al., 2009). Drought episodes, forest fires, drainage of rice fields, and oil palm plantations are drying peatlands, which are then more susceptible to fires (van der Werf et al., 2008). Peatland fires are an important issue given the difficulties of extinguishing them and their potential effects on climate.

4.4.4. Central and South America

4.4.4.1. Extreme Rainfalls in South America

Extreme rainfall episodes have caused disasters in parts of South America, with hundreds to thousands of fatalities in mudslides and landslides, as typified, for example, by the December 1999 incident in Venezuela (Lyon, 2003). However, there is *low to medium confidence* in observed (Table 3-2) and in projected (Table 3-3) changes in heavy precipitation in the region.

4.4.4.2. Wildfires

There is a *low to medium confidence* in projections of trends in dryness in South America (see Table 3-3). Magrin et al. (2007) indicated that

more frequent wildfires are probable (an increase in frequency of 60% for a temperature increase of 3°C) in much of South America. In most of central and northern Mexico, the semi-arid vegetation could be replaced by the vegetation of arid regions (Villers and Trejo, 2004). Due to the interrelated nature of forest fires, deforestation, drought, and climate change, isolating one of the processes fails to describe the complexity of the interconnected whole.

4.4.4.3. Regional Costs

Climatic disasters account for the majority of natural disasters in Central America, with most of its territory located in tropical and equatorial areas. Low-lying states are especially vulnerable to hurricanes and tropical storms. In October 1998, Hurricane Mitch, one of the most powerful hurricanes of the tropical Atlantic Basin of the 20th century, caused direct and indirect damages to Honduras of US\$ 5 billion, equivalent to 95% of Honduras' 1998 GDP (Cardemil et al., 2000). Some literature indicates that hurricane losses, when corrected for population and wealth in Latin America and the Caribbean, have not increased since the 1940s (Pielke Jr. et al., 2003); and that increasing population and assets at risk are the main reason for increasing impacts.

4.4.5. Europe

4.4.5.1. Introduction

This section assesses vulnerability and exposure to climate extremes in Europe, evaluating observed and projected impacts, disasters, and risks. Europe has a higher population density and lower birth rate than any other continent. It currently has an aging population; life expectancy is high and increasing, and child mortality is low and decreasing (Eurostat, 2010). European exposure to climate- and weather-related hazards has increased whereas vulnerability has decreased as a result of implementation of policy, regulations, and risk prevention and management (EEA, 2008; UNISDR, 2009).

4.4.5.2. Heat Waves

Summer heat waves have increased in frequency and duration in most of Europe (Section 3.3.1 and Table 3-2) and have affected vulnerable segments of European society. During the 2003 heat wave, several tens of thousands of additional heat-related deaths were recorded (see Case Study 9.2.1 and Box 4-4). Urban heat islands pose an additional risk to urban inhabitants. Those most affected are the elderly, ill, and socially isolated (Kunst et al., 1993; Laschewski and Jendritzky, 2002; see Case Study 9.2.1). There are mounting concerns about increasing heat intensity in major European cities (Wilby, 2003) because of the large population that inhabits urban areas. Building characteristics, emissions of anthropogenic heat from air conditioning units and vehicles, as well as lack of green open areas in some parts of the cities, may exacerbate

heat load during heat waves (e.g., Stedman, 2004; Wilby, 2007). However, as high summer temperatures and urban heat waves become more common, populations are able to adapt to such 'expected' temperature conditions, decreasing mortality during subsequent heat waves (Fouillet et al., 2008).

4.4.5.3. Droughts and Wildfires

Drought risk is a function of the frequency, severity, and spatial and temporal extent of dry spells and of the vulnerability and exposure of a population and its economic activity (Lehner et al., 2006). In Mediterranean countries, droughts can lead to economic damages larger than floods or earthquakes (e.g., the drought in Spain in 1990 affected 6 million people and caused material losses of US\$ 4.5 billion; after CRED, 2010). The most severe human consequences of droughts are often found in semiarid regions where water availability is already low under normal conditions, water demand is close to, or exceeds, natural availability, and/or society lacks the capacity to mitigate or adapt to drought (Iglesias et al., 2009). Direct drought impacts affect all forms of water supply (municipal, industrial, and agricultural). Other sectors and systems affected by drought occurrence are hydropower generation, tourism, forestry, and terrestrial and aquatic ecosystems.

Forest fire danger (length of season, frequency, and severity) depends on the occurrence of drought. There is *medium confidence* in observed changes in drought in Europe (Table 3-2). Projections indicate increasing dryness in central Europe and the Mediterranean, with no major change in Northern Europe (*medium confidence*) (see Table 3-3). In the Mediterranean, an increase in dryness may lead to increased dominance of shrubs over trees (Mouillot et al., 2002); however, it does not translate directly into increased fire occurrence or changes in vegetation (Thonicke and Cramer, 2006). Analysis of post-fire forest resilience contributes to identifying 'risk hotspots' where post-fire management measures should be applied as a priority (Arianoutsou et al., 2011).

4.4.5.4. Coastal Flooding

Coastal flooding is an important natural disaster, since many Europeans live near the coasts. Storm surges can be activated as a result of wind-driven waves and winter storms (Smith et al., 2000), whereas long-term processes are linked to global mean sea level rise (Woodworth et al., 2005). Locations currently experiencing adverse impacts such as coastal erosion and inundation will continue to do so in the future (see Section 3.5.5). Expected sea level rise is projected to have impacts on Europe's coastal areas including land loss, groundwater and soil salinization, and damage to property and infrastructure (Devoy, 2008). Hinkel et al. (2010) found that the total monetary damage in coastal areas of the Member Countries of the European Union caused by flooding, salinity intrusion, land erosion, and migration is projected to rise without adaptation by 2100 to roughly € 17 billion per year under the A2 and

Box 4-4 | Extraordinary Heat Wave in Europe, Summer 2003

The extraordinarily severe heat wave over large parts of the European continent in the summer of 2003 produced record-breaking temperatures particularly during June and August (Beniston, 2004; Schär et al., 2004). Average summer (June to August) temperatures were by up to five standard deviations above the long-term mean, implying that this was an extremely unusual event (Schär and Jendritzky, 2004). Regional climate model simulations suggest the 2003 heat wave bears resemblance to summer temperatures in the late 21st century under the A2 scenario (Beniston, 2004).

Electricity demand increased with the high heat levels. Additionally, drought conditions created stress on health, water supplies, food storage, and energy systems; for example, reduced river flows reduced the cooling efficiency of thermal power plants (conventional and nuclear), and six power plants were shut down completely (Létard et al., 2004). Many major rivers (e.g., the Po, Rhine, Loire, and Danube) were at record low levels, resulting in disruption of inland navigation and irrigation, as well as power plant cooling (Beniston and Diaz, 2004; Zebisch et al., 2005). In France, electricity became scarce, construction productivity fell, and the cold storage systems of approximately 20 to 30% of all food-related establishments were found to be inadequate (Létard et al., 2004). The (uninsured) economic losses for the agriculture sector in the European Union were estimated at € 13 billion (Sénat, 2004). A record drop in crop yield of 36% occurred in Italy for maize grown in the Po valley, where extremely high temperatures prevailed (Ciais et al., 2005). The hot and dry conditions led to many very large wildfires. Glacier melting in the Alps prevented even lower river flows in the Danube and Rhine (Fink et al., 2004).

Health and health service-related impacts of the heat wave were dramatic, with excess deaths of about 35,000 (Kosatsky, 2005). Elderly people were among those most affected (WHO, 2003; Borrell et al., 2006; Kovats and Ebi, 2006), but deaths were also associated with housing and social conditions, for example, being socially isolated or living on the top floor (Vandentorren et al., 2006). The high mortality during the 2003 heat wave marked an inflection point in public awareness of the dangers of high temperatures, conducive to increasing the preventive measures set up by health institutions and authorities (Koppe et al., 2004; Pascal et al., 2006).

During the July 2006 heat wave, about 2,000 excess deaths occurred in France (Rey et al., 2007). The excess mortality during the 2006 heat wave was markedly lower than that predicted by Fouillet et al. (2008) based on the quantitative association between temperature and mortality observed during 1975–2003. Fouillet et al. (2008) interpreted this mortality reduction (~4,400 deaths) as a decrease in the population's vulnerability to heat, together with increased awareness of the risk related to extreme temperatures, preventive measures, and the warning system established after the 2003 heat wave.

B1 emission scenarios. The Netherlands is an example of a country that is highly susceptible to both sea level rise and coastal flooding, with damage costs relative to GDP of up to 0.3% of GDP under the A2 scenario (Hinkel et al., 2010). By 2100, adaptation can reduce the number of people flooded by two orders of magnitude and the total damage costs by a factor of seven to nine (Hinkel et al., 2010).

4.4.5.5. Gale Winds

Storms have been one of the most important climate hazards for the insurance industry in Europe (Munich Re NatCatSERVICE data cited in EEA, 2008). In the most severe extratropical windstorm month, December 1999, when three events struck Europe (Anatol – December 3, Denmark; Lothar – December 26, France, Germany, and Switzerland; and Martin – December 28, France, Spain, and Italy), insured damage was in excess of US\$ 12 billion (Schwierz et al., 2010). Typical economic losses were generated by gale winds via effects on electrical distribution systems, transportation, and communication lines; by damage to vulnerable elements of buildings (e.g., lightweight roofs); and by trees

falling on houses. Some researchers have found no contribution from climate change to trends in the economic losses from floods in Europe since the 1970s (Barredo, 2009). Some studies have found evidence of increasing damages to forests in Sweden and Switzerland (Nilsson et al., 2004; Usbeck et al., 2010). Still other studies assert that increases in forest disturbances in Europe are mostly due to changes in forest management (e.g., Schelhaas et al., 2003).

There is *medium confidence* in projected poleward shifts of mid-latitude storm tracks but *low confidence* in detailed regional projections (see Section 3.4.5). According to a study by Swiss Re (2009), if by the end of this century once-in-a-millennium storm surge events strike northern Europe every 30 years, this could potentially result in a disproportionate increase in annual expected losses from a current € 0.6 to 2.6 billion by end of the century. Similar results are obtained from global and regional climate models run under the IPCC SRES A1B emission scenario (Donat et al., 2010). Adaptation to the changing wind climate may reduce by half the estimated losses (Leckebusch et al., 2007; Donat et al., 2010), indicating that adaptation through adequate sea defenses and the management of residual risk is beneficial.

4.4.5.6. Flooding

Flooding is the most frequent natural disaster in Europe (EEA, 2008). Economic losses from flood hazards in Europe have increased considerably over previous decades (Lugeri et al., 2010), and increasing exposure of people and economic assets is probably the major cause of the long-term changes in economic disaster losses (Barredo, 2009). Exposure is influenced by socioeconomic development, urbanization, and infrastructure construction on flood-prone areas. Large flood impacts have been caused by a few individual flood events (e.g., the 1997 floods in Poland and Czech Republic, the 2002 floods in much of Europe, and the 2007 summer floods in the United Kingdom). The projected increase in frequency and intensity of heavy precipitation over large parts of Europe (Table 3-3) may increase the probability of flash floods, which pose the highest risk of fatality (EEA, 2004). Particularly vulnerable are new urban developments and tourist facilities, such as camping and recreation areas (e.g., a large flash flood in 1996 in the Spanish Pyrenees, conveying a large amount of water and debris to a camping site, resulted in 86 fatalities; Benito et al., 1998). Apart from new developed urban areas, linear infrastructure, such as roads, railroads, and underground rails with inadequate drainage, will probably suffer flood damage (DEFRA, 2004; Arkell and Darch, 2006). Increased runoff volumes may increase risk of dam failure (small water reservoirs and tailings dams) with high environmental and socioeconomic damages as evidenced by historical records (Rico et al., 2008).

In glaciated areas of Europe, glacial lake outburst floods, although infrequent, have the potential to produce immense socioeconomic and environmental impacts. Glacial lakes dammed by young, unstable, and unconsolidated moraines, and lakes in contact with the active ice body of a glacier, increase the potential of triggering an event (e.g., Huggel et al., 2004). Intense lake level and dam stability monitoring on most glacial lakes in Europe helps prevent major breach catastrophes. In case of flooding, major impacts are expected on infrastructure and settlements even at long distances downstream from the hazard source area (Haeberli et al., 2001; Huggel et al., 2004).

4.4.5.7. Landslides

There is a general lack of information on trends in landslide activity, and for regions with reasonably well-established databases (e.g., Switzerland), significant trends have not been found in the number of events and impacts (Hilker et al., 2009). Reactivation of large movements usually occurs in areas with groundwater flow and river erosion. In southern Europe the risk is reduced through revegetation on scree slopes, which enhances cohesion and slope stability coupled with improved hazard mitigation (Corominas, 2005; Clarke and Rendell, 2006).

4.4.5.8. Snow

Snow avalanches are an ever-present hazard with the potential for loss of life, property damage, and disruption of transportation. Due to an

increased use of mountainous areas for recreation and tourism, there is increased exposure for the population leading to an increased rate of mortality due to snow avalanches. During the period 1983 to 2003, avalanche fatalities have averaged about 25 per year in Switzerland (McClung and Schaerer, 2006). In economic terms, direct losses related to avalanches are small (Voigt et al., 2010), although short-term reactions by tourists may result in a reduction in overnight stays one year after a disaster (Nöthiger and Elsasser, 2004). Increased winter precipitation may result in higher than average snow depth or duration of snow cover, which could contribute to avalanche formation (Schneebeli et al., 1997). Climate change impacts on snow cover also include decreases in its duration, depth, and extent and a possible altitudinal shift of the snow/rain limit (Beniston et al., 2003), with adverse consequences to winter tourism. Increased avalanche occurrence would have a negative impact on humans (loss of life and infrastructure) but could have a positive result in mountain forests due to higher biodiversity within the affected areas (Bebi et al., 2009).

4.4.6. North America

4.4.6.1. Introduction

North America (Canada, Mexico, and the United States) is relatively well developed, although differentiation in living standards exists across and within countries. This differentiation in adaptive capacity, combined with a decentralized and essentially reactive response capability, underlies the region's vulnerability (Field et al., 2007). Furthermore, population trends within the region have increased vulnerability by heightening exposure of people and property in areas that are affected by extreme events. For example, population in coastline regions of the Gulf of Mexico region in the United States increased by 150% from 1960 to 2008, while total US population increased by 70% (U.S. Census Bureau, 2010).

4.4.6.2. Heat Waves

For North America, there is *medium confidence* in observations (Table 3-2) and *high confidence* in projections (Table 3-3) of increasing trends in heat wave frequency and duration.

Heat waves have impacts on many sectors, most notably on human health, agriculture, forestry and natural ecosystems, and energy infrastructure. One of the most significant concerns is human health, in particular mortality and morbidity. In 2006 in California, at least 140 deaths and more than 1,000 hospitalizations were recorded during a severe heat wave (CDHS, 2007; Knowlton et al., 2008). In 1995 in Chicago, more than 700 people died during a severe heat wave. Following that 1995 event, the city developed a series of response measures through an extreme heat program. In 1999, the city experienced another extreme heat event but far fewer lives were lost. While conditions in the 1999 event were somewhat less severe, the city's response measures were

also credited with contributing to the lower mortality (Palecki et al., 2001).

While heat waves are projected to increase in intensity and duration (Table 3-3), their net effect on human health is uncertain, largely because of uncertainties about the structure of cities in the future, adaptation measures, and access to cooling (Ebi and Meehl, 2007). Many cities have installed heat watch warning systems. Several studies show that the sensitivity of the population of large US cities to extreme heat events has been declining over time (e.g., Davis et al., 2003; Kalkstein et al., 2011).

Heat waves have other effects. There is increased likelihood of disruption of electricity supplies during heat waves (Wilbanks et al., 2008). Air quality can be reduced, particularly if stagnant high-pressure systems increase in frequency and intensity (Wang and Angell, 1999). Additionally, extreme heat can reduce yields of grain crops such as corn and increase stress on livestock (Karl et al., 2009).

4.4.6.3. Drought and Wildfire

There is *medium confidence* in an overall slight decrease in dryness since 1950 across the continent, with regional variability (Table 3-2). For some regions of North America, there is *medium confidence* in projections of increasing dryness (Table 3-3).

Droughts are currently the third most costly category of natural disaster in the United States (Carter et al., 2008). The effects of drought include reduced water quantity and quality, lower streamflows, decreased crop production, ecosystem shifts, and increased wildfire risk. The severity of impacts of drought is related to the exposure and vulnerability of affected regions.

From 2000 to 2010, excluding 2003, crop losses accounted for nearly all direct damages resulting from US droughts (NWS, 2011). Similarly, drought has had regular recurring impacts on agricultural activities in Northern Mexico (Endfield and Tejedo, 2006). In addition to impacts on crops and pastures, droughts have been identified as causes of regional-scale ecosystem shifts throughout southwestern North America (Allen and Breshears, 1998; Breshears et al., 2005; Rehfeldt et al., 2006).

Drought also has multiple indirect impacts in North America, although they are more difficult to quantify. Droughts pose a risk to North American power supplies due to associated reliance on sufficient water supplies for hydropower generation and cooling of nuclear, coal, and natural gas generation facilities (Goldstein, 2003; Wilbanks et al., 2008). Studies of water availability in heavily contested reservoir systems such as the Colorado River Basin indicate that climate change is projected to reduce states' abilities to meet existing agreements (Christensen et al., 2004). The effects of climate change on the reliability of the water supply have been thoroughly explored by Barnett and Pierce (2008, 2009).

Additionally, droughts and dry conditions more generally have been linked to increases in wildfire activity in North America. Westerling et al. (2006) found that wildfire activity in the western United States increased substantially in the late 20th century and that the increase is caused by higher temperatures and earlier snowmelt. Similarly, increases in wildfire activity in Alaska from 1950 to 2003 have been linked to increased temperatures (Karl et al., 2009). Anthropogenic warming was identified as a contributor to increases in Canadian wildfires (Gillett et al., 2004).

In Canada, forest fires are responsible for one-third of all particulate emissions, leading to heightened incidence of respiratory and cardiac illnesses as well as mortality (Rittmaster et al., 2006). Wildfires not only cause direct mortality, but the air pollution produces increases in eye and respiratory illnesses (Ebi et al., 2008). The principal economic costs of wildfires include timber losses, property destruction, fire suppression, and reductions in the tourism sector (Butry et al., 2001; Morton et al., 2003).

4.4.6.4. Inland Flooding

There has been a *likely* increase in heavy precipitation in many areas of North America since 1950 (Table 3-2), with projections suggesting further increases in heavy precipitation in some regions (Table 3-3). Flooding and heavy precipitation events have a variety of significant direct and indirect human health impacts (Ebi et al., 2008). Heavy precipitation events are strongly correlated with the outbreak of waterborne illnesses in the United States – 51% of waterborne disease outbreaks were preceded by precipitation events in the top decile (Curriero et al., 2001). In addition, heavy precipitation events have been linked to North American outbreaks of vector-borne diseases such as Hantavirus and plague (Engelthaler et al., 1999; Parmenter et al., 1999; Hjelle and Glass, 2000).

Beyond direct destruction of property, flooding has important negative impacts on a variety of economic sectors including transportation and agriculture. Heavy precipitation and field flooding in agricultural systems delays spring planting, increases soil compaction, and causes crop losses through anoxia and root diseases; variation in precipitation is responsible for the majority of the crop losses (Mendelsohn, 2007). In 1993, heavy precipitation flooded 8.2 million acres (~3.3 million ha) of American Midwest soybean and corn fields, leading to a 50% decrease in corn yields in Iowa, Minnesota, and Missouri, and a 20 to 30% decrease in Illinois, Indiana, and Wisconsin (Changnon, 1996). Furthermore, flood impacts include temporary damage or permanent destruction of infrastructure for most modes of transportation (Zimmerman and Faris, 2010). For example, heavy precipitation events are a very costly weather condition facing US rail transportation (Changnon, 2006).

4.4.6.5. Coastal Storms and Flooding

Global observed and projected changes in coastal storms and flooding are complex. Since 1950, there has been a *likely* increase in extreme sea

level, related to trends in mean sea level. With upward trends in sea level *very likely* to continue (Section 3.5.3), there is *high confidence* that locations currently experiencing coastal erosion and inundation will continue to do so in the future (Section 3.5.5).

North America is exposed to coastal storms, and in particular, hurricanes. 2005 was a particularly severe year with 14 hurricanes (out of 27 named storms) in the Atlantic (NCDC, 2005). There were more than 2,000 deaths during 2005 (Karl et al., 2009) and widespread destruction on the Gulf Coast and in New Orleans in particular. Property damages exceeded US\$ 100 billion (Beven et al., 2008; Pielke Jr. et al., 2008). Hurricanes Katrina and Rita destroyed more than 100 oil and gas platforms in the Gulf and damaged 558 pipelines, halted all oil and gas production in the Gulf, and disrupted 20% of US refining capacity (Karl et al., 2009). It is reported that the direct overall losses of Hurricane Katrina were about US\$ 138 billion in 2007 dollars (Spranger, 2008). However, 2005 may be an outlier for a variety of reasons – the year saw storms of higher than average frequency, with greater than average intensity, which made more frequent landfall, including in the most vulnerable region of the country (Nordhaus, 2010). The major factor increasing the vulnerability and exposure of North America to hurricanes is the growth in population (see, e.g., Pielke Jr. et al., 2008) and increase in property values, particularly along the Gulf and Atlantic coasts of the United States. While some of this increase has been offset by adaptation and improved building codes, Nordhaus (2010) suggests the ratio of hurricane damages to national GDP has increased by 1.5% per year over the past half-century. However, the choice of start and end dates influences this figure.

Future sea level rise and potential increases in storm surge could increase inundation and property damage in coastal areas. Hoffman et al. (2010) assumed no acceleration in the current rate of sea level rise through 2030 and found that property damage from hurricanes would increase by 20%. Frey et al. (2010) simulated the combined effects of sea level rise and more powerful hurricanes on storm surge in southern Texas in the 2080s. They found that the area inundated by storm surge could increase from 6-25% to 60-230% across scenarios evaluated. No adaptation measures were assumed in either study. Globally, uncertainties associated with changes in tropical and extratropical cyclones mean that a general assessment of the projected effects of storminess on future storm surge is not currently possible (Section 3.5.3).

4.4.7. Oceania

The region of Oceania consists of Australia, New Zealand, and several small island states that are considered separately in Section 4.4.10.

4.4.7.1. Introduction

Extreme events have severe impacts in both Australia and New Zealand. In Australia, weather- and climate-related events cause around 87% of economic damage due to natural disasters (storms, floods, cyclones,

earthquakes, fires, and landslides; BTE, 2001). In New Zealand, floods and droughts are the most costly climate disasters (Hennessy et al., 2007). Economic damage from extreme weather is projected to increase and provide challenges for adaptation (Hennessy et al., 2007).

Observed and projected trends in temperature and precipitation extremes for the region are extensively covered in Chapter 3 (e.g., Tables 3-2 and 3-3). ENSO is a strong driver of climate variability in this region (see Section 3.4.2).

4.4.7.2. Temperature Extremes

During the Eastern Australian heat wave, in February 2004, temperatures reached 48.5°C in western New South Wales. About two-thirds of continental Australia recorded maximum temperatures over 39°C. Due to heat-related stresses, the Queensland ambulance service recorded a 53% increase in ambulance call-outs (Steffen et al., 2006). A week-long heat wave in Victoria in 2009 corresponded with a sharp increase in deaths in the state. For the week of the heat wave a total of 606 deaths were expected and there were a total of 980 deaths, representing a 62% increase (DHS, 2009).

An increase in heat-related deaths is projected given a warming climate (Hennessy et al., 2007). In Australian temperate cities, the number of deaths is projected to more than double in 2020 from 1,115 per year at present and to increase to between 4,300 and 6,300 per year by 2050 for all emission scenarios, including demographic change (McMichael et al., 2003b). In Auckland and Christchurch, a total of 14 heat-related deaths occur per year in people aged over 65, but this number is projected to rise approximately two-, three-, and six-fold for warming of 1, 2, and 3°C, respectively (McMichael et al., 2003b). An aging society in Australia and New Zealand would amplify these figures. For example, it has been projected that, by 2100, the Australian annual death rate in people aged over 65 would increase from a 1999 baseline of 82 per 100,000 to a range of between 131 and 246 per 100,000 in 2100 for the scenarios examined (SRES B2 and A2, with stabilization of atmospheric CO₂ at 450 ppm; Woodruff et al., 2005). In Australia, cities with a temperate climate are expected to experience more heat-related deaths than those with a tropical climate (McMichael et al., 2003b).

4.4.7.3. Droughts

There is a complex pattern of observed and projected changes in dryness over the region, with increasing dryness in some areas, and decreasing dryness or inconsistent signals in others (Tables 3-2 and 3-3). However, several high-impact drought events have been recorded (OCDESC, 2007).

In Australia, the damages due to the droughts of 1982-1983, 1991-1995, and 2002-2003 were US\$ 2.3, 3.8, and 7.6 billion, respectively (Hennessy et al., 2007). Droughts have a negative impact on water security in the

Murray-Darling Basin in Australia, as it accounts for most of the water for irrigated crops and pastures in the country.

New Zealand has a high level of economic dependence on agriculture, and drought can cause significant disruption for this industry. The 1997-1998 El Niño resulted in severe drought conditions across large areas of New Zealand with losses estimated at NZ\$ 750 million (2006 values) or 0.9% of GDP (OCDESC, 2007). Severe drought in two consecutive summers, 2007-2009, affected a large area of New Zealand and caused on-farm net income to drop by NZ\$ 1.9 billion (Butcher and Ford, 2009). Drought conditions also have a serious impact on electricity production in New Zealand where around two-thirds of supply is from hydroelectricity and low precipitation periods result in increased use of fossil fuel for electricity generation, a maladaptation to climate change. Auckland, New Zealand's largest city, suffered from significant water shortages in the early 1990s, but has since established a pipeline to the Waikato River to guarantee supply (OCDESC, 2007).

Climate change may cause land use change in southern Australia. Cropping could become non-viable at the dry margins if rainfall substantially decreases, even though yield increases from elevated CO₂ partly offset this effect (Luo et al., 2003).

4.4.7.4. Wildfire

Wildfires around Canberra in January 2003 caused AUS\$ 400 million damage (Lavorel and Steffen, 2004), with about 500 houses destroyed, four people killed, and hundreds injured. Three of the city's four water storage reservoirs were contaminated for several months by sediment-laden runoff (Hennessy et al., 2007). The 2009 fire in the state of Victoria caused immense damage (see Box 4-1 and Case Study 9.2.2).

An increase in fire danger in Australia is associated with a reduced interval between fire events, increased fire intensity, a decrease in fire extinguishments, and faster fire spread (Hennessy et al., 2007). In southeast Australia, the frequency of very high and extreme fire danger days is expected to rise 15 to 70% by 2050 (Hennessy et al., 2006). By the 2080s, the number of days with very high and extreme fire danger are projected to increase by 10 to 50% in eastern areas of New Zealand, the Bay of Plenty, Wellington, and Nelson regions (Pearce et al., 2005), with even higher increases (up to 60%) in some western areas. In both Australia and New Zealand, the fire season length is expected to be extended, with the window of opportunity for fuel reduction burning shifting toward winter (Hennessy et al., 2007).

4.4.7.5. Intense Precipitation and Floods

There has been a *likely* decrease in heavy precipitation in many parts of southern Australia and New Zealand (Table 3-2), while there is generally *low to medium confidence* in projections due to a lack of consistency between models (Table 3-3).

Floods are New Zealand's most frequently experienced hazard (OCDESC, 2007) affecting both agricultural and urban areas. Being long and narrow, New Zealand is characterized by small river catchments and accordingly shorter time-to-peak and shorter flood warning times, posing a difficult preparedness challenge. Projected increases in heavy precipitation events across most parts of New Zealand (Table 3-3) is expected to cause greater erosion of land surfaces, more landslides, and a decrease in the protection afforded by levees (Hennessy et al., 2007).

4.4.7.6. Storm Surges

Over 80% of the Australian population lives in the coastal zone, and outside of the major capital cities is also where the largest population growth occurs (Harvey and Caton, 2003; ABS, 2010). Over 500,000 addresses are within 3 km of the coast and less than 5 m above sea level (Chen and McAneney, 2006). As a result of being so close to sea level, the risk of inundation from sea level rise and large storm surges increases with climate change (Hennessy et al., 2007). The risk of a 1-in-100 year storm surge in Cairns is expected to more than double by 2050 (McInnes et al., 2003). Projected changes in coastal hazards from sea level rise and storm surge are also an issue for New Zealand (e.g., Ministry for the Environment, 2008).

4.4.8. Open Oceans

The ocean's huge mass in comparison to the atmosphere gives it a crucial role in global heat budgets and chemical budgets. Possible extreme impacts can be triggered by (1) warming of the surface ocean, with a major cascade of physical effects, (2) ocean acidification induced by increases in atmospheric CO₂, and (3) reduction in oxygen concentration in the ocean due to a temperature-driven change in gas solubility and physical impacts from (1). All have potentially nonlinear multiplicative impacts on biodiversity and ecosystem function, and each may increase the vulnerability of ocean systems, triggering an extreme impact (Kaplan et al., 2010; Griffith et al., 2011). Surface warming of the oceans can itself directly impact biodiversity by slowing or preventing growth in temperature-sensitive species. One of the most well-known biological impacts of warming is coral bleaching, but ocean acidification can also affect coral growth rates (Bongaerts et al., 2010). The seasonal sea ice cycle affects biological habitats. Such species of Arctic mammals as polar bears, seals, and walruses depend on sea ice for habitat, hunting, feeding, and breeding. Declining sea ice can decrease polar bear numbers (Stirling and Parkinson, 2006).

4.4.9. Polar Regions

4.4.9.1. Introduction

The polar regions consist of the Arctic and the Antarctic, including associated water bodies. The Arctic region consists of a vast treeless

permafrost territory (parts of northern Europe, northern Asia, and North America, and several islands including Greenland). Delimitation of the Arctic may differ according to different disciplinary and political definitions (ACIA, 2004). Population density in the polar regions is low, so that impacts of climate change and extremes on humans may not be as noticeable as elsewhere throughout the world. The territory of the Russian Arctic is more populated than other polar regions, hence impacts of climate change are most noticeable there as they affect human activities. Specific impacts of climate extremes on the natural physical environment in polar regions are discussed in Section 3.5.7.

4.4.9.2. Warming Cryosphere

Polar regions have experienced significant warming in recent decades. Warming has been most pronounced across the Arctic Ocean Basin and along the Antarctic Peninsula, with significant decreases in the extent and seasonal duration of sea ice, while in contrast, temperatures over mainland Antarctica have not warmed over recent decades (Lemke et al., 2007; Trenberth et al., 2007). Sea ice serves as primary habitat for marine organisms central to the food webs of these regions. Changes in the timing and extent of sea ice can impose temporal and spatial mismatches between energy requirements and food availability for many higher trophic levels, leading to decreased reproductive success, lower abundances, and changes in distribution (Moline et al., 2008).

Warming in the Arctic may be leading to a shift of vegetation zones (e.g., Sturm et al., 2001; Tape et al., 2006; Truong et al., 2006), bringing wide-ranging impacts and changes in species diversity and distribution.

In the Russian North, the seasonal soil thawing depth has increased overall over the past four decades (Sherstyukov, 2009). As frozen ground thaws, many existing buildings, roads, pipelines, airports, and industrial facilities are destabilized. In the 1990s, the number of damaged buildings increased by 42 to 90% in comparison with the 1980s in the north of western Siberia (Anisimov and Belolutskaya, 2002; Anisimov and Lavrov, 2004). Arctic infrastructure faces increased risks of damage due to changes in the cryosphere, particularly the loss of permafrost and land-fast sea ice (SWIPA, 2011).

An apartment building collapsed in the upper part of the Kolyma River Basin, and over 300 buildings were severely damaged in Yakutsk as a result of retreating permafrost (Anisimov and Belolutskaya, 2002; Anisimov and Lavrov, 2004). Changes in permafrost damage the foundations of buildings and disrupt the operation of vital infrastructure in human settlements (Anisimov et al., 2004; see also Case Study 9.2.10). Transport options and access to resources are altered by differences in the distribution and seasonal occurrence of snow, water, ice, and permafrost in the Arctic. This affects both daily living and commercial activities (SWIPA, 2011).

In conditions of land impassability, frozen rivers are often used as transport ways. In the conditions of climate warming, rivers freeze later

and melt earlier than before, and the duration of operation of transport routes to the far north of Russia decreases with the increase in air temperature in winter and spring (Mirvis, 1999).

Ice cover does not allow ship navigation. Navigation in the Arctic Ocean is only possible during the ice-free period off the northern coasts of Eurasia and North America. During periods of low ice concentration, ships navigate toward ice-free passages, away from multi-year ice that has accumulated over several years. Regional warming provides favorable conditions for sea transport going through the Northern Sea Route along the Eurasian coasts and through the Northwest Passage in the north of Canada and Alaska (ACIA, 2004).

In September 2007, when the Arctic Sea ice area was extremely low, the Northwest Passage was opened up. In Russia, this enabled service to ports of the Arctic region and remote northern regions (import of fuel, equipment, food, timber, and export of timber, oil, and gas). However, owing to deglaciation in Greenland, New Land, and Northern Land, the number of icebergs may increase, creating navigation hazards (Roshydromet, 2005, 2008; Rignot et al., 2010; Straneo et al., 2010).

4.4.9.3. Floods

From the mid-1960s to the beginning of the 1990s, winter runoff in the three largest rivers of Siberia (Yenisei, Lena, and Ob; jointly contributing approximately 70% of the global river runoff to the Arctic Ocean) increased by 165 km³ (Savelieva et al., 2004).

Rivers in Arctic Russia experience floods, but their frequency, stage, and incidence are different across the region, depending on flood formation conditions. Floods on the Siberian rivers can be produced by a high peak of the spring flood, by rare heavy rain, or by a combination of snow and rain, as well as by ice jams, hanging dams, and combinations of factors (Semyonov and Korshunov, 2006).

Maximum river discharge was found to decrease from the mid-20th century through 1980 in Western Siberia and the Far East (except for the Yenisei and the Lena rivers). However, since 1980, maximum streamflow values began to increase over much of Russia (Semyonov and Korshunov, 2006).

Snowmelt and rain continue to be the most frequent cause of hazardous floods on the rivers in the Russian Arctic (85% of all hazardous floods in the past 15 years). Hazardous floods produced by ice jams and wind tides make up 10 and 5% of the total number of hazardous floods, respectively. For the early 21st century, Pomeranets (2005) suggests that the probability of catastrophic wind tide-related floods and ice jam-related floods increased. The damage from floods depends not only on their level, but also on the duration of exposure. On average, a flood lasts 5 to 10 days, but sometimes high water marks have been recorded to persist longer, for example, for 20 days or more (Semyonov and Korshunov, 2006).

4.4.9.4. Coastal Erosion

Coastal erosion is a significant problem in the Arctic, where coastlines are highly variable due to environmental forcing (wind, waves, sea level changes, sea ice, etc.), geology, permafrost, and other elements (Rachold et al., 2005). For example, the amount of coastal erosion along a 60 km stretch of Alaska's Beaufort Sea doubled between 2002 and 2007. Jones et al. (2009) considered contributing factors to be melting sea ice, increasing summer sea surface temperature, sea level rise, and increases in storm power and associated stronger ocean waves.

Increasing coastal retreat will have further ramifications for Arctic landscapes, including losses in freshwater and terrestrial wildlife habitats, in subsistence grounds for local communities, and in disappearing cultural sites, as well as adverse impacts on coastal villages and towns. In addition, oil test wells may be impacted (Jones et al., 2009). Coastal erosion has also become a problem for residents of Inupiat and on the island of Sarichev (Russian Federation) (Revich, 2008).

Permafrost degradation along the coast of the Kara Sea may lead to intensified coastal erosion, driving the coastline back by up to 2 to 4 m per year (Anisimov and Belolutskaya, 2002; Anisimov and Lavrov, 2004). Coastline retreat poses considerable risks for coastal population centers in Yamal and Taymyr and other littoral lowland areas.

4.4.10. Small Island States

Small Island States (SIS) in the Pacific, Indian, and Atlantic Oceans have been identified as being among the most vulnerable to climate change and climate extremes (e.g., UNFCCC, 1992; DSD, 1994; UNISDR, 2005). In the light of current experience and model-based projections, SIS, with high vulnerability and low adaptive capacity, have substantial future risks (Mimura et al., 2007). Smallness renders island countries at risk of high proportionate losses when impacted by a climate extreme (Pelling and Uitto, 2001; see also Case Study 9.2.9 and Box 3-4).

Sea level rise could lead to a reduction in island size (FitzGerald et al., 2008). Island infrastructure, including international airports, roads, and capital cities, tends to predominate in coastal locations (Hess et al., 2008). Sea level rise exacerbates inundation, erosion, and other coastal hazards; threatens vital infrastructure, settlements, and facilities; and thus compromises the socioeconomic well-being of island communities and states (Hess et al., 2008).

In 2005, regionally averaged temperatures were the warmest in the western Caribbean for more than 150 years (Eakin et al., 2010). These extreme temperatures caused the most severe coral bleaching ever recorded in the Caribbean: more than 80% of the corals surveyed were bleached, and at many sites more than 40% died. Recovery from such large-scale coral mortality is influenced by the extent to which coral reef health has been compromised and the frequency and severity of subsequent stresses to the system.

Since the early 1950s, when the quality of disaster monitoring and reporting improved in the Pacific Islands region, there has been a general increasing trend in the number of disasters reported annually (Hay and Mimura, 2010).

Pacific Island Countries and Territories (PICs) exhibit a variety of characteristics rendering generalization difficult (see Table 4-2; Campbell, 2006). One form of PICs is large inter-plate boundary islands formed by subduction and found in the southwest Pacific Ocean. These may be compared to the Oceanic (or intra-plate) islands which were, or are being, formed over 'hot spots' in the Earth's mantle into volcanic high islands. Some of these are still being formed and some are heavily eroded with steep slopes and barrier reefs. Another form of PICs is atolls that consist of coral built on submerging former volcanic high islands, through raised limestone islands (former atolls stranded above contemporary sea levels). Each island type has specific characteristics in relation to disaster risk reduction, with atolls being particularly vulnerable to tropical cyclones, where storm surges can completely inundate them and there is no high ground to which people may escape. In contrast, the inter-plate islands are characterized by large river systems and fertile flood plains in addition to deltas, both of which tend to be heavily populated. Fatalities in many of the worst weather- and climate-related disasters in the region have been mostly from river flooding (AusAID, 2005). Raised atolls are often saved from the storm surge effects of

Table 4-2 | Pacific Island type and exposure to climate extremes. Adapted from Campbell, 2006.

Island Type	Exposure to climate risks
Plate-Boundary Islands <ul style="list-style-type: none"> • Large land area • High elevations • High biodiversity • Well-developed soils • River flood plains • Orographic rainfall 	These islands are located in the western Pacific. River flooding is more likely to be a problem than in other island types. In Papua New Guinea, high elevations expose areas to frost (extreme during El Niño). Most major settlements are on the coast and exposed to storm damage.
Intra-Plate (Oceanic) Islands Volcanic High Islands <ul style="list-style-type: none"> • Steep slopes • Different stages of erosion • Barrier reefs • Relatively small land area • Less well-developed river systems • Orographic rainfall 	Because of size these islands have substantial exposure to tropical cyclones, which cause the most damage in coastal areas and catchments. Streams and rivers are subject to flash flooding. Most islands are exposed to drought. Barrier reefs may ameliorate storm surge and tsunamis.
Atolls <ul style="list-style-type: none"> • Very small land areas • Very low elevations • No or minimal soil • Small islets surround a lagoon • Shore platform on windward side • Larger islets on windward side • No surface (fresh) water • Ghyben Herzberg (freshwater) lens • Convective rainfall 	These islands are exposed to storm surge, 'king' tides, and high waves. They are exposed to freshwater shortages and drought. Freshwater limitations may lead to health problems.
Raised Limestone Islands <ul style="list-style-type: none"> • Steep outer slopes • Concave inner basin • Sharp karst topography • Narrow coastal plains • No surface water • No or minimal soil 	Depending on height these islands may be exposed to storm surges and wave damage during cyclones and storms. They are exposed to freshwater shortages and drought. Freshwater problems may lead to health problems.

tropical cyclones, but during Cyclone Heta that struck Niue in 2004, the cliffs were unable to provide protection.

Drought is a hazard of considerable importance in SIS. In particular, atolls have very limited water resources, being dependent on their freshwater lens, whose thickness decreases with sea level rise (e.g., Kundzewicz et al., 2007), floating above sea water in the previous coral, and is replenished by convectional rainfall. During drought events, water shortages in SIS become acute on atolls in particular, resulting in rationing in some cases (Campbell, 2006).

The main impacts from climatic extremes in PICs are damage to structures, infrastructure, and crops during tropical cyclones and crop damage and water supply shortages during drought events. On atolls, salinization of the freshwater lens and garden areas is a serious problem following storm surges, high wave events, and 'king' tides (Campbell, 2006).

4.5. Costs of Climate Extremes and Disasters

The following section focuses on the economic costs imposed by climate extremes and disasters on humans, societies, and ecosystems and the costs of adapting to the impacts. Cost estimates are composed of observed and projected economic impacts, including economic losses, future trends in extreme events and disasters in key regions, and the costs of adaptation. The section stands at the interface between chapters, using the conceptual framework of Chapters 1 and 2 and the scientific foundation of Chapter 3 and earlier subsections in this chapter, and leading into the following Chapters 5 through 9.

4.5.1. Framing the Costs of Extremes and Disasters

The economic costs associated with climate extremes and disasters can be subdivided into impact or damage costs (or simply losses) and adaptation costs. Costs arise due to economic, social, and environmental impacts of a climate extreme or disaster and adaptation to those impacts in key sectors. Residual damage costs are the impact and damage costs after all desirable and practical adaptation actions have been implemented. Conceptually, comparing costs of adaptation with damages before adaptation and residual damages can help in assessing the economic efficiency of adaptation (Parry et al., 2009).

The *impact of climate extremes and disasters* on economies, societies, and ecosystems can be measured as the *damage costs* and *losses* of economic assets or stocks, as well as consequential indirect effects on economic flows, such as on GDP or consumption. In line with general definitions in Chapters 1 and 2, economic disaster *risk* may be defined as a probability distribution indicating *potential* economic damage costs and associated return periods. The cost categories of direct, indirect, and intangible are rarely fully exclusive, and items or activities can have elements in all categories.

Direct damage costs or losses are often defined as those that are a direct consequence of the weather or climate event (e.g., floods, windstorms, or droughts). They refer to the costing of the physical impacts of climate extremes and disasters – on the lives and health of directly affected persons; on all types of tangible assets, including private dwellings, and agricultural, commercial, and industrial stocks and facilities; on infrastructure (e.g., transport facilities such as roads, bridges, and ports, energy and water supply lines, and telecommunications); on public facilities (e.g., hospitals, schools); and on natural resources (ECLAC, 2003; World Bank, 2010).

Indirect impact costs generally arise due to the disruption of the flows of goods and services (and therefore economic activity) because of a disaster, and are sometimes termed consequential or secondary impacts as the losses typically flow from the direct impact of a climate event (ECLAC, 2003; World Bank, 2010). Indirect damages may be caused by the direct damages to physical infrastructure or sources of livelihoods, or because reconstruction pulls resources away from production. Indirect damages include additional costs incurred from the need to use alternative and potentially inferior means of production and/or distribution of normal goods and services (Cavallo and Noy, 2010). For example, electricity transmission lines may be destroyed by wind, a direct impact, causing a key source of employment to cease operation, putting many people out of work, and in turn creating other problems that can be classified as indirect impacts. These impacts can emerge later in the affected location, as well as outside the directly affected location (Pelling et al., 2002; ECLAC, 2003; Cavallo and Noy, 2010). Indirect impacts include both negative and positive factors – for example, transport disruption, mental illness or bereavement resulting from disaster shock, rehabilitation, health costs, and reconstruction and disaster-proof investment, which can include changes in employment in a disaster-hit area (due to reconstruction and other recovery activity) or additional demand for goods produced outside of a disaster-affected area (ECLAC, 2003; World Bank, 2010). As another example, long-running droughts can induce indirect losses such as local economic decline, out-migration, famine, the partial collapse of irrigation areas, or loss of livelihoods dependent on hydroelectricity or rain-fed agriculture. It is important to note that impacts on the informal or undocumented economy may be very important in some areas and sectors, but are generally not counted in reported estimates of losses.

Many impacts, such as loss of human lives, cultural heritage, and ecosystem services, are difficult to measure as they are not normally given monetary values or bought and sold, and thus they are also poorly reflected in estimates of losses. These items are often referred to as *intangibles* in contrast to tangibles such as tradable assets, structures, and infrastructure (Handmer et al., 2002; Pelling et al., 2002; Benson and Clay, 2003; ECLAC, 2003; Cavallo and Noy, 2010; World Bank, 2010).

Adaptation costs are those associated with adaptation and facilitation in terms of planning (e.g., developing appropriate processes including key stakeholders), actual adaptation (e.g., risk prevention, preparedness, and risk financing), reactive adaptation (e.g., emergency disaster responses,

rehabilitation, and reconstruction), and finally the implementation of adaptation measures (including transition costs) (Smit et al., 2001; also see the Glossary). The benefits of adaptation can generally be assessed as the value of avoided impacts and damages as well as the co-benefits generated by the implementation of adaptation measures (Smit et al., 2001). The value of all avoidable damage can be taken as the gross (or theoretically maximum) benefit of adaptation and risk management, which may be feasible to adapt to but not necessarily economically efficient (Pearce et al., 1996; Tol, 2001; Parry et al., 2009). The *adaptation deficit* is identified as the gap between current and optimal levels of adaptation to climate change (Burton and May, 2004). However, it is difficult to assess the optimal adaptation level due to the uncertainties inherent in climate scenarios, the future patterns of exposure and vulnerability to climate events, and debates over methodological issues such as discount rates. In addition, as social values and technologies change, what is considered avoidable also changes, adding additional uncertainty to future projections.

4.5.2 Extreme Events, Impacts, and Development

The relationship between socioeconomic development and disasters, including those triggered by climatic events, has been explored by a number of researchers over the last few years using statistical techniques and numerical modeling approaches. It has been suggested that natural disasters exert adverse impacts on the pace and nature of economic development (Benson and Clay, 1998, 2003; Kellenberg and Mobarak, 2008). (The ‘poverty trap’ created by disasters is discussed in Chapter 8.) A growing literature has emerged that identifies these important adverse macroeconomic and developmental impacts of natural disasters (Cuny, 1983; Otero and Martí, 1995; Benson and Clay, 1998, 2000, 2003, 2004; Charveriat, 2000; Crowsdorff, 2000; ECLAC, 2003; Mechler, 2004; Raddatz, 2009; Noy, 2009; Okuyama and Sahin, 2009; Cavallo and Noy, 2010). Yet, confidence in the adverse economic impacts of natural disasters is only *medium*, as, although the bulk of studies identify negative effects of disasters on shorter-term economic growth (up to three years after an event), others find positive effects (Albala-Bertrand, 1993; Skidmore and Toya, 2002; Caselli and Malhotra, 2004; see Section 4.2). Differences can be partly explained by the lack of a robust counterfactual in some studies (e.g., what would GDP have been if a disaster had not occurred?), failure to account for the informal sector, varying ways of accounting for insurance and aid flows, different patterns of impacts resulting from, for example, earthquakes versus floods, and the fact that national accounting does not record the destruction of assets, but reports relief and reconstruction as additions to GDP (World Bank and UN, 2010). In terms of longer-run economic growth (beyond three years after events), there are mixed findings with the exception of very severe disasters, which have been found to set back development (World Bank and UN, 2010).

In terms of the nexus between development and disaster vulnerability, researchers argue that poorer developing countries and smaller economies are more likely to suffer more from future disasters than

developed countries, especially in relation to extreme impacts (Hallegatte et al., 2007; Heger et al., 2008; Hallegatte and Dumas, 2009; Loayza et al., 2009; Raddatz, 2009). In general, the observed or modeled relationship between development and disaster impacts indicates that a wealthier country is better equipped to manage the consequences of extreme events by reducing the risk of impacts and by managing the impacts when they occur. This is due (*inter alia*) to higher income levels, more governance capacity, higher levels of expertise, amassed climate-proof investments, and improved insurance systems that can act to transfer costs in space and time (Wildavsky, 1988; Albala-Bertrand, 1993; Burton et al., 1993; Tol and Leek, 1999; Mechler, 2004; Rasmussen, 2004; Brooks et al., 2005; Kahn, 2005; Toya and Skidmore, 2007; Raschky, 2008; Noy, 2009). While the countries with highest income account for most of the total economic and insured losses from disasters (Swiss Re, 2010), in developing countries there are higher fatality rates and the impacts consume a greater proportion of GDP. This in turn imposes a greater burden on governments and individuals in developing countries. For example, during the period from 1970 to 2008 over 95% of deaths from natural disasters occurred in developing countries (Cavallo and Noy, 2010; CRED, 2010). From 1975 to 2007, Organisation for Economic Co-operation and Development (OECD) countries accounted for 71.2% of global total economic losses from tropical cyclones, but only suffered 0.13% of estimated annual loss of GDP (UNISDR, 2009).

There is general consensus that, as compared to developed countries, developing countries are more economically vulnerable to climate extremes largely because: (i) developing countries have less resilient economies that depend more on natural capital and climate-sensitive activities (cropping, fishing, etc.; Parry et al., 2007); (ii) they are often poorly prepared to deal with the climate variability and physical hazards they currently face (World Bank, 2000); (iii) more damages are caused by maladaptation due to the absence of financing, information, and techniques in risk management, as well as weak governance systems; (iv) there is generally little consideration of climate-proof investment in regions with a fast-growing population and asset stocks (such as in coastal areas) (IPCC, 2001; Nicholls et al., 2008); (v) there is an adaptation deficit resulting from the low level of economic development (World Bank, 2007) and a lack of ability to transfer costs through insurance and fiscal mechanisms; and vi) they have large informal sectors. However, in some cases like Hurricane Katrina in New Orleans, United States, developed countries also suffer severe disasters because of social vulnerability and inadequate disaster protection (Birch and Wachter, 2006; Cutter and Finch, 2008).

While some literature has found that the relationship between income and some natural disaster consequences is nonlinear (Kellenberg and Mobarak, 2008; Patt et al., 2010), much empirical evidence supports a negative relationship between the relative share of GDP and fatalities, with fatalities from hydrometeorological extreme events falling with rising level of income (Kahn, 2005; Toya and Skidmore, 2007; World Bank and UN, 2010). Some emerging developing countries, such as China, India, and Thailand, are projected to face increased future exposure to

extremes, especially in highly urbanized areas, as a result of the rapid urbanization and economic growth in those countries (Bouwer et al., 2007; Nicholls et al., 2008).

It should also be noted that in a small country, a disaster can directly affect much of the country and therefore the magnitude of losses and recovery demands can be extremely high relative to GDP and public financial resources (Mechler, 2004). This is particularly the case in the event of multiple and/or consecutive disasters in short periods. For example, in Fiji, consecutive natural disasters have resulted in reduced national GDP as well as decreased socioeconomic development as captured by the Human Development Index (HDI) (Lal, 2010). In Mexico, natural disasters resulted in the HDI regressing by approximately two years and in an increase in poverty levels (Rodriguez-Oreggia et al., 2010). Patt et al. (2010) indicated that vulnerability in the least-developed countries will rise most quickly, which implies an urgent need for international assistance.

Costs and impacts not only vary among developing and developed countries, but also between and within countries, regions, local areas, sectors, systems, and individuals due to the heterogeneity of vulnerability and resilience (see Chapter 2). Some individuals, sectors, and systems would be less affected, or may even benefit, while other individuals, sectors, and systems may suffer significant losses in the same event. In general, the poorest and those who are socially or economically marginalized will be the most at risk in terms of being exposed and vulnerable (Wisner et al., 2004). For example, women and children are found to be more vulnerable to disasters in many countries, with larger disasters having an especially unequal impact (Neumayer and Plümper, 2007).

4.5.3. Methodologies for Evaluating Impact and Adaptation Costs of Extreme Events and Disasters

4.5.3.1. Methods and Tools for Costing Impacts

Direct, tangible impacts are comparatively easy to measure, but costing approaches are not necessarily standardized and assessments are often incomplete, which can make aggregation and comparability across the literature difficult. In some countries, flood impact assessment has long been standardized, for example, in Britain and parts of the United States (e.g., Handmer et al., 2002). Intangible losses can generally be estimated using valuation techniques such as loss of life/morbidity (usually estimated using value of statistical life benchmarks), replacement value, benefits transfer, contingent evaluation, travel cost, hedonic pricing methods, and so on (there is a vast literature on this subject, e.g., Handmer et al., 2002; Carson et al., 2003; Pagiola et al., 2004; Ready and Navrud, 2006; TEEB, 2009). Yet, assessing the intangible impacts of extremes and disasters in the social, cultural, and environmental fields is more difficult, and there is little agreement on methodologies (Albalá-Bertrand, 1993; Tol, 1995; Hall et al., 2003; Huigen and Jens, 2006; Schmidt et al., 2009).

Studies and reports on the economic impacts of extremes, such as insurance or post-disaster reports, have mostly focused on direct and tangible losses, such as on impacts on produced capital and economic activity. Intangibles such as loss of life and impacts on the natural environment are generally not considered using monetary metrics (Parry et al., 2009). Loss of life due to natural disasters, including future changes, is accounted for in some studies (e.g., BTE, 2001; Jonkman, 2007; Jonkman et al., 2008; Maaskant et al., 2009). Estimates of impacts that account for tangibles and intangibles are expected to be much larger than those that consider tangible impacts only (Handmer et al., 2002; Parry et al., 2009). Potential impacts include all direct, indirect, and intangible costs, including the losses from public goods and natural capital (in particular ecosystem services), as well as the longer-term economic impact of disasters. Indirect impacts and intangible impacts can outweigh those of direct impacts. There will therefore often be a large gap between potential impacts and the estimates from studies that consider only direct impacts.

Indirect economic loss assessment methodologies exist but produce uncertain and method-dependent results. Such assessments at national, regional, and global levels fall into two categories: a 'top down' approach that uses models of the whole economy under study, and a bottom-up or partial equilibrium approach that identifies and values changes in specific parts of an economy (van der Veen, 2004).

The top-down approach is grounded in macroeconomics under which the economy is described as an ensemble of interacting economic sectors. Most studies have focused on impact assessment remodeling actual events in the past and aim to estimate the various, often hidden follow-on impacts of disasters (e.g., Ellson et al., 1984; Yezer and Rubin, 1987; Guimaraes et al., 1993; West and Lenze, 1994; Brookshire et al., 1997; Hallegatte et al., 2007; Rose 2007). Existing macroeconomic or top-down approaches utilize a range of models such as the Input-Output, Social Accounting Matrix multiplier, Computable General Equilibrium models, economic growth frameworks, and simultaneous-equation econometric models. These models attempt to capture the impact of the extreme event as it is felt throughout the whole economy. Only a few models have aimed at representing extremes in a risk-based framework in order to assess the potential impacts of events and their probabilities using a stochastic approach, which is desirable given the fact that extreme events are non-normally distributed and the tails of the distribution matter (Freeman et al., 2002; Mechler, 2004; Hallegatte and Ghil, 2007; Hallegatte, 2008).

The bottom-up approach, derived from microeconomics, scales up data from sectors at the regional or local level to aggregate an assessment of disaster costs and impacts (see van der Veen, 2004). The bottom-up approach to disaster impact assessment attempts to evaluate the impact of an actual or potential disaster on consumers' willingness to pay (or willingness to accept). This approach values direct loss of or damage to property, as well as that of the interruption to the economy, impacts on health and well-being, and impacts on environmental amenity and

ecosystem services. In short, it attempts to value the impact of the disaster on society.

Overall, measuring the many effects of disasters is problematic, prone to both overestimation (for example, double counting) and underestimation (because it is difficult to value loss of life or damage to the environment). Both over- and underestimation can be issues in different parts of the same impact assessment, for example, ecological and quality of life impacts may be ignored, while double counting occurs in the measurement of indirect impacts. As discussed earlier in this section, most large-scale estimates leave out significant areas of cost and are therefore underestimates. Biases also affect the accuracy of estimates; for example, the prospect of aid may create incentives to inflate losses. How disaster impacts are evaluated depends on numerous factors, such as the types of impacts being evaluated, the objective of the evaluation, the spatial and temporal scale under consideration, and importantly, the information, expertise, and data available. In practice, the great majority of post-disaster impact assessments are undertaken pragmatically using whatever data and expertise are available. Many studies utilize both partial and general equilibrium analysis in an ‘integrated assessment’ that attempts to capture both the bottom-up and the economy-wide impacts of disasters (Ciscar, 2009; World Bank, 2010).

4.5.3.2. Methods and Tools for Evaluating the Costs of Adaptation

Over the last few years, a wide range of methodologies using different metrics, time periods, and assumptions has been developed and applied for assessing adaptation costs and benefits. However, much of the literature remains focused on gradual changes such as sea level rise and effects on agriculture (IPCC, 2007). Extreme events are generally represented in an ad hoc manner using add-on damage functions based on averages of past impacts and contingent on gradual temperature increase (see comment in Nordhaus and Boyer, 2000). In a review of existing literature, Markandya and Watkiss (2009) identify the following types of analyses: investment and financial flows; impact assessments (scenario-based assessments); vulnerability assessments; adaptation assessments; risk management assessments; economic integrated assessment models; multi-criteria analysis; computable general equilibrium models; cost-benefit analysis; cost effectiveness analysis; and portfolio/real options analysis.

Global and regional assessments of adaptation costs, the focus of this section, have essentially used two approaches: (1) determining the pure *financial costs*, that is, outlays necessary for specific adaptation interventions (known as *investment and financial flow analyses*); and (2) *economic costs* involving estimating the wider overall costs and benefits to society and comparing this to mitigation, often using Integrated Assessment Models (IAMs). The IAM approach leads to a broader estimate of costs (and benefits) over long time scales, but requires detailed models of the economies under study (UNFCCC, 2007). One way of measuring the costs of adaptation involves first establishing a baseline development path (for a country or all countries)

with no climate change, and then altering the baseline to take into account the impacts of climate change (World Bank, 2010). Then the potential effects of various adaptation strategies on development or growth can be examined. Adaptation cost estimates are based on various assumptions about the baseline scenario and the effectiveness of adaptation measures. The difference between these assumptions makes it very difficult to compare or aggregate results (Yohe et al., 1995, 1996; West et al., 2001).

An example illustrating methodological challenges comes from agriculture, where estimates have been made using various assumptions about adaptation behavior (Schneider et al., 2000). These assumptions about behavior range from the farmers who do not react to observed changes in climate conditions (especially in studies that use crop yield sensitivity to weather variability) (Deschênes and Greenstone, 2007; Lobell et al., 2008; Schlenker and Lobell, 2010), to the introduction of selected adaptation measures within crop yield models (Rosenzweig and Parry, 1994), to the assumption of ‘perfect’ adaptation – that is, farmers have complete or ‘perfect’ knowledge and apply that knowledge in ways that ensure outcomes align exactly with theoretical predictions (Kurukulasuriya and Mendelsohn, 2008a,b; Seo and Mendelsohn, 2008). Realistic assessments fall between these extremes, and a realistic representation of future adaptation patterns depends on the in-due-time detection of the climate change signal (Schneider et al., 2000; Hallegatte, 2009); the inertia in adoption of new technologies (Reilly and Schimmelpfennig, 2000); the existence of price signals (Fankhauser et al., 1999); and assessments of plausible behavior by farmers.

Cost-benefit analysis (CBA) is an established tool for determining the economic efficiency of development interventions. CBA compares the costs of conducting such projects with their benefits and calculates the net benefits or economic efficiency (Benson and Twigg, 2004). Ideally CBA accounts for all costs and benefits to society including environmental impacts, not just financial impacts on individual businesses. All costs and benefits are monetized so that tradeoffs can be compared with a common measure. The fact that intangibles and other items that are difficult to value are often left out is one of the major criticisms of the approach (Gowdy, 2007). In the case of disaster risk reduction (DRR) and adaptation interventions, CBA weighs the costs of the DRR project against the disaster damage costs avoided. While the benefits created by development interventions are the additional benefits due to, for example, improvements in physical or social infrastructure, in DRR the benefits are mostly the avoided or reduced potential damages and losses (Smyth et al., 2004). The net benefit can be calculated in terms of net present value, the rate of return, or the benefit-cost ratio. OECD countries such as the United Kingdom and the United States, as well as international financial institutions such as the World Bank, Asian Development Bank, and Inter-American Development Bank, have used CBA for evaluating disaster risk management (DRM) in the context of development assistance (Venton and Venton, 2004; Ghesquiere et al., 2006) and use it routinely for assessing engineering DRM strategies domestically. CBA can be, and has been, applied at any level from the global to local (see Kramer, 1995; Benson and Twigg, 2004; Venton and

Venton, 2004; UNFCCC, 2007; Mechler, 2008). Because the chance of occurrence of a disaster event can be expressed as a probability, it follows that the benefits of reducing the impact of that event can be expressed in probabilistic terms. Costs and benefits should be calculated by multiplying probability by consequences; this leads to risk estimates that account for hazard intensity and frequency, vulnerability, and exposure (Smyth et al., 2004; Ghesquiere et al., 2006).

National-level studies of adaptation effectiveness in the European Union, the United Kingdom, Finland, and The Netherlands, as well as in a larger number of developing countries using the National Adaptation Programme of Action approach, have been conducted or are underway (Ministry of Agriculture and Forestry, 2005; DEFRA, 2006; Lemmen et al., 2008; de Bruin et al., 2009; Parry et al., 2009). Yet the evidence base on the economic aspects including economic efficiency of adaptation remains limited and fragmented (Adger et al., 2007; Moench et al., 2007; Agrawala and Fankhauser, 2008; Parry et al., 2009). As noted at the start of Section 4.5.3.2, many adaptation studies focus on gradual change, especially for agriculture. Those studies considering extreme events, and finding or reporting net benefits over a number of key options (Agrawala and Fankhauser, 2008; Parry et al., 2009), do so by treating extreme events similarly to gradual onset phenomena and using deterministic impact metrics, which is problematic for disaster risk. A recent, risk-focused study (ECA, 2009) concentrating on national and sub-national levels went so far as to suggest an adaptation cost curve, which organizes relevant adaptation options around their cost-benefit ratios. However, given available data including future projections of risk and the effectiveness of options, this is probably at most heuristic rather than a basis for policy.

There are several complexities and uncertainties inherent in the estimates required for a CBA of DRR. As these are compounded by climate change, CBA's utility in evaluating adaptation may be reduced. These include difficulties in handling intangibles and, as is particularly important for extremes, in the discounting of future impacts; CBA does not account for the distribution of costs and benefits or the associated equity issues. Moench et al. (2007) argue that CBA is most useful as a decision support tool that helps the policymaker categorize, organize, assess, and present information on the costs and benefits of a potential project, rather than give a definite answer. Overall, the applicability of rigorous CBAs for evaluations of adaptation is thus limited based on *limited evidence* and *medium agreement*.

4.5.3.3. Attribution of Impacts to Climate Change: Observations and Limitations

Attribution of the impacts of climate change can be defined and used in a way that parallels the well-developed applications for the physical climate system (IPCC, 2010). Detection is the process of demonstrating that a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. Attribution is the process of establishing the most probable causes, natural or

anthropogenic, for the detected change with some defined level of confidence.

The IPCC Working Group II Fourth Assessment Report found, with *very high confidence*, that observational evidence shows that biological systems on all continents and in most oceans are already being affected by recent climate changes, particularly regional temperature increases (Rosenzweig et al., 2007).

Attribution of changes in individual weather and climate events to anthropogenic forcing is complicated because any such event might have occurred by chance in an unmodified climate as a result of natural climate variability (see FAQ 3.2). An approach that addresses this problem is to look at the likelihood of such an event occurring, rather than the occurrence of the event itself (Stone and Allen, 2005). For example, human-induced changes in mean temperature have been shown to increase the likelihood of extreme heat waves (Meehl and Tebaldi, 2004; Stott et al., 2004). For a large region of continental Europe, Stott et al. (2004) showed that anthropogenic climate change *very likely* doubled the probability of surpassing a mean summer temperature not exceeded since advent of the instrumental record in 1851, but which was by the 2003 event in Europe. More recent work provides further support for such a linkage (Barriopedro et al., 2011; see Section 3.3.1).

Most published studies on the attribution of impacts of extremes to natural and anthropogenic climate change have focused on long-term records of disaster losses, or examine the likelihood of the event occurring. Most published effort has gone into the analysis of long-term disaster loss records.

There is *high confidence*, based on *high agreement* and *medium evidence*, that economic losses from weather- and climate-related disasters have increased (Cutter and Emrich, 2005; Peduzzi et al., 2009, 2011; UNISDR, 2009; Mechler and Kundzewicz, 2010; Swiss Re 2010; Munich Re, 2011). A key question concerns whether trends in such losses, or losses from specific events, can be attributed to climate change. In this context, changes in losses over time need to be controlled for exposure and vulnerability. Most studies of long-term disaster loss records attribute these increases in losses to increasing exposure of people and assets in at-risk areas (Miller et al., 2008; Bouwer, 2011), and to underlying societal trends – demographic, economic, political, and social – that shape vulnerability to impacts (Pielke Jr. et al., 2005; Bouwer et al., 2007). Some authors suggest that a (natural or anthropogenic) climate change signal can be found in the records of disaster losses (e.g., Mills, 2005; Höppe and Grimm, 2009), but their work is in the nature of reviews and commentary rather than empirical research. Attempts have been made to normalize loss records for changes in exposure and wealth. There is *medium evidence* and *high agreement* that long-term trends in normalized losses have not been attributed to natural or anthropogenic climate change (Choi and Fisher, 2003; Crompton and McAneney, 2008; Miller et al., 2008; Neumayer and Barthel, 2011). The evidence is *medium* because of the issues set out toward the end of this section.

The statement about the absence of trends in impacts attributable to natural or anthropogenic climate change holds for tropical and extratropical storms and tornados (Boruff et al., 2003; Pielke Jr. et al., 2003, 2008; Raghavan and Rajesh, 2003; Miller et al 2008; Schmidt et al., 2009; Zhang et al., 2009; see also Box 4-2). Most studies related increases found in normalized hurricane losses in the United States since the 1970s (Miller et al., 2008; Schmidt et al., 2009; Nordhaus, 2010) to the natural variability observed since that time (Miller et al., 2008; Pielke Jr. et al., 2008). Bouwer and Botzen (2011) demonstrated that other normalized records of total economic and insured losses for the same series of hurricanes exhibit no significant trends in losses since 1900.

The absence of an attributable climate change signal in losses also holds for flood losses (Pielke Jr. and Downton, 2000; Downton et al., 2005; Barredo, 2009; Hilker et al., 2009), although some studies did find recent increases in flood losses related in part to changes in intense rainfall events (Fengqing et al., 2005; Chang et al., 2009). For precipitation-related events (intense rainfall, hail, and flash floods), the picture is more diverse. Some studies suggest an increase in damages related to a changing incidence in extreme precipitation (Changnon, 2001, 2009), although no trends were found for normalized losses from flash floods and landslides in Switzerland (Hilker et al., 2009). Similarly, a study of normalized damages from bushfires in Australia also shows that increases are due to increasing exposure and wealth (Crompton et al., 2010).

Increasing exposure of people and economic assets has been the major cause of long-term increases in economic losses from weather- and climate-related disasters (*high confidence*). The attribution of economic disaster losses is subject to a number of limitations in studies to date: data availability (most data are available for standard economic sectors in developed countries); type of hazards studied (most studies focus on cyclones, where confidence in observed trends and attribution of changes to human influence is *low*; Section 3.4.4); and the processes used to normalize loss data over time. Different studies use different approaches to normalization, and most normalization approaches take account of changes in exposure of people and assets, but use only limited, if any, measures of vulnerability trends, which is questionable. Different approaches are also used to handle variations in the quality and completeness of data on impacts over time. Finding a trend or ‘signal’ in a system characterized by large variability or ‘noise’ is difficult and requires lengthy records. These are all areas of potential weakness in the methods and conclusions of longitudinal loss studies and more empirical and conceptual efforts are needed. Nevertheless, the results of the studies mentioned above are strengthened as they show similar results, although they have applied different data sets and methodologies.

A general area of uncertainty in the studies concerns the impacts of weather and climate events on the livelihoods and people of informal settlements and economic sectors, especially in developing countries. Some one billion people live in informal settlements (UNISDR, 2011), and over half the economy in some developing countries is informal (Schneider et al., 2010). These impacts have not been systematically documented, with the result that they are largely excluded from both

longitudinal impact analysis and attribution to defined weather episodes.

Another general area of uncertainty comes from confounding factors that can be identified but are difficult to quantify, and relates to the usual assumption of constant vulnerability in studies of loss trends. These include factors that would be expected to increase resilience (Chapters 2 and 5 of this report) and thereby mask the influence of climate change, and those that could act to increase the impact of climate change. Those that could mask the effects of change include gradual improvements in warnings and emergency management (Adger et al., 2005), building regulations (Crichton, 2007), and changing lifestyles (such as the use of air conditioning), and the almost instant media coverage of any major weather extreme that may help reduce losses. In the other direction are changes that may be increasing risk, such as the movement of people in many countries to coastal areas prone to cyclones (Pompe and Rinehart, 2008) and sea level rise.

4.5.4. Assessment of Impact Costs

Much work has been conducted on the analysis of direct economic losses from natural disasters. The examples mentioned below mainly focus on national and regional economic losses from particular climate extremes and disasters, and also discuss uncertainty issues related to the assessment of economic impacts.

4.5.4.1. Estimates of Global and Regional Costs of Disasters

Observed trends in extreme impacts: Data on global weather- and climate-related disaster losses reported since the 1960s reflect mainly monetized direct damages to assets, and are unequally distributed. Estimates of annual losses have ranged since 1980 from a few US\$ billion to above 200 billion (in 2010 dollars) for 2005 (the year of Hurricane Katrina) (UNISDR, 2009; Swiss Re 2010; Munich Re, 2011). These estimates do not include indirect and intangible losses.

On a global scale, annual material damage from large weather and climate events has been found to have increased eight-fold between the 1960s and the 1990s, while the insured damage has been found to have increased by 17-fold in the same interval, in inflation-adjusted monetary units (Mechler and Kundzewicz, 2010). Between 1980 and 2004, the total costs of extreme weather events totaled US\$ 1.4 trillion, of which only one-quarter was insured (Mills, 2005). Material damages caused by natural disasters, mostly weather- and water-related, have increased more rapidly than population or economic growth, so that these factors alone may not fully explain the observed increase in damage. The loss of life has been brought down considerably (Mills, 2005; UNISDR, 2011).

Developing regions are vulnerable both because of exposure to weather- and climate-related extremes and their status as developing economies. However, disaster impacts are unevenly distributed by type of

disaster, region, country, and the exposure and vulnerability of different communities and sectors.

Percentage of direct economic losses by regions: The concentration of information on disaster risk generally is skewed toward developed countries and the Northern Hemisphere (World Bank and UN, 2010). Some global databases, however, do allow a regional breakdown of disaster impacts. The unequal distribution of the human impact of natural disasters is reflected in the number of disasters and losses across regions (Figure 4-7). In the period 2000 to 2008, Asia experienced the highest number of weather- and climate-related disasters. The Americas suffered the most economic loss, accounting for the highest proportion (54.6%) of total loss, followed by Asia (27.5%) and Europe (15.9%). Africa accounted for only 0.6% of global economic losses, but economic damages from natural disasters are underreported in these data compared to other regions (Vos et al., 2010). Although reporting biases exist, they are judged to provide *robust evidence* of the regional distribution of the number of disasters and of direct economic losses for this recent period 2000 to 2008, and there is *high agreement* regarding this distribution among different databases collected by independent organizations (Guha-Sapir et al., 2011; Munich Re, 2011; Swiss Re, 2011).

Damage losses in percentage of GDP by regions: The relative economic burden in terms of direct loss expressed as a percentage of GDP has been substantially higher for developing states. Middle-income countries

with rapidly expanding asset bases have borne the largest burden, where during the period from 2001 to 2006 losses amounted to about 1% of GDP, while this ratio has been about 0.3% of GDP for low-income countries and less than 0.1% of GDP for high-income countries, based on *limited evidence* (Cummins and Mahul, 2009). In small exposed countries, particularly small island developing states, these wealth losses expressed as a percentage of GDP and averaged over both disaster and non-disaster years can be considerably higher, exceeding 1% in many cases and 8% in the most extreme cases over the period from 1970 to 2010 (World Bank and UN, 2010), and individual events may consume more than the annual GDP (McKenzie et al., 2005). This indicates a far higher vulnerability of the economic infrastructure in developing countries (Cavallo and Noy 2009; UNISDR, 2009).

Increasing weather- and climate-related disasters: The number of reported weather- and climate-related disasters and their direct financial costs have increased over the past decades. Figure 4-8 illustrates an increasing trend (coupled with large interannual variability) in losses based on data for large weather-and climate-related disasters over the period 1980 to 2010, for which data have been gathered consistently and systematically (see Neumayer and Barthel, 2011).

This increase in affected population and direct economic losses is also coupled with the increasing numbers of reported weather- and climate-related disasters (UNISDR, 2009; Munich Re, 2011; Swiss Re 2011).

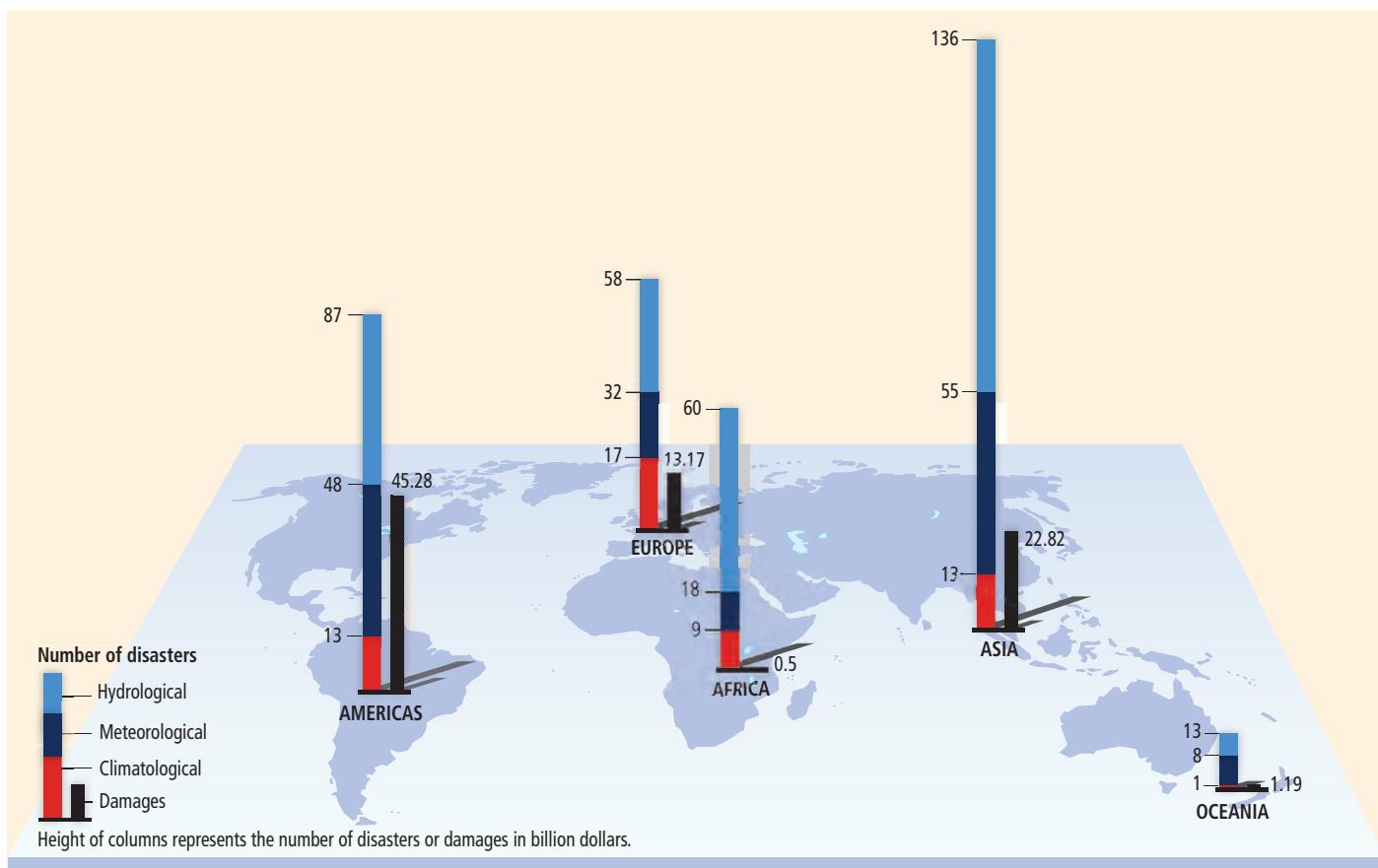


Figure 4-7 | Weather- and climate-related disaster occurrence and regional average impacts from 2000 to 2008. The number of climatological (e.g., extreme temperature, drought, wildfire), meteorological (e.g., storm), and hydrological (e.g., flood, landslides) disasters is given for each region, along with damages (2009 US\$ billion). Data from Vos et al., 2010.

These statistics imply the increasing cost of such disasters to society, regardless of cause. It is also important to note that the number of weather- and climate-related disasters has increased more rapidly than losses from non-weather disasters (Mills, 2005; Munich Re, 2011; Swiss Re, 2011). This could indicate a change in climate extremes, but there are other possible explanations (Bouwer, 2011). Drought and flood losses may have grown due to a number of non-climatic factors, such as increasing water withdrawals effectively exacerbating the impact of droughts, decrease in storage capacity in catchments (urbanization, deforestation, sealing surfaces, channelization) adversely affecting both flood and drought preparedness, increase in runoff coefficients, and growing settlements in floodplains around urban areas (see Section 4.2.2; Field et al., 2009).

4.5.4.2. Potential Trends in Key Extreme Impacts

As indicated in Sections 3.3 to 3.5 and Tables 3-1 and 3-3, climate extremes may have different trends in the future; some such as heat waves are projected to increase over most areas in length, frequency, and intensity, while projected changes in some other extremes are given with less confidence. However, uncertainty is a key aspect of disaster/climate change trend analysis due to attribution issues discussed above,

incomparability of methods, changes in exposure and vulnerability over time, and other non-climatic factors such as mitigation and adaptation. A challenge is ensuring that the projections of losses from future changes in extreme events are examined not for current populations and economies, but for scenarios of possible future socioeconomic development. See Box 4-2 for a discussion of this with respect to cyclones.

It is *more likely than not* that the frequency of the most intense tropical cyclones will increase substantially in some ocean basins (Section 3.4.4). Many studies have investigated impacts from tropical cyclones (e.g., ABI, 2005a, 2009; Hallegatte, 2007; Pielke Jr., 2007; Narita et al., 2009; Bender et al., 2010; Nordhaus, 2010; Crompton et al., 2011). Table 4-3 presents the projected percentage increase in direct economic losses from tropical cyclones from a number of these studies, scaled to the year 2040 relative to a common baseline (year 2000). There is *high confidence* that increases in exposure will result in higher direct economic losses from tropical cyclones and that losses will also depend on future changes in tropical cyclone frequency and intensity. One study, building on global climate model results from Bender et al. (2010), found that to attribute increased losses to increased tropical cyclone activity in the United States with a high degree of certainty would take another 260 years of records, due to the high natural variability of storms and their impacts

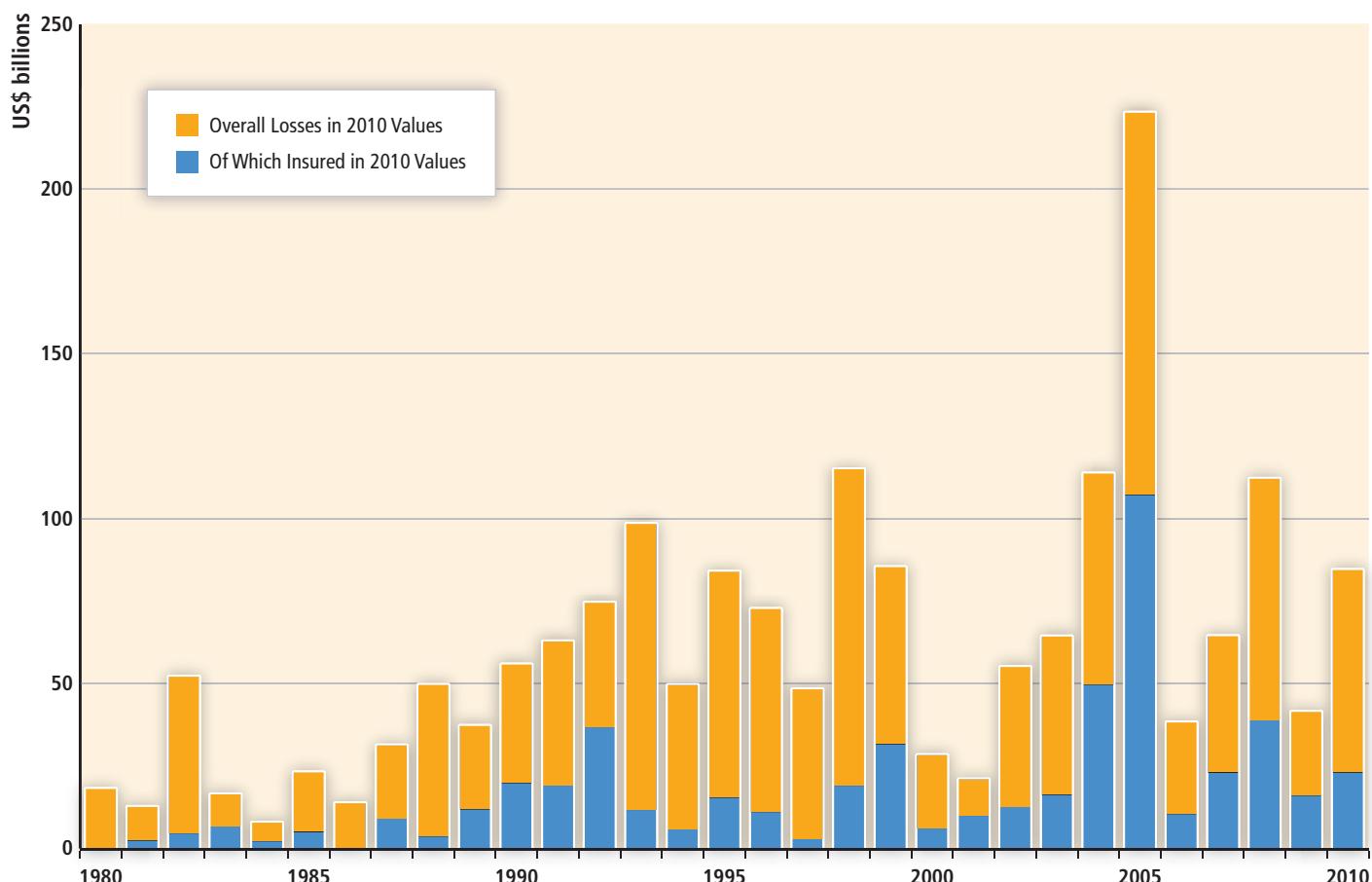


Figure 4-8 | The overall losses and insured losses from weather- and climate-related disasters worldwide (in 2010 US\$). These data for weather- and climate-related 'great' and 'devastating' natural catastrophes are plotted without inclusion of losses from geophysical events. A catastrophe in this data set is considered 'great' if the number of fatalities exceeds 2,000, the number of homeless exceeds 200,000, the country's GDP is severely hit, and/or the country is dependent on international aid. A catastrophe is considered 'devastating' if the number of fatalities exceeds 500 and/or the overall loss exceeds US\$ 650 million (in 2010 values). Data from Munich Re, 2011.

Table 4-3 | Estimated change in disaster losses in 2040 under projected climate change and exposure change, relative to 2000, from 21 impact studies including median estimates by type of weather hazard. Source: Bouwer, 2010.

A. Impact of projected climate change

Study	Hazard type	Region	Estimated loss change [%] in 2040			
			Min	Max	Mean	Median
Pielke (2007)	Tropical storm	Atlantic	58	1,365	417	30
Nordhaus (2010)	Tropical storm	United States	12	92	47	
Narita et al. (2009)	Tropical storm	Global	23	130	46	
Hallegatte (2007)	Tropical storm	United States	-	-	22	
ABI (2005a,b)	Tropical storm	United States, Caribbean	19	46	32	
ABI (2005a,b)	Tropical storm	Japan	20	45	30	
ABI (2009)	Tropical storm	China	9	19	14	
Schmidt et al. (2009)	Tropical storm	United States	-	-	9	
Bender et al. (2010)	Tropical storm	United States	-27	36	14	
Narita et al. (2010)	Extra-tropical storm	High latitude	-11	62	22	
Schwierz et al. (2010)	Extra-tropical storm	Europe	6	25	16	15
Leckebusch et al. (2007)	Extra-tropical storm	United Kingdom, Germany	-6	32	11	
ABI (2005a,b)	Extra-tropical storm	Europe	-	-	14	
ABI (2009)	Extra-tropical storm	United Kingdom	-33	67	15	
Dorland et al. (1999)	Extra-tropical storm	Netherlands	80	160	120	
Bouwer et al. (2010)	River flooding	Netherlands	46	201	124	
Feyen et al. (2009)	River flooding	Europe	-	-	83	
ABI (2009)	River flooding	United Kingdom	3	11	7	
Feyen et al. (2009)	River flooding	Spain (Madrid)	-	-	36	
Schreider et al. (2000)	Local flooding	Australia	67	514	361	
Hoes (2007)	Local flooding	Netherlands	16	70	47	

B. Impact of projected exposure change

Study	Hazard type	Region	Estimated loss change [%] in 2040			
			Min	Max	Mean	Median
Pielke (2007)	Tropical storm	Atlantic	164	545	355	172
Schmidt et al. (2009)	Tropical storm	United States	-	-	240	
Dorland et al. (1999)	Extra-tropical storm	Netherlands	12	93	50	
Bouwer et al. (2010)	River flooding	Netherlands	35	172	104	
Feyen et al. (2009)	River flooding	Spain (Mad)	-	-	349	
Hoes (2007)	Local flooding	Netherlands	-4	72	29	

(Crompton et al., 2011). See Section 4.5.3.3 on attribution and the use of a risk-based approach to cope with this issue. Other studies have investigated impacts from increases in the frequency and intensity of extratropical cyclones at high latitudes (Dorland et al., 1999; ABI, 2005a, 2009; Narita et al., 2010; Schwierz et al., 2010; Donat et al., 2011). In general there is *medium confidence* that increases in losses due to extratropical cyclones will occur with climate change, with possible decreases or no change in some areas. Projected increases generally are slightly lower than increases in tropical cyclone losses (see Table 4-3). Patt et al. (2010) projected future losses due to weather- and climate-related extremes in least-developed countries.

Many studies have addressed future economic losses from river floods, most of which are focused on Europe, including the United Kingdom (Hall et al., 2003, 2005; ABI, 2009), Spain (Feyen et al., 2009), and The Netherlands (Bouwer et al., 2010) (see Table 4-3). Maaskant et al. (2009) is one of the few studies that addresses future loss of life from flooding, and projects up to a four-fold increase in potential flood victims in The Netherlands by the year 2040, when population growth

is accounted for. Some studies are available on future coastal flood risks (Hall et al., 2005; Mokrech et al., 2008; Nicholls et al., 2008; Dawson et al., 2009; Hallegatte et al., 2010). Although future flood losses in many locations will increase in the absence of additional protection measures (*high agreement, medium evidence*), the size of the estimated change is highly variable, depending on location, climate scenarios used, and methods used to assess impacts on river flow and flood occurrence (see Table 4-3 for a comparison of some regional studies) (Bouwer, 2010).

Some studies have addressed economic losses from other types of weather extremes, often smaller-scale compared to river floods and cyclones. These include hail damage, for which mixed results are found: McMaster (1999) and Niall and Walsh (2005) found no significant effect on hailstorm losses for Australia, while Botzen et al. (2010) find a significant increase (up to 200% by 2050) for damages in the agricultural sector in The Netherlands, although the approaches used vary considerably. Rosenzweig et al. (2002) report on a possible doubling of losses to crops due to excess soil moisture caused by more intense rainfall. Hoes (2007), Hoes and Schuurmans (2006), and Hoes et al.

(2005) estimated increases in damages due to extreme rainfall in The Netherlands by mid-century.

It is well known that the frequency and intensity of extreme weather and climate events are only one factor that affects risks, as changes in population, exposure of people and assets, and vulnerability determine loss potentials (see Sections 4.2 to 4.4). Few studies have specifically quantified these factors. However, the ones that do generally underline the important role of projected changes (increases) in population and capital at risk. Some studies indicate that the expected changes in exposure are much larger than the effects of climate change (see Table 4-3), which is particularly true for tropical and extratropical storms (Pielke Jr., 2007; Feyen et al., 2009; Schmidt et al., 2009). Other studies show that the effect of increasing exposure is about as large as the effect of climate change (Hall et al., 2003; Maaskant et al., 2009; Bouwer et al., 2010), or estimate that these are generally smaller (Dorland et al., 1999; Hoes, 2007). There is therefore *medium confidence* that, for some climate extremes in many regions, the main driver for future increasing losses in many regions will be socioeconomic in nature (based on *medium agreement* and *limited evidence*). Finally, many studies underline that both factors need to be taken into account, as the factors do in fact amplify each other, and therefore need to be studied jointly when expected losses from climate change are concerned (Hall et al., 2003; Bouwer et al., 2007, 2010; Pielke Jr., 2007; Feyen et al., 2009).

4.5.5. Assessment of Adaptation Costs

The World Bank (2006) estimated the cost of climate-proofing foreign direct investments, gross domestic investments, and Official Development Assistance, which was taken up and modified by Stern (2007), Oxfam (2007), and UNDP (2007). The second source of adaptation cost estimates is UNFCCC (2007), which calculated the value of existing and planned investment and financial flows required for the international community

to effectively and appropriately respond to climate change impacts. The third source is World Bank (2010), which also conducted a number of country-level studies to complement the global assessment, following UNFCCC (2007), but aimed at improving upon this by assessing the climate-proofing of existing and new infrastructure, using more precise unit cost estimates and including the costs of maintenance as well as those of port upgrading and the risks from sea level rise and storm surges. Also, the investment in education necessary to neutralize impacts of extreme weather is calculated. Estimates of costs to adapt to climate change (rather than simply to extremes and disasters), which have mostly been made for developing countries, exhibit a large range and relate to different assessment periods (such as today, 2015, or 2030). For 2030, the estimated global cost from UNFCCC (2007) ranges from US\$ 48 to 171 billion per year for developed and developing countries, and US\$ 28 to 67 billion per year for developing countries (in 2005 dollars). Recent estimates from World Bank (2010) for developing countries lead to higher projected costs and broadly amount to the average of this range with annual costs of up to US\$ 100 billion (in 2005 US\$) (see Table 4-4). Confidence in individual global estimates is *low* because, as mentioned above and discussed by Parry et al. (2009), the estimates are derived from only three relatively independent studies, which explains the seeming convergence of the estimates in latter studies. As well, Parry et al. (2009) consider the estimates a significant underestimation by at least a factor of two to three and possibly more if the costs incurred by other sectors were included, such as ecosystem services, energy, manufacturing, retailing, and tourism. The adaptation cost estimates are also based mostly on low levels of investment due to an existing adaptation deficit in many regions. Unavoidable residual damages remain absent from these analyses.

In terms of regional costs and as reported in the World Bank (2010) study, the largest absolute adaptation costs would arise in East Asia and the Pacific, followed by the Latin American and Caribbean region as well as sub-Saharan Africa. This pattern held for the two scenarios assessed

Table 4-4 | Estimates of global costs of adaptation to climate change. Source: Extended based on Agrawala and Fankhauser (2008) and Parry et al. (2009).

Study	Results (billion US\$ yr ⁻¹)	Time Frame and Coverage	Sectors	Methodology and Comment
World Bank (2006)	9–41 ¹	Present, developing countries	Unspecified	Cost of climate-proofing foreign direct investments, gross domestic investments, and Official Development Assistance
Stern (2007)	4–37 ¹	Present, developing countries	Unspecified	Update of World Bank (2006)
Oxfam (2007)	>50 ¹	Present, developing countries	Unspecified	World Bank (2006) plus extrapolation of cost estimates from National Adaptation Programmes of Action and NGO projects
UNDP (2007)	86–109 ²	In 2015, developing countries	Unspecified	World Bank (2006) plus costing of targets for adapting poverty reduction programs and strengthening disaster response systems
UNFCCC (2007)	48–171 (28–67 for developing countries) ²	In 2030, developed and developing countries	Agriculture, forestry, and fisheries; water supply; human health; coastal zones; infrastructure; ecosystems (but no estimate for 2030 for ecosystem adaptation)	Additional investment and financial flows needed for adaptation in 2030
World Bank (2010)	70–100 ²	Annual from 2010 to 2050, developing countries	Agriculture, forestry, and fisheries; water supply and flood protection; human health; coastal zones; infrastructure; extreme weather events	Impact costs linked to adaptation costs, improvement upon UNFCCC (2007); climate-proofing existing and new infrastructure, more precise unit cost, inclusion of cost of maintenance and port upgrading, risks from sea level rise and storm surges, riverine flood protection, education investment to neutralize impacts of extreme weather events

Notes: 1. in 2000 US\$; 2. in 2005 US\$.

Table 4-5 | Range of regionalized annual costs of adaptation for wet and dry scenarios (in 2005 US\$ billion). Reflecting the full range of estimated costs, the wet scenario costs do not include benefits from climate change while the dry scenario costs include benefits from climate change within and across countries. Source: World Bank, 2010.

Scenario/Region	East Asia & Pacific	Europe & Central Asia	Latin America & Caribbean	Middle East & North America	South Asia	sub-Saharan Africa	Total
Wet	25.7	12.6	21.3	3.6	17.1	17.1	97.5
Dry	17.7	6.5	14.5	2.4	14.6	13.8	69.6

in the study, which were a scenario with the most precipitation ('wet') and one with the least precipitation ('dry') among all scenarios chosen for the study, which employ socioeconomic driver information from IPCC's SRES A2 scenario (see Table 4-5).

Taking Africa as an example, based on various estimates the potential additional costs of adaptation investment range from US\$ 3 to 10 billion per year by 2030 (UNFCCC, 2007; PACJA, 2009). However, this could be also an underestimate considering the desirability of improving Africa's resilience to climate extremes as well as the flows of international humanitarian aid in the aftermath of disasters.

4.5.6. Uncertainty in Assessing the Economic Costs of Extremes and Disasters

Upon reviewing the estimates to date, the costing of weather- and climate-related disasters and estimating adaptation costs is still preliminary, incomplete, and subject to a number of assumptions with the result that there is considerable uncertainty (Agrawala and Fankhauser, 2008; Parry et al., 2009). This is largely due to modeling uncertainties in climate change and damage estimates, limited data availability, and methodological shortcomings in analyzing disaster damage statistics. Such costing is further limited by the interaction between numerous adaptation options and assumptions about future exposure and vulnerabilities, social preferences, and technology, as well as levels of resilience in specific societies. Additionally the following challenges can be identified.

Risk assessment methods: Technical challenges remain in developing robust risk assessment and damage costing methods. Study results can vary significantly between top-down and bottom-up approaches. Risk-based approaches are utilized for assessing and projecting disaster risk (Jones, 2004; Carter et al., 2007), for which input from both climate and social scenarios is required. All climatic phenomena are subject to the limitation that historically based relationships between damages and disasters cannot be used with confidence to deduce future risk of extreme events under changing characteristics of frequency and intensity (UNDP, 2004). Yet climate models are today challenged when reproducing spatially explicit climate extremes, due to coarse resolution and physical understanding of the relevant process, as well as challenges in modeling low-probability, high-impact events (see Section 3.2.3). Therefore,

projections of future extreme event risk involve uncertainties that can limit understanding of sudden onset risk, such as flood risk. Future socioeconomic development is also inherently uncertain. A uniform set of assumptions can help to provide a coherent global picture and comparison and extrapolation between regions.

Data availability and consistency: Lack of data and robust information increases the uncertainty of costing when scaling up to global levels from a very limited (and often very local) evidence base. There are double-counting problems and issues of incompatibility between types of impacts in the process of multi-sectoral and cross-scale analyses, especially for the efforts to add both market and non-market values (e.g., ecosystem services) (Downton and Pielke Jr., 2005; Pielke Jr. et al., 2008; Parry et al., 2009). Moreover the full impacts of weather- and climate-related extremes in developing countries are not fully understood, and a lack of comprehensive studies on damage, adaptation, and residual costs indicates that the full costs are underestimated.

Information on future vulnerability: Apart from climate change, vulnerability and exposure will also change over time, and the interaction of these aspects should be considered (see, e.g., Hallegatte, 2008; Hochrainer and Mechler, 2011). This has been recognized and assessments of climate change impacts, vulnerability, and risk are changing in focus, leading to more integration across questions. While initial studies focused on an analysis of the problem, the field proceeded to assess potential impacts and risks, and now more recently started to combine such assessments with the consideration of specific risk management methods (Carter et al., 2007).

Some studies have suggested incorporating an analysis of the ongoing or chronic economic impact of disasters into the adaptation planning process (Freeman, 2000). A fuller assessment of disaster cost at varying spatial and temporal scales and costs related to impacts on human, social, built, and natural capital, and their associated services at different levels can set the stage for comparisons of post-disaster development strategies. This would make disaster risk reduction planning and preparedness investment more cost-effective (Gaddis et al., 2007). For example, there is consensus on the important role of ecosystems in risk reduction and well-being, which would make the value of ecosystem services an integral part of key policy decisions associated with adaptation (Tallis and Kareiva, 2006; Costanza and Farley, 2007).

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