10. Key Economic Sectors and Services

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Contents

Executive Summary

10.1. Introduction and Context

10.2. Energy
- 10.2.1. Energy Demand
- 10.2.2. Energy Supply
- 10.2.3. Transport and Transmission of Energy
- 10.2.4. Market Impacts
- 10.2.5. Summary

10.3. Water
- 10.3.1. Water-Related Damages
- 10.3.2. Municipal and Industrial Water Supply
- 10.3.3. Wastewater and Urban Stormwater
- 10.3.4. Energy: Hydropower and Cooling Water
- 10.3.5. Inland Navigation
- 10.3.6. Irrigation
- 10.3.7. Nature Conservation
- 10.3.8. Recreation and Tourism
- 10.3.9. Water Management and Allocation

10.4. Transport
- 10.4.1. Roads
- 10.4.2. Rail
- 10.4.3. Pipeline
- 10.4.4. Shipping
- 10.4.5. Air

10.5. Other Primary and Secondary Economic Activities
- 10.5.1. Primary Economic Activities
  - 10.5.1.1. Crop and Animal Production
  - 10.5.1.2. Forestry and Logging
  - 10.5.1.3. Fisheries and Aquaculture
  - 10.5.1.4. Mining and Quarrying

10.5.2. Secondary Economic Activities
10.5.2.1. Manufacturing
10.5.2.2. Construction and Housing

10.6. Recreation and Tourism
10.6.1. Recreation and Tourism Demand
10.6.1.1. Recreation
10.6.1.2. Tourism
10.6.2. Recreation and Tourism Supply
10.6.3. Market Impacts

10.7. Insurance
10.7.1. Main Results of AR4 and SREX
10.7.2. Societal Role of Insurance Covering Weather Hazards
10.7.3. Observed and Projected Losses from Weather Hazards
10.7.4. Supply-Side Challenges and Sensitivities
10.7.4.1. High-Income Countries
10.7.4.2. Middle- and Low-Income Countries
10.7.5. Products and Systems Responding to Changes in Weather Risks
10.7.5.1. High-Income Countries
10.7.5.2. Middle- and Low-Income Countries
10.7.6. Governance, Public-Private Partnerships, and Insurance Market Regulation
10.7.6.1. High-Income Countries
10.7.6.2. Middle- and Low-Income Countries

10.8. Services Other than Tourism and Insurance
10.8.1. Sectors Other than Health
10.8.2. Health

10.9. Impacts on Markets and Development
10.9.1. General Equilibrium Effects
10.9.2. Growth Effects
10.9.2.1. The Rate of Economic Growth
10.9.2.2. Poverty Traps
10.9.2.3. Conclusion

10.10. Research Needs and Priorities

Frequently Asked Questions

Appendices
10.A1. Industrial Classification and Chapter Outline
10.B. Industrial Classification and Literature Search

References

Executive Summary

Climate change is *very likely to* reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors (high agreement, robust evidence); the balance of the two depends on the geographic, socioeconomic and technological conditions. Increasing income will allow people to regulate indoor temperatures to comfort level that leads to fast growing energy demand for air conditioning even in the absence of climate change in warm regions with low income levels at present. Energy demand will be influenced by changes in

demographics (upwards by increasing population and decreasing average household size), lifestyles (upwards by larger floor area of dwellings), the design and heat insulation properties of the housing stock, the energy efficiency of heating/cooling devices and the abundance and energy efficiency of other electric household appliances. The relative importance of these drivers varies across regions and will change over time. [10.2]

Climate change will *virtually certainly* affect different energy sources and technologies differently, depending on the resources (water flow, wind, insolation), the technological processes (cooling) or the locations (coastal regions, floodplains) involved (high agreement, robust evidence). Gradual changes in various climate attributes (temperature, precipitation, windiness, cloudiness, etc.) and possible changes in the frequency and intensity of extreme weather events will progressively affect operation over time. Climate-induced changes in the availability and temperature of water for cooling are the main concern for thermal and nuclear power plants, but several options are available to cope with reduced water availability. Similarly, already available or newly developed technological solutions allow firms to reduce the vulnerability of new structures and enhance the climate suitability of existing energy installations. [10.2]

Climate change is *about as likely as not* to influence the integrity and reliability of pipelines and electricity grids (medium agreement, medium evidence). Pipelines and electric transmission lines have been operated for over a century in diverse climatic conditions on land from hot deserts to permafrost areas and increasingly at sea. Climate change is *about as likely as not* to require the adoption of technological solutions for the construction and operation of pipelines and power transmission and distribution lines from other geographical and climatic conditions, adjustments in existing pipelines and improvements in the design and deployment of new ones in response to the changing climate and weather conditions. [10.2]

Climate change is *very likely* to have substantial impacts on water resources and water use (high agreement, robust evidence), but the economic implications are not well understood. Economic impacts include flooding, scarcity and cross sectoral competition. Flooding can have major economic costs, both in term of impacts (capital destruction, disruption) and adaptation (construction, defensive investment). Water scarcity and competition for water, driven by institutional, economic or social factors, may mean that water assumed to be available for a sector is not. [10.3]

Transportation is vulnerable to climate impacts. Transport infrastructure malfunctions if the weather is outside the design range, which would happen more frequently should climate change. All infrastructure is vulnerable to freeze-thaw cycles and paved roads are particularly vulnerable to temperature extremes, unpaved roads to precipitation extremes. Transport infrastructure on ice or permafrost is especially vulnerable. [10.4]

Climate change is anticipated to affect tourism resorts, particularly ski resorts, beach resorts, and nature resorts (high agreement, robust evidence) and tourists may be more inclined to spend their holidays at higher altitudes and latitudes (high agreement, medium evidence). The economic implications of climate-change-induced changes in tourism demand and supply may be substantial, with gains for countries closer to the poles and losses for countries closer to the equator. The demand for outdoor recreation is affected by weather and climate, and impacts will vary geographically. [10.6]

Climate change strongly influences insurance and related financial industries (high agreement, robust evidence). More frequent and/or intensive weather disasters would increase losses and loss volatility in various regions and challenge insurance systems to offer affordable coverage while generating more risk-based capital, particularly in low- and middle-income countries. Economic-vulnerability reduction through insurance has proven effective. Large-scale public risk prevention programmes and government insurance of the non-diversifiable portion of risk offer a mechanism for adaptation, but adaptation to avoid large losses due to extreme events may be prohibitively expensive. Commercial reinsurance and risk-linked securitization markets also have a role in ensuring financially healthy insurance systems. [10.7]

Climate change will *very likely* affect the health sector (high agreement, medium evidence) through increases in the frequency, intensity, and extent of extreme weather events adversely affecting infrastructure and increase the demands for services due to the human health impacts of climate change, placing additional burdens on public health, disease burden, and health care personnel and supplies; these have economic consequences. [10.8]

The impacts of climate change on one sector of the economy of one country in turn affect other sectors and other countries through product and input markets. For an individual sector or country, ‘the market’ provides an additional mechanism for adaptation and thus reduces negative impacts and increases positive ones. However, published literature reports tend to understate the total economic impact as sectoral or national studies do not include market spillovers. [10.9]

The impacts of climate change will *likely* affect productivity and economic growth, but the magnitude of this effect is not well understood (high agreement, limited evidence). Climate change variability could be one of the causes why some countries are trapped in poverty, and climate change may make it harder to escape poverty traps. [10.9]

Based on a comprehensive assessment across economic sectors, few key sectors have been subject to detailed research. Few studies have evaluated the possible impacts of climate change on mining, manufacturing or services (apart from health, insurance and tourism).Further research, collection and access to more detailed economic data and the advancement of analytic methods and tools will be required to further assess the potential impacts of climate on key economic systems and sectors. [10.5, 10.8, 10.10]

10.1. Introduction and Context

This chapter discusses the implications of climate change on key economic sectors and services. An inclusive approach was taken, discussing all sectors of the economy. Appendix A shows the list of sectors according to the International Standard Industrial Classification.

This assessment reflects the breadth and depth of the state of knowledge across these sectors; many of which have not been evaluated in the literature. We extensively discuss five sectors: Energy (10.2), water (10.3), transport (10.4), tourism (10.6), and insurance (10.7). Other primary and secondary sectors are discussed in 10.5, and 10.8 is devoted to other service sectors. Food and agriculture is addressed in Chapter 7. Section 10.10 discusses whether there may be vulnerable sectors that have yet to be studied.

This chapter focuses on the impact of climate change on economic activity. Other chapters discuss impacts from a physical, chemical, biological, or social perspective. Economic impacts cannot be isolated; and therefore, there are a large number of cross-references to other chapters in this report. In some cases, particularly agriculture, the discussion of the economic impacts is integrated with the other impacts.

Focusing on the potential impact of climate change on economic activity, this chapter addresses questions such as: how does climate change affect the demand for a particular good or service? What is the impact on its supply? How do supply and demand interact in the market? What are the effects on producers and consumers? Chapter 19 assesses the impact of climate change on economic welfare – that is, the sum of changes in consumer and producer surplus, including for goods and services not traded within the formal economy. This is not attempted here. The focus is on economic activity.

Sections 10.2 through 10.8 discuss individual sectors in isolation. Markets are connected, however. Section 10.9 therefore assesses the implications of changes in any one sector on the rest of the economy. It also discusses the effect of the impacts of climate change on economic growth and development.

Previous assessment reports by the IPCC did not have a chapter on “key economic sectors and services”. Instead, the material assembled here was spread over a number of chapters. AR4 is referred to in the context of the sections below. In some cases, however, the literature is so new that previous IPCC reports did not discuss these impacts at any length.

10.2. Energy

Studies conducted since AR4 and assessed here confirm the main insights about the impacts of climate change on energy as reported in the SAR (Acosta Moreno, 1995) and reinforced by the TAR (Scott, 2001) and AR4(Wilbanks and Romero Lankao, 2007): ceteris paribus, in a warming world, energy demand for heating will decline and energy demand for cooling will increase; the balance of the two depends on the geographic, socioeconomic and technological conditions. The relative importance of temperature changes among the drivers of energy demand varies across regions and will change over time. On the supply side, an increasing number of studies explore the vulnerability, impacts and the adaptation options in the energy sector, compared to what was available for earlier IPCC assessments.

10.2.1. Energy Demand

Most studies and modelling exercises conducted since AR4 explore the impacts of climate change on residential energy demand, particularly electricity. Some studies encompass the commercial sector as well but very few deal with industry and agriculture. In addition to a few global studies based on global energy or integrated assessment models, the new studies tend to focus on specific countries or regions, rely on improved methods (ranging from advanced statistical techniques to global integrated assessment models) and data (both historical and regional climate projections) and many of them explicitly include non-climatic drivers of energy demand. A few studies consider changes in demand together with changes in climate-dependent energy sources, like hydropower.

Energy demand for heating increases too, but much less rapidly, since in most regions with the highest need for heating incomes are already high enough to allow people heat their homes to the desired comfort level, except in some poor regions/households.

Figure 10-1 sorts the assessed studies according to the present climate (represented by mean annual temperature) and current income (represented by GDP per capita). Neither indicator is very explicit: country-level mean annual temperatures for large countries can hide large regional differences and average incomes may conceal large disparities, but they help cluster the national and regional studies in the search for general findings (Toth, 2012).

[INSERT FIGURE 10-1 HERE
Figure 10-1: _____________. Source: (Williams and Toth, 2012).]

The general patterns are that in countries and regions with already high incomes, climate-related changes in energy demand will be primarily driven by increasing temperatures: heavier use of air-conditioning (hence increasing electricity demand) in warm climatic zones, and lower demands for various energy forms (electricity, gas, coal, oil) in temperate and cold climatic zones, while increasing incomes will play a marginal role. In contrast, changes in income will be the main driver of increasing demand for energy (mainly electricity for air conditioning) in present-day low-income countries in warm climatic zones. At the global scale, energy demand for air conditioning increases rapidly in the 21st century under the reference climate change scenario (driven by medium population and economic growth globally albeit with a faster economic growth in developing countries and no additional climate mitigation policies relative to those in place in 2008) from the TIMER/IMAGE model (Isaac and van Vuuren, 2009). The increase is from close to 300 TWh in 2000, to about 4,000 TWh in 2050 and more than 10,000 TWh in 2100, mostly driven by increasing income in emerging market countries. Energy demand for heating increases too, but much less rapidly, since in most regions with the highest need for heating, incomes are already high enough for people to heat their homes to the desired comfort level, except in some poor households.

These general patterns and especially the quantitative results of the projected shifts in energy and electricity demand can be modified by many other factors. In addition to changes in temperatures and incomes, the actual energy demand will be influenced by changes in demographics (upwards by increasing population and decreasing average household size), lifestyles (upwards by larger floor area of dwellings), the design and heat insulation properties of the housing stock, the energy efficiency of heating/cooling devices, the abundance and energy efficiency of other electric household appliances, the price of energy, etc. Some of these factors are considered implicitly or explicitly in some of the studies in Figure 10-1 but ignored in many others.

10.2.2. Energy Supply

Changes in various climate attributes (temperature, precipitation, windiness, cloudiness, etc.) will affect different energy sources and technologies differently. Gradual climate change (CC) will progressively affect operation over time. Possible changes in the frequency and intensity of extreme weather events (EWEs) represent a different kind of hazard for energy installations and infrastructure. This section assesses the most important impacts and adaptation options in both categories. Table 10-1 provides an overview.

[INSERT TABLE 10-1 HERE
Table 10-1: Main impacts of CC and EWEs on energy supply.]

Currently thermal power plants provide about 80% of global electricity and their share is projected to remain high in most mitigation scenarios (IEA, 2010a). Thermal power plants are operated under diverse climatic conditions from the cold artic to the hot tropical regions and are well adapted to the prevailing conditions. However, they might face new challenges and will need to respond by hard (design or structural methods) or soft (operating procedures) measures as a result of climate change

The most significant impact of CC on thermal power generation in many countries is the decreasing efficiency of thermal conversion as a result of rising temperature. This follows from Carnot's rule and cannot be offset per se. Yet there is much room to improve the efficiency of currently operating subcritical steam power plants (IEA, 2010b). As new materials allow higher operating temperatures in coal-fired power plants (Gibbons, 2012), supercritical and ultra-supercritical steam-cycle plants will reach even higher efficiency that can more than compensate the efficiency losses due to higher temperatures. Yet in the absence of CC, these efficiency gains from improved technology would reduce the costs of energy, so there is still a net economic loss in the energy sector. Another problem facing thermal power generation is the decreasing volume and increasing temperature of water for cooling, leading to reduced power generation, operation at reduced capacity and even temporary shutdown of power plants(Ott and Richter, 2008)(Hoffmann *et al*., 2010) (Nee Schulz, 2012)(Hoffmann *et al*., 2010; Ott and Richter, 2008)(Ott and Richter, 2008). Both problems will be exacerbated if CO_2 capture and handling equipment is added at the power plants: energy efficiency declines by 8-14 % and water requirement per MWh electricity generated can double (IPCC, 2005).

Adaptation possibilities range from relatively simple and low-cost options like exploiting non-traditional water sources and re-using process water to measures like installing dry cooling towers, heat pipe exchangers and regenerative cooling (De Bruin *et al*., 2009; Ott and Richter, 2008), all which increase costs. While it is easier to plan for changing climatic conditions and select the conforming cost-efficient cooling technology for new builds, response options are more limited for existing power plants, especially for those towards the end of their economic lifetime.

CC impacts on thermal efficiency and cooling water availability affect nuclear power plants similarly to their thermal counterparts (Williams and Toth, 2012). Whereas there is no escape from Carnot's rule affecting efficiency, a range of alternative cooling options are available or increasingly considered to deal with water deficiency, ranging from re-using wastewater and recovering evaporated water (Feeley III *et al*., 2008) to installing dry cooling (EPA, 2001).

The implications of EWEs for nuclear plants can be severe due to the nature of the technology if not properly addressed. Reliable interconnection (onsite power and instrumentation connections) of intact key components (reactor vessel, cooling equipment, control instruments, back-up generators) is indispensable for the safe operation and/or shutdown of a nuclear reactor. For most of the existing global nuclear fleet, a reliable connection to the grid for power to run cooling systems and control instruments in emergency situations is another crucial item (IAEA, 2011). Several EWEs can damage the components or disrupt their interconnections. Preventive and protective measures include technical and engineering solutions (circuit insulation, shielding, flood protection) and adjusting operation to extreme conditions (reduced capacity, shutdown) (Williams and Toth, 2012).

Amongst the renewable energy sources, hydropower represents by far the largest share in the current energy mix. It is also projected to remain important in the future, irrespective of the climate change mitigation targets in many countries (IEA, 2010a)(IEA, 2010b). The resource base of hydropower is the hydrologic cycle driven by prevailing climate and geography (differences in elevation). The former makes the resource base and hence hydropower generation highly dependent on future changes in climate and related changes in extreme weather events(Ebinger and Vergara, 2011; Mukheibir).

Assessing the impacts of climate change on hydropower generation is the most complex endeavour in the energy sector. A series of non-linear and region-specific changes in mean annual and seasonal precipitation and temperatures, the resulting evapotranspiration losses, shifts in the share of precipitation falling as snow and the timing of its release from high elevation make resource estimates difficult (see Chapters 3 and 4) while regional changes in water demand due to changes in population, economic activities (especially irrigation demand for agriculture) present competition for water resources that are hard to project (see Section 10.3). Further complications stem from the possibly increasing need to combine hydropower generation with changing flood control and ecological (minimum dependable flow) objectives induced by changing climate regime.

Focusing on the possible impacts of CC on hydroelectricity and the adaptation options in the sector in response to the changes in the amount, seasonal and inter-annual variations of available water after changes in the resource base and other demands are accounted, the overall conclusion from the literature is that the impacts of CC and EWEs on hydropower generation is *likely* to be diverse across large global regions (increases in most, decreases in some), across watersheds within regions and even across river basins within watersheds. Planning tools for long-term hydrogeneration may need to be enhanced to cope with slow but persistent shifts in water availability, and short-term management models may need to be enhanced to deal with the impacts of EWEs. A series of hard (raising dam walls, add bypass channels) and soft (adjust water release) measures are available to protect the related infrastructure (dams, channels, turbines, etc.) and optimize incomes by timing generation when electricity prices are high (Mukheibir,).

Solar energy is expected to increase its currently negligible share in the global energy balance (see, for example, (IEA, 2008; IEA, 2009; IEA, 2009; IEA, 2010a; IEA, 2010b).. The three main types of technologies for harnessing energy from insolation include thermal heating (TH) (by flat plate, evacuated tube (aka vacuum) and unglazed collectors), photovoltaic (PV) cells (crystalline silicon (Si) and thin film technologies) and concentrating solar power (CSP) (power tower and power trough producing heat to drive a steam turbine for generating electricity). The increasing body of literature exploring the vulnerability and adaptation options of solar technologies to CC and EWEs is reviewed by (Patt, 2012).

All types of solar energy are sensitive to changes in climatic attributes that directly or indirectly influence the amount of insolation reaching them. Increasing cloudiness reduces the intensity of solar radiation and hence the output of heat (warm water) or electricity. Efficiency losses in cloudy conditions are less for technologies that can operate with diffuse light (evacuated tube collectors for TH, PV collectors with rough surface). Since diffuse light cannot be concentrated, CSP output would cease under cloudy conditions but the easy and relatively inexpensive possibility to store heat reduces this vulnerability if sufficient volume of heat storage is installed (Khosla, 2008; Richter *et al.*, 2009).

The exposure of sensitive material to harsh weather conditions is another source of vulnerability for all types of solar technologies. Windstorms can damage the mounting structures directly and the conversion units by flying debris, whereby technologies with smaller surface areas are less vulnerable. Hail can also cause material damage and thus reduced output and increased need for repair. Depending on regional conditions, strong wind can deposit sand and dust on the collectors' surface, reducing efficiency and increasing the need for cleaning.

CC and EWE hazards per se do not pose any particular constraints for the future deployment of solar technologies. Technological development continues in all three (TH, PV and CSP) solar technologies towards new designs, models and materials. One of the objectives of these development efforts is to make new models less vulnerable to current climate and EWEs. Technological development also results in a diverse portfolio of models to choose from according to the climatic and weather characteristics of the deployment site. These development efforts can be integrated in addressing the key challenge for solar technologies today: reducing the costs.

Harnessing wind energy for power generation is an important part of the climate change mitigation portfolio in many countries. Assessing the possible impacts of CC and EWEs on this technology and exploring possible adaptation options are complicated by the complex dynamics characterizing wind energy. Relevant attributes of climate are expected to change; the technology is evolving (blade design, other components; see (Barlas and Van Kuik, 2010)(Kong *et al.*, 2005); there is an increasing deployment offshore and a transition to larger turbines (Garvey, 2010) and larger sites (multi megawatt arrays) (Barthelmie et al., 2008).

The key question concerning the impacts of a changing climate regime on wind power is related to the resource base: how climate change will rearrange the temporal (inter- and intra-annual variability) and spatial (geographical distribution) characteristics of the wind resource. Pryor and Barthelmie (Pryor and Barthelmie, 2010) find that in the next few decades wind resources (measured in terms of multi-annual wind power densities) are estimated to remain within the ±50% of the values compared to the past 20 year mean values. The wide range of the estimates results from the circulation and flow regimes in different GCMs and regional climate models (RCMs)(Bengtsson *et al.*, 2006; Pryor and Barthelmie, 2010). A set of four GCM-RCM combinations for the period 2041-2062 indicates that average annual mean energy density will be within ±25% of the 1979-2000 values in all 50 km grid cells over the contiguous USA (Pryor and Barthelmie, 2012; Pryor *et al.*, 2011(a)). Yet little is known about changes in the inter-annual, seasonal or diurnal variability of wind resources.

Wind turbines already operate in diverse climatic and weather conditions. Engineering solutions have been developed to install the turbine design and material combination most suitable for the site conditions. As shown in Table 10-1, siting, design and engineering solutions are available to cope with various impacts of gradual changes in relevant climate attributes over the coming decades. The requirements to withstand extreme loading conditions resulting from climate change are within the safety margins prescribed in the design standards, although load from combinations of extreme events may exceed the design thresholds (Pryor and Barthelmie, 2012). In summary, the wind energy sector does not face insurmountable challenges resulting from climate change.

10.2.3. Transport and Transmission of Energy

Primary energy sources (coal, oil, gas, uranium), secondary energy forms (electricity, hydrogen, warm water) and waste products (CO_2, coal ash, radioactive waste) are transported in diverse ways to distances ranging from a few kilometres to thousands of kilometres. The transport of energy-related materials by ships (ocean and inland waters), rail and road are exposed to the same impacts of climate change as the rest of the transport sector (see Section 10.4). This subsection deals only with transport modes that are unique to the energy sector (power grid) or predominantly used by it (pipelines). Table 10-2 provides an overview of the impacts of CC and EWEs on energy transmission, together with the options to reduce vulnerability.

[INSERT TABLE 10-2 HERE
Table 10-2: Main impacts of CC and EWEs on pipelines and the electricity grid.]

Pipelines play a central role in the energy sector by transporting oil and gas from the wells to processing and distributing centres to distances from a few hundred to thousands of kilometres. With the spread of the carbon dioxide capture and storage (CCS) technology, another important function will be to deliver CO_2 from the capture site (typically thermal power plants) to the disposal site onshore or offshore. Pipelines have been operated for over a century in diverse climatic conditions on land from hot deserts to permafrost areas and increasingly at sea. This implies that technological solutions are available for the construction and operation of pipelines under diverse geographical and climatic conditions. Yet adjustments may be needed in existing pipelines and improvements in the design and deployment of new ones in response to the changing climate and weather conditions.

Pipelines will be mainly affected by secondary impacts of climate change: sea-level rise in coastal regions, melting permafrost in cold regions, and floods and landslides triggered by heavy rainfall. A proposed way to reduce vulnerability to these events is the amendment of land zoning codes, and the design and construction standards for new pipelines and structural upgrade for existing ones (Antonioni *et al.*, 2009) (Cruz and Krausmann, 2012).

Due to the very function of the electricity grid to transmit power from generation units to consumers, the bulk of its components (overhead lines, substations, transformers) are located outdoors and exposed to the vagaries of weather. The power industry has developed numerous technical solutions and related standards to protect those assets and to secure a reliable electricity supply under prevailing climate and weather conditions worldwide.

Higher average temperatures decrease transmission efficiency by about 0.4%/°C but this effect is relatively small compared to the physical and monetary damages that can be caused by EWEs (Ward, 2012). Historically, high wind conditions, including storms, hurricanes and tornados, have been the most frequent cause of grid disruptions (mainly due to damages to the distribution networks), and more than half of the damage was caused by trees (Reed, 2008). If the frequency and power of high wind conditions will increase in the future, vegetation management along existing power lines and rerouting new transmission lines along roads or across open fields might help reduce wind related risks.

The economic importance of a reliable transmission and distribution network is highlighted by the fact that the damage to customers tend to be much higher than the value of electricity not delivered (lost production and service delivery, decay of frozen or refrigerated food and other stocks). The economically efficient balance between the higher costs for the transmission and distribution companies and the benefits of lower fault frequency for the clients will be an outcome of technical standards, market regulation and possibly other arrangements depending on the type and degree of liberalization and deregulation of grid services.

10.2.4. Market Impacts

Most economic research related to climate change has focused on mitigation rather than the economic implications of climate change itself. Table 10-3 summarizes the recent studies on the economic implications of climate change and extreme weather impacts in the energy sector.

[INSERT TABLE 10-3 HERE
Table 10-3: Summary of recent literature on the economic impacts of climate change and extreme weather on the energy sector.]

Related studies have refined the understanding of the relationship between climate change and energy demand, albeit, comparing results across studies is challenging because they focus on different regions and regional divisions, examine different climate change impacts, include a different mix of sectors, model different timeframes, make different assumptions about adaptation, and employ different types of models with different output metrics. Despite the many differences among the studies, the overall conclusion from the literature to date is that the macroeconomic impact of climate change on energy demand is likely to be moderate in developed countries(Aaheim *et al.*, 2009; Bosello *et al.*, 2007; Bosello *et al.*, 2009; Eboli *et al.*, 2010a; Jochem *et al.*, 2009; Jochem *et al.*, 2009). The current literature sheds less light on the implications for developing countries and on other climate impacts in the energy sector.

Europe is the focus of most of the literature so far. Little analysis has been done in developing countries. Asia, Africa, and Latin America are not well represented, appearing in only two global studies. The limited results indicate that developing countries, which are more vulnerable to rising temperatures, sea-level rise, etc., likely face a greater negative GDP impact with respect to climate change implications for the energy sector than developed countries (Aaheim *et al.*, 2009; Boyd and Ibarraran, 2009; Eboli *et al.*, 2010a).

Despite the considerable number of potential climate change and extreme weather impacts on the energy sector – higher mean temperatures, changes in rainfall patterns, changes in wind patterns, changes in cloud cover and average insolation, lightning, high winds, hail, sand storms and dust, extreme cold, extreme heat, floods, drought, and sea-level rise (Williams and Toth, 2012) – the range of impacts modeled in the literature (Table 10-3) is quite narrow. Most studies consider changing energy demand resulting from rising temperatures as the only or primary climate change impact. These studies draw upon recent literature refining the relationship between climate change and energy demand: the demand for natural gas and oil in residential and commercial sectors tends to decline with climate change because of less need for space heating, and demand for electricity tends to increase because of greater need for space cooling (Gabrielsen *et al.*, 2005; Gabrielsen *et al.*, 2005; Gunnar and Torben, 2010; Kirkinen *et al.*, 2005; Mansur *et al.*, 2005; Mideksa and Kallbekken, 2010)(Rübbelke and Vögele, 2010).

Studies using a computation general equilibrium (CGE) model that consider only climate impacts in the energy sector find that the effect on GDP in 2050 is quite modest at -0.3% to 0.03% (Bosello et al. 2007) and -1.3% to -0.6% (Jochem *et al.*, 2009). These findings are largely consistent despite the fact that (Bosello *et al.*, 2009)(Bosello *et al.*, 2007) are global studies that models only the change in demand due to rising temperatures, whereas (Jochem *et al.*, 2009) focus on the EU and models the change in demand plus six other climate impacts. Had the studies focused on the same regions and considered the same climate implications, the results could conceivably diverge

Studies using CGE models that examine the aggregate changes in GDP brought on by climate impacts in energy and several other sectors have also primarily found moderate shifts in GDP. (Aaheim *et al.*, 2009) conclude that in 2100 in cooler regions in the EU, GDP changes by -1% to -0.25% and in warmer regions changes by -3% to -0.5%. (Boyd and Ibarraran, 2009) project a -3% change in GDP in 2026 for Mexico, consistent with the warmer regions modeled by Aaheim et al. Roughly consistent with (Aaheim *et al.*, 2009; Eboli *et al.*, 2010a) summarize GDP impacts for the predominantly cooler regions of Japan, the EU, EEFSU, and Rest of Annex I as having a “significant positive impact”, while the predominantly warmer regions of the USA, EEx (China/India, Middle East/Most of Africa/Mexico/parts of Latin America), and the Rest of the World have a “significantly negative impact.” (Jorgenson and Goettle, 2004) find that overall GDP impacts are -0.6% to 0.7% in 2050 for the United States, which stands in contrast to (Eboli *et al.*, 2010a) with a “significantly negative impact“ in the United States.

Several CGE studies attempt to evaluate how adaptation changes in the energy sector impact GDP but do not examine specific adaptation options since CGE models lack the necessary technological detail. They make general assumptions about the effectiveness of adaptation policy in reducing climate impacts. (Jorgenson and Goettle, 2004) find that pessimistic assumptions about adaptation imply a 0.6% reduction in GDP in 2050 but optimistic assumptions lead to a 0.7% gain in GDP. (Aaheim *et al.*, 2009) conclude that adaptation can mitigate the costs of climate change by 80% to 85%, and (Boyd and Ibarraran, 2009) find that adaptation can shift a 3% GDP loss in 2026 in Mexico to a gain in GDP of 0.33%.

Partial equilibrium models, by their nature, do not have a full macroeconomic representation and therefore do no report changes in GDP (exceptions are models that include a simple GDP feedback mechanism or reduced form econometric GDP model). Instead, these models focus on details in the energy sector, such as price and quantity effects for fuels and electricity (and the mix of generation). (Golombek *et al.*, 2012) report a 1% increase in the price of electricity for Western Europe in 2030 stemming from rising temperatures that affect demand and thermal efficiency of supply, as well as water inflow. (Gabrielsen *et al.*, 2005)conclude that for Nordic countries in 2040, as a result of rising temperatures that affect demand, changes in water inflow, and changes in wind speeds, the price of electricity will decline by 1%. Although the change in price differs in sign, the magnitude of change is small in both studies. In contrast, (Bye *et al.*, 2006)in looking at a hypothetical water shortage scenario in Nordic countries, conclude that the price of electricity can double over a 2 year period and then return to normal as water flow returns. (DOE, 2009) also finds that a drought scenario can lead to average monthly electricity prices that are 8.1% (November) to 24.1% (July) higher. In contrast to the significant price impacts found by (Bye *et al.*, 2006) and (DOE, 2009). (Koch *et al.*, 2012) conclude that thermal plant outages in Berlin resulting from heat wave-driven water temperatures that exceed regulatory limits can amount to a cumulative cost of 60 million EURO over the period 2010 through 2050 for 2850 MW of capacity. Assuming an 80% capacity factor, the premium for high water temperatures in Berlin is 0.075 EURO per MWh.

10.2.5. Summary

The balance of evidence emerging from the literature assessed in this section suggests that climate change per se will increase the demand for energy in most regions of the world. At the same time, increasing temperature will decrease the thermal efficiency of fossil, nuclear and solar power generation, the potential and dependability of hydropower, etc. However, temperature-induced impacts will make a relatively small contribution to the overall increase in demand for energy and electricity. Similarly, CC impacts on energy supply will be part of an evolving picture dominated by technological development in the pursuit for safer, cheaper and more reliable energy sources and technologies.

Given the limitations in the literature, sweeping conclusions about results may be premature on macroeconomic implications. However, some narrow conclusions are possible. The change in GDP due to temperature-induced changes in energy demand – even if combined with other climate impacts – is relatively small in all of the studies. The highest reported increase in GDP is 1.2% (Bosello *et al.*, 2009), and the greatest decrease is -3% (Aaheim *et al.*, 2009). (Jochem *et al.*, 2009)which is the most detailed and comprehensive study, report only a 1.3% drop in GDP in 2050 due to at least seven climate impacts in the energy sector. The GDP impact in warmer regions tends to be greater than in cooler regions, which benefit from less need for space cooling ((Aaheim *et al.*, 2009; Jochem *et al.*, 2009). Similarly, Eboli et al. (Eboli *et al.*, 2010a) found that the overall economic impact for developing countries is negative while for developed countries is positive. Adaptation can lower the cost of climate change, but these results may be driven largely by assumption since specific policies have not been modeled. Results from some of the partial equilibrium models suggests that CGE modeling studies, which largely focus on changes in energy demand, may be neglecting some potentially costly impacts from extreme weather events like drought, which, if modeled, may lead to greater GDP impacts than reported thus far in the literature.

Much research is still needed to understand the implications of climate change and extreme weather on the energy sector and to identify cost-effective adaptation options. The best understood area is the implications of climate on energy demand. A comprehensive evaluation of a full range of supply-side climate change impacts and adaptation options as outlined in Williams (Williams and Toth, 2012) is needed. This information will help modelers make much better, empirically-based assumptions about the relationship of climate impacts and the economy, as well as about the effectiveness of adaptation options. Expanding research into developing countries is also much needed, as developing countries are more vulnerable to climate change impacts and likely face more significant economic implications.

10.3. Water

This section focuses on economic aspects of climate change and adaptation in water related economic sectors. The biophysical water system, including infrastructure, is assessed in Chapter 3.

We qualitatively assess climate change impacts, costs and benefits, to individual economic sectors that utilize water resources as an input to production and/or mechanism for waste disposal, costs to adapt to these impacts, and the costs to public and private infrastructure of climate change impacts and adaptation due to flooding.

10.3.1. Water-Related Damages

Between the 1950s and the 1990s, the annual economic losses from large extreme events, including floods and droughts, increased tenfold, with developing countries being hardest hit (Kabat et al., 2003). Over the past few decades, flood damage constitutes about a third of the economic losses inflicted by natural hazards worldwide (Munich Re, 2005). The economic losses associated with floods worldwide have increased by a factor of five between the periods 1950-1980 and 1996-2005 (Kron and Bertz, 2007). From 1990 to 1996 alone, there were six major floods throughout the world in which the number of fatalities exceeded 1,000, and 22 floods with losses exceeding US$1 billion each (Kabat et al., 2003). Although these increases are primarily due to several non-climatic drivers, climatic factors are also partly responsible (Kundzewicz et al., 2007).

Most of the studies examining the economic impacts of climate change on the water sector have been carried out at the local, national, or river-basin scale; and, the global distribution of such studies is skewed towards developed countries (e.g., Chen et al., 2001; Choi and Fisher, 2003; Dore and Burton, 2001; Evans et al., 2004; Hall et al., 2005; Kirshen et al., 2005, 2006; Middelkoop et al., 2001; Schreider et al., 2000). In other studies, the economic impacts of climate variability on floods and droughts in developing countries were reported as substantial. For example, the cost to Kenya of two extreme events, namely the floods associated with the 1997/8 El Niño event and the drought associated with the 1998-2000 La Niña event, show a cost to the country of 11% of its GDP for the former, and 16% of GDP for the latter (World Bank, 2006a). According to (World Bank, 2006a), floods and droughts are estimated to cost Kenya at mid-century about 2.4% of its GDP annually, and water resources degradation a further 0.5%. For Ethiopia, economy-wide models incorporating hydrological variability show a drop in projected GDP growth by up to 38% compared to when hydrological variability is not included (Mogaka et al., 2006). However, it is not hydrological variability per se that causes the problem, but rather an extreme vulnerability to it due a lack of the necessary capacity, infrastructure, and institutions to mitigate the impacts (Grey and Sadoff, 2007). Similarly, future flood damages will depend not only on changes in the climate regime, but also on settlement patterns, land use decisions, flood forecasting quality, warning and response systems, and other adaptive measures (Ward *et al*., 2008) (e.g., Andréassian, 2004; Calder, 1993; Changnon, 2005; Mileti, 1999; Pielke and Downton, 2000; Ward and Robinson, 1999; WCD, 2000). In many developing countries, water related impacts are *likely* to be more pronounced with climate change (Chapter 3) and associated economic costs can be expected to be more substantial in the future, holding all other factors constant.

The Association of British Insurers (ABI) estimated the financial costs of climate change through its effects on extreme storms (hurricanes, typhoons, and windstorms) by using insurance catastrophe models in the UK and across Europe. They found that climate change could increase the annual cost of flooding in the UK almost 15-fold by the 2080s under high emission scenarios. If climate change increased European flood losses by a similar magnitude, they estimate that costs could increase by up to $120 – 150 billion, for the same high emission scenarios (ABI, 2005).

(Ward *et al*., 2008) found the average annual costs of adaptation for riverine flood protection for low- to upper-middle-income countries to range from $3.5 to $6.0 billion per year over the period 2010–50, but do not consider the damages that would be caused by flood events with longer return periods.

10.3.2. Municipal and Industrial Water Supply

At the local, national, and river basin level, the costs of adaptation to maintain supply, infrastructure and quality of water for municipal and industrial uses and treatment have been reported for the Assabet River near Boston (Kirshen et al., 2006), Toronto (Dore and Burton, 2001) and Quito, as a result of glacier retreat (Vergara et al., 2007). Since much of this infrastructure has an economic and engineering life of less than 25 years, building flexibility into these systems is in most cases the best action now.

In sub-Sarahan Africa, Muller (2007) estimated the costs of adapting urban water infrastructure to climate change to be USD 2-5 billion per year. The costs of adapting existing urban water storage facilities are estimated at $50-150 million/year, and the costs of additional new developments are estimated at $15-50 million/year. For wastewater treatment, the adaptation costs of existing facilities are estimated at $100-200 million/year, and the costs of additional new facilities are estimated at $75-200 million/year.

In the U.S., relative impacts are small, less than 1% of municipal and industrial welfare (Hurd et al 2004).
On a global scale, Ward et al 2010 estimate the adaptation costs to provide enough raw water to meet future global industrial and municipal water demand, based on country-level demand projections to 2050. Increased demand is assumed to be met through a combination of increased reservoir yield and alternative backstop measures. The global adaptation costs are estimated to be US$12B/yr (on top of US$73B/yr to meet the needs of development), with 83-90% in developing countries; the highest costs are in Sub Saharan Africa, and may be as high has 16% of global adaptation costs. The global cost estimates (developing and developed countries combined) of climate-change

related adaptation in the water resources sector amount to 0.04–0.06 percent of world GDP. The costs to bring developing countries millennium goals standards are significantly higher than climate change impact costs, but still low (0.33 percent of GDP).

10.3.3. Wastewater and Urban Stormwater

More frequent heavy rainfall events associated with increased climate variability may overload the capacity of sewer systems and water and wastewater treatment plants more often. Increased occurrences of low flows will lead to decreased contaminant dilution capacities, and therefore higher pollutant concentrations. Hughes, et al 2010 estimate the average annual costs of adaptation for the A2 scenario and 17 Global Circulation Models for urban sewers for low- to upper-middle-income nations at $3.0 billion per year over the period 2010–50. Price et 2010 estimate for Canada the cost of building and maintaining additional storm water storage capacity necessary to manage the additional runoff associated with anticipated intensity of 100-year, 24-hour storms at between $140 million to $2 billion present value from 2010 to 2100 with a 3% discount rate. In a similar analysis for 19 major USA cities, Price et al 2011 estimate the increase in annual cost from the changes in the 10-year, 24-hour storm for Los Angeles in 2100 is $135 million, Boston $7 million and Chicago $40 million.

10.3.4. Energy: Hydropower and Cooling Water

Hurd et al 2004, looking at intersectoral competition for water using a set of partial equilibrium river basin models, estimate that for the USA welfare loses associated with climate change induced thermal cooling water changes to be as great as $622 million per year, equivalent to 6.5 % welfare loss in the energy sector. Awadala et al 2012 found that in the southeastern USA, a coal fired once-through cooled powerplant facing summertime temperature increases of 2 degree coupled with a 10% decrease in streamflow would results in a reduction of electric of 50%? over the summer months due to river temperature regulations.

Block et al 2010 find that for Ethiopia, adaption to climate change to maintain hydropower output from 2010 to 2050 would mean an increase of 4% of capital cost under the most severe dry scenario and a reduction of 3% under the extreme wet scenario. Strzepek et al 2012 show that in the Zambezi river basin a reduction in firm hydropower of just over 10 percent basin-wide by 2030, and by 35 percent basin-wide by 2050 occurs under the driest scenario. Fant, et al 2012 using a uncertainty approach found for the Zambezi hydropower system that decreased energy generation is *likely* in the upstream powerstations of the basin and increases are likely in downstream powerstations.

10.3.5. Inland Navigation

Inland navigation is discussed in 10.4.4.

10.3.6. Irrigation

Fischer et al 2007 analyze the additional global irrigation water required under various climate change scenarios and the associated costs. The cost of supplying water from different sources, investment in irrigation equipment, facilities, land improvement, and computer technology; maintenance and repair, and labor were included, as were additional pumping and energy cost, water price, operation and maintenance, and labor. Additional capital costs of increasing irrigation on already irrigated land were assumed to be minimal. By 2080, the global annual costs of additional irrigation water withdrawals for existing irrigated land caused by climate change are estimated at $24–27 billion. Benefits of climate mitigation are small or even negative up to around 2040, but amount to some $8–10 billion annually by 2080.

Nelson et al 2010 estimate that the global cost of improved irrigation efficiency to adapt to climate change in 2050 to maintain current climate project yields in developing countries to be between $1.5 and 2.0 billion dollar per year.

Strzepek, et al 2010 find that adaptation for Ethiopia to maintain agricultural production at non-climate change level would be best achieved by soil water management from increased irrigated and drained areas, improved irrigation efficiency and research related to on-farm practices. The range of costs for these adaptions was from $68 million per year for the dry scenario dominated by irrigation to $71 million per year under the wet scenario dominated by installation of agricultural drainage.

10.3.7. Nature Conservation

Climate change is expected to worsen many forms of water pollution, including the load of sediments, nutrients, dissolved organic carbon, pathogens, pesticides, and salt, as well as thermal pollution, as a result of higher water temperatures, increased precipitation intensity, and low flow periods (Kundzewicz et al., 2007). Future water demands for nature conservation will be different than today's (see Chapter 4). There is no published assessment of the economic implications.

10.3.8. Recreation and Tourism

The impact of climate-change-induced change in water resources on tourism and recreation are discussed in Section 10.6. Tourism and recreation use substantial amounts of water but the implications of climate-change-induced changes in tourism and recreation on water demand have yet to be quantified.

10.3.9. Water Management and Allocation

Changes of water availability, demand and quality associated with climate change are anticipated to impact water management and allocation decisions. Traditionally, water managers and users have relied on historical experience when planning water supplies and distribution (Adger et al. 2007, UNFCCC, 2007). Water has been allocated based on societies' social and economic preferences. Under a changing climate, existing allocations may no longer be optimal, socially or economically. Arndt et al 2012 has examined the economy-wide implications of existing water allocations as well examined alternative development paths (with water allocation implications) to suggest climate-smart development strategies in Africa. Under stress situations, allocations of water for energy-generation and irrigation may have economy-wide welfare implications (Strzepek,et al 2012).

10.4. Transport

The issue of climate change in the transport sector is one that has received qualitative, but limited quantitative, focus in the published literature. The impact of climate change on transportation depends greatly on the climatic zone the infrastructure is in and how climate change will be manifest. There are three major zones that face the effects of climate change on the array of transportation areas.

Geographic Zone	Vulnerabilities to Changes in Climate
Freezing/Frost Zone	Permafrost, freeze-thaw cycles, precipitation intensity
Temperate Zone	Change in Precipitation intensity, maximum daily precipitation
Tropical Zone	Change in Precipitation intensity, maximum daily precipitation

As detailed below, several studies have actively explored the potential impacts of climate change on the transport sector, focusing on overall impacts such as impacts on transportation safety or disruptions of transportation service. Initial quantitative, economic analyses of the impact on the physical infrastructure include (Larsen *et al*., 2008) and (Chinowsky et al 2010, 2011). (Hallegatte and Ghil 2008) provide insights to the role of the transport sector in natural disasters, but does not center on the sector itself. Additionally, work is in the early stages on the economy-wide impacts of climate change impacts on the efficiency of transportation services and increased investments in the sector (Arndt et al, 2012).

10.4.1. Roads

Studies on the effects of climate change on road networks are primarily focused on qualitative predictions concerning road impacts on both safety and road durability (TRB 2008; Galbraith et al 2005; AUSTROADS 2004). Paved road degradation is directly related to weather stressors that can lead to softening of the pavement as temperatures exceed design thresholds (Lavin 2003) and, an increase in the number of freeze-thaw cycles impacts both the base and pavement surface (FHWA 2006).

Warming and the melting of permafrost in northern climates as well as increased precipitation and flooding threaten the integrity of road base and sub-bases. Drainage presents a specific problem for urban areas that experience precipitation events that are above their built environment capacity (Hunt and Watkiss, 2010; Chicago Climate Action Plan: Our City, our Future,). Projected changes in intensity of precipitation will impact design standards for urban transport (Climate Change Impacts and Adaptation: A Canadian Perspective, 2010).

Unpaved roads are vulnerable to a number of climate-based factors especially to increasing in intense precipitation events, leading to wash out and disruption of the service. In cold climates, temporary winter roads are susceptible to warming and associated lower connectivity of rural areas and reduced economic activity in Northern climates (Mills and Andrey 2002). Warming impacts on ice roads, maintained over bodies of water, place in doubt the ability to maintain these roads for the current usage cycles, raising economic concerns.

10.4.2. Rail

Rail beds are susceptible to increases in precipitation, sea level rise, extreme events and incidence of freeze-thaw cycles. In Northern climates, the melting of permafrost (Adapting Energy, Transport, and Water Infrastructure to the Long-Term Impacts of Climate Change, Summary Report, 2010) may lead to ground settlement, undermining stability (Larsen *et al*., 2008). Increased temperatures pose a threat to rail integrity. In urban areas, increased temperatures pose a threat to underground transport systems that will see a burden on increased need for cooling systems (Hunt and Watkiss, 2010). In London, £178 million has been allocated to finding a workable solution for increasing the capacity of the Tube's underground cooling system (Arkell and Darch G.J.C., 2006).

10.4.3. Pipeline

Increases in precipitation and temperature affect pipelines through scouring of base areas and unearthing of buried pipelines, compromised stability of bases built on permafrost, and increases in necessary maintenance (Potential Impacts of Climate Change on U.S. Transportation: Transportation Research Board Special Report 290, 2008; Adapting Energy, Transport, and Water Infrastructure to the Long-Term Impacts of Climate Change, Summary Report, 2010). Temperature increase can result in thermal expansion of the pipelines, causing cracking at material connection points. There has been no economic assessment of the impacts.

10.4.4. Shipping

Inland navigation impacts from climate change vary widely due to projected rise or fall in water levels. Overall, the effects on inland navigation are projected to be negative, and are region-specific.

In areas such as the Rhine Basin, projected prolonged periods of low flow will increase the number of days during which inland navigation is hampered or stopped. (Middelkoop *et al*., 2001) examine climate change impacts on inland navigation on the Rhine. Increased frequency of flood periods will stop ship traffic more often. Longer periods of low flow will also increase the average annual number of days during which inland navigation is hampered or stagnates due to limited load carrying capacity of the river. Current projects on channel improvements can only partly alleviate these problems. Economic impact could be substantial given the value of navigation on the Rhine.

(Millerd, 2010) analyzes the economic impacts of lower water levels in the Great Lakes, with consequent reductions in vessel cargo capacities and increases in shipping costs. The lower water levels predicted as a result of a doubling of the atmospheric concentration of carbon dioxide could increase annual transportation costs by 29 percent, more moderate climate change could result in a 13 percent increase in annual shipping costs, based on current prices. The impacts vary between commodities and routes.

Warming is *very likely* to lead to increased ice-free navigation and longer shipping season, but *is very likely* also lead to lower water levels from reduced runoff (Climate Change Impacts and Adaptation: A Canadian Perspective, 2010). In Northern regions, increased days of ice-free navigation and a longer shipping season could positively impact shipping and reduce transportation costs (Koetse, et al, 2009; UNCTAD 2009, United Nations 2010;TRB 2008).

Ports will be affected by climatic change events including increased temperatures, sea level rise, increased severe storm events, and increased precipitation. The total assets of 136 of the world's largest port cities were examined and over $3 trillion in assets were deemed vulnerable to weather events (United Nations 2010; UNCTAD 2009; Potter, et al, 2008).

Increased storminess in certain routes may affect safety considerations and raise cost of shipping through requiring additional safety measures or longer routes that are less prone to severe events (Maritime Transport and the Climate Change Challenge, Summary of Proceedings, 2009; Note by the united nations economic commission for europe and united nations conference on trade and development secretariats. In: 2010). In ports where storms disrupt supply chains by destroying port infrastructure, delaying through debris or soil deposits, or affects connecting road or rail infrastructure for transportation of goods, transport costs will increase and/or new routes will be sought, creating modal or geographic shifts in transportation (Becker *et al*., 2011). Increased storminess may also affect passage through lock systems, increasing weather-related delays and raising costs (Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I, 2008; Maritime Transport and the Climate Change Challenge, Summary of Proceedings, 2009). Increased storminess may increase maintenance costs for ships and ports and result in more frequent weather-related delays.

10.4.5. Air

Hotter air is less dense. In summer months, especially at airports located at high altitudes or with extreme temperatures, this will result in limitations for freight capacity, safety, and weather-related delays (Potential Impacts of Climate Change on U.S. Transportation: Transportation Research Board Special Report 290, 2008; Pejovic *et al*., 2009). Hotter air requires less cargo or longer runways. (Chapman, 2007) suggests that technological innovations will negate the challenges posed by extreme temperatures Increased storminess at airports, particularly those located in coastal regions, may increase the number of weather-related delays and cancellations (Climate Change Impacts and Adaptation: A Canadian Perspective, 2010; Pejovic *et al*., 2009), with associated economic losses.

Airport pavement studies relating to climate change have shown these effects to be very similar to paved roads (DOT 2002; Fortier, et al). Therefore the effect of temperature on airports is not restricted to runways, but rather imposes a risk on the entire facility (Pejovic *et al*., 2009).

10.5. Other Primary and Secondary Economic Activities

This section assesses the impact of climate change on primary (agriculture, mining) and secondary economic activities (manufacturing, construction), unless they are discussed elsewhere in the chapter or the report.

10.5.1. Primary Economic Activities

Primary economic activities (e.g. agriculture, forestry, fishing, mining) are particularly sensitive to the consequences of climate change because of their immediate dependence on the natural environment. In some regions, these activities dominate the economy.

10.5.1.1. Crop and Animal Production

Chapter 7 assesses the impact of climate change on agriculture, including the effects on (international) markets for crops.

10.5.1.2. Forestry and Logging

Chapter 4 assesses the biophysical impact of climate change on forestry, but does not address the economic effects. (Sohngen and Mendelsohn, 1997; Sohngen and Mendelsohn, 1998; Sohngen *et al.*, 2001) develop an integrated biophysical-economic model of forestry and the world market for forestry products. Including adaptation in forest management, they find that climate change would accelerate tree growth. This would reduce prices to the benefits of consumers all around the world. Low to mid latitude producers would benefit too as they switch to short-rotation plantations. Mid to high latitude producers would be hurt by lower prices while their productivity increases only modestly. Other studies reach very similar conclusions (Adaptation of Forests and People to Climate Change -- A Global Assessment Report, 2009; Lee and Lyon, 2004; Perez-Garcia *et al.*, 2002).

10.5.1.3. Fisheries and Aquaculture

Chapter 4 assesses the impact of climate change on freshwater ecosystems, and Chapter 5, 6 and 30 on marine ecosystems. These assessments include the effects on commercially valuable fish stocks, but exclude the effects on markets.

Climate change impact the commercial fishing process through fish stock, capital, labour and enterprise, technological changes, prices and management practices (Link and Tol, 2009; Yazdi and Fashandi, 2010). (Allison *et al.*, 2009), using an indicator based approach, analyzed the vulnerability of capture fishery of 132 economies. They find, incongruously, that the precise impacts and direction of climate-driven change for particular fish stocks and fisheries are uncertain but are likely to lead to either increased economic hardship or missed opportunities for development in countries that depend upon fisheries but lack the capacity to adapt.(Floc'h *et al.*, 2008), for the Bay of Biscay fisheries, analyze the market position and its evolution in nine key fish and cephalopod species and find that a major part of the gross turnover remains potentially unaffected by long-term changes related to climate. On the other hand, (Garza-Gil *et al.*, 2011) find a decline in Iberian-Atlantic sardine biomass and profitability due to climate change. The economic impact of climate change on fisheries is dominated by the impact of management regime and market (Eide and Heen, 2002; Eide, 2008; McGoodwin, 2007; McIlgorm, 2010; Merino *et al.*, 2010). There are two handfuls of studies, recently published or at the final stages of peer-review, on the economic impact of ocean acidification. These will be assessed in the next draft.

10.5.1.4. Mining and Quarrying

Climate change would affect exploration, extraction, production, and shipping processes in the mining and quarrying industry (Pearce *et al.*, 2011). An increase in climate-related hazards (such as forest fires, flooding, windstorm and likes) affects the viability of mining operations and potentially increases operating, transportation, and decommissioning costs. Most infrastructure was built based on presumption of a stable climate, and is thus not adapted to climate change (Ford *et al.*, 2010; Ford *et al.*, 2011; Pearce *et al.*, 2011).

10.5.2. Secondary Economic Activities

10.5.2.1. Manufacturing

Climate change would impact manufacturing through three channels. First, climate change affects primary economic activities (see above), and this means that prices and qualities of inputs are different. Second, the production process is affected, or the quality of the product. The impact of climate change on energy demand is well understood (see 10.2). Using a biophysical model of the human body, (Kjellstrom *et al*., 2009a) project labour productivity to fall, particularly of manual labour in humid climates. (Hsiang, 2010) corroborate this with a statistical analysis of weather data and labour productivity in the Caribbean for 1970-2006. Some manufacturing activity is location specific, perhaps because it is tied to an input or product market, and will thus have to cope with the current and future climate; other manufacturing has discretion over its location (and hence its climate). Third, climate change affects the demand for products. This is pronounced in manufactures that supply primary sectors (Kingwell and Farré, 2009) and construction material (see below). Unfortunately, there is no literature that quantifies these effects (see Appendix B).

10.5.2.2. Construction and Housing

Climate and climate change affect construction in three ways. First, weather conditions are one of the key factors in construction delays and thus costs. Climate change would change the length of the building season. Additionally, precipitation affects the cost of construction through temporary flood protection (coffer) structures, slope stabilization management and dewatering of foundations. There are adaptation measures that may reduce some of the costs. (Apipattanavis *et al*., 2010)develop a probabilistic operational tool that shows a reduction in the expected value of road construction delays and associated costs. Second, buildings and building materials are designed and selected to withstand a particular range of weather conditions. As climate changes, design standards will change too. Exterior building components including windows, roofing, and siding are all specified according to narrow environmental constraints. Climate change would introduce conditions that are outside the prescribed operating environment for many materials, resulting in increased failures of window seals, increased leaks in roofing materials, and reduced lifespan of timber or glass-based cladding materials. Similarly, the interior building systems that allow for proper airflow in a facility face significant issues with climate change. For example, the increases in temperature and precipitation will lead to increased humidity as well as indoor temperatures. These increases require increased airflow in facilities that were designed to be temperature controlled such as hospitals, schools, and office buildings. However, these changes will require upgrades to air conditioning and fan units to ensure the capacity is available to meet environmental conditions. These upgrades will require renovations that may be significant in scope and cost. Third, a change in the pattern of natural disasters would imply a change in the demand for rebuilding and repair. Unfortunately, these impacts have yet to be quantified.

10.6. Recreation and Tourism

Recreation and tourism is one of the largest sectors of the world economy. It accounts for a substantial share of consumer spending in rich countries, and employs many people. Supply of tourism services is the dominant activity in many regional economies.

Recreation and tourism encompass many activities, some of which are more sensitive to weather and climate than others: compare sunbathing to angling, gambling, business seminars, family visits, and pilgrimage. Climate change would affect the place, time and nature of these activities.

There is a large literature on the impact of climate change on tourism. Some studies focus on the changes in the behavior of tourists, that is, the demand for recreation and tourism services (see 10.6.1). Other studies look at the implications for tourists resorts, that is, the supply of recreation and tourism services (see 10.6.2). A few studies consider the interactions between changes in supply and demand (see 10.6.3).

10.6.1. Recreation and Tourism Demand

Conventionally, recreation does not involve an overnight stay whereas tourism does. That implies that recreation, unlike tourism, is done close to home. Whereas tourists, to a degree, chose the climate of their holidays, recreationists do not (although climate is a consideration in the choice where to live). Tourists would adapt to climate change by changing the location, timing and activities of their holidays; recreationists would adapt only timing and activities (Smith, 1990).

10.6.1.1. Recreation

There has been no research on systematic differences of recreational behaviour due to differences in climate. The impact of climate change on recreation is therefore unknown. The economic impact is probably limited, as people are more likely to change the composition rather than the level of their time and money spent on recreation. For instance, (Shaw and Loomis, 2008) find a probable increase, due to climate change, in boating, golfing and beach recreation at the expense of skiing.

There are case studies of the impact of climate change on recreation.(Dempson *et al.*, 2001) note that the salmon fishery in Newfoundland is closed during hot weather and low water levels. (Ahn *et al.*, 2000) study the impact of climate change on recreational trout fishing in the Southern Appalachian Mountains. (Whitehead *et al.*, 2009) study the effect of sea level rise on sea shore fishing in North Carolina. Both studies find a substantial decrease in the value recreationists would derive from these activities – so much so that one could expect people to adopt other ways of enjoying themselves. Such alternatives were excluded from the studies. Similarly, (Daugherty *et al.*, 2011) conclude that climate change will make it more difficult to guarantee adequate water levels for boating and angling in artificial reservoirs – but do not study what recreationists would do instead. (Pouta *et al.*, 2009) project a reduction in cross-country skiing in Finland, particularly among women, the lower classes, and urban dwellers. (Shih *et al.*, 2009) find that weather affects the demand for ski lift trips. There are positive effects too. (Richardson and Loomis, 2005) find that climate change would make trips to the Rocky Mountain National Park more enjoyable. (Scott and Jones, 2006; Scott and Jones, 2007) foresee an increase in golf in Canada due to climate change, (Kulshreshtha, 2011) sees positive impacts on Canadian recreation in general, and (Coombes *et al.*, 2009) predict an increase in beach tourism in East Anglia; but none of these studies accounts for budget constraints on time or money.

Some studies incorrectly claim to assess the impact of climate change. Some studies confuse weather and climate. (Graff Zivin and Neidell, 2010) find that people recreate indoors when the weather is inclement. (Scott *et al.*, 2007) estimate the relationship between visitors to Waterton Lakes National Park and *weather* variables for eight years of monthly observations; and use this to project an increase in visitor numbers due to *climate change*. A survey among current visitors indicates that a deterioration of the quality of nature would reduce visitor numbers. (Taylor and Ortiz, 2009) show that domestic tourists in the UK often respond to past weather. The hot summer of 2003 had a positive impact on revenues of the tourist sector. Other studies suffer from selection bias. (Denstadli *et al.*,) find that tourists in the Arctic do not object to the weather in the Arctic. (Gössling *et al.*, 2006) reaches the same conclusion for tourists on Zanzibar.

10.6.1.2. Tourism

Climate (Becken and Hay, 2007; Besancenot, 1989; Braun *et al.*, 1999; Gossling and Hall, 2006; Gómez Martín, 2005; Hall, 2005; Wall and Badke, 1994; WTO and UNEP, 2008) and weather (Agnew and Palutikof, 2006; Garbas, 2006; Lohmann and Kaim, 1999; Rossello, 2011; Rosselló-Nadal *et al.*, 2010; Álvarez-Díaz and Rosselló-Nadal, 2010) are important factors in tourist destination choice. (Eijgelaar *et al.*, 2010), for instance, argues that so-called “last chance tourism” is a strong pull for tourists to visit Antarctica to admire the glaciers while they still can. (Farbotko, 2010) uses a similar mechanism to explain the rise in popularity of Tuvalu as a destination choice.

(Maddison, 2001) estimates a statistical model of the holiday destinations of British tourists. (Lise and Tol, 2002) replicate this for Dutch tourists and (Bigano *et al.*, 2006) for tourists from 45 countries. Tourists have a clear preference for the climate that is currently found in Southern France, Northern Italy and Northern Spain. People from hot climates care more about where they spend their holidays than people from cool climates.

However, whereas (Bigano *et al.*, 2006) find regularity in revealed preferences, (Scott *et al.*, 2008b) find pronounced differences in stated preferences between types of people. The impact of climate change on tourism demand may be more complicated than suggest by the econometric analyses reviewed above (Gössling and Hall, 2006).

(Bigano *et al.*, 2007; Hamilton *et al.*, 2005a; Hamilton *et al.*, 2005b) use the above econometric analyses to construct a simulation of domestic and international tourism. (Hamilton and Tol, 2007) downscale the national results of these studies to the regions of selected countries. The advantage of such a model is that it considers the simultaneous change in the attractiveness of all potential holiday destinations. The disadvantage is its stylized representation of the effect of climate on destination choice. Two main findings emerge. First, climate change would drive tourists to higher latitudes and altitudes. International tourist arrivals would fall, relative to the scenario without warming, in hotter countries, and rise in colder countries. Tourists from Northwestern Europe, the main origin worldwide of international travelers at present, would be more inclined to spend the holiday in their home country, so that the total number of international tourists falls. Second, the impact of climate change is dominated by the impact of population growth and, particularly, economic growth. In the worst affected countries, climate change slows down, but nowhere reverses, growth in the tourism sector.

10.6.2. Recreation and Tourism Supply

There are a number of so-called biometeorological studies of the impact of climate change on tourism. (Yu *et al.*, 2009a) construct a Modified Climate Index for Tourism and apply it to fifty years of past data for Alaska and Florida. They find that Alaska has become more attractive, and Florida less attractive to tourists. (Yu *et al.*, 2009b) use the same approach to conclude that the climate for sightseeing has improved in Alaska, while the climate for skiing has deteriorated. (Scott *et al.*, 2004) use a similar index. Climate change would make Mexico less attractive to tourists, and Canada more attractive. Florida and Arizona would lose market share in US tourism. (Perry, 2006) notes that the hot summer of 2003 had a negative impact on tourism in the Mediterranean. (Matzarakis *et al.*, 2010) construct a composite index of temperature, humidity, wind speed and cloud cover, and use this to map tourism potential. (Lin and Matzarakis, 2011) apply the index to Taiwan and Eastern China. (Endler and Matzarakis, 2010a; Endler and Matzarakis, 2010b; Endler and Matzarakis, 2011) use this index to study the Black Forest in Germany in detail, highlighting the differences between summer and winter tourism, and between high and low altitudes; the latter aspect is thoroughly investigated by (Endler *et al.*, 2010). (Matzarakis and Endler, 2010) uses this method to study Freiburg. (Matzarakis *et al.*, 2007) use the same method to project this potential into the future, finding that the Mediterranean will probably become less attractive to tourists. (Amelung and Viner, 2006; Giannakopoulos *et al.*, 2011; Hein *et al.*, 2009; Perch-Nielsen *et al.*, 2009) use a different index to reach the same conclusion, but also point out that Mediterranean tourism may shift from summer to the other seasons. (Giannakopoulos *et al.*, 2011) notes that coastal areas in Greece may be affected more than inland areas because, although temperature would be lower, humidity would be higher. (Moreno and Amelung, 2009), on the other hand, conclude that climate change will not have a major impact (before 2050) on beach tourism in the Mediterranean because sunbathers like it hot. (Amelung *et al.*, 2007) use a weather index for a global study of the impact of climate change on tourism, finding shifts from equator to pole, summer to spring and autumn, and low to high altitudes. (Perch-Nielsen, 2010) combines a meteorological indicator of exposure with indicators of sensitivity and adaptive capacity. She uses this to rank the vulnerability of beach tourism in 51 countries. India stands out as the most vulnerable, and Cyprus as the least vulnerable.

The main criticism of most biometeorological studies is that the predicted gradients and changes in tourism attractiveness have rarely been tested to observations of tourist behaviour. (De Freitas *et al.*, 2008) validate their proposed meteorological index to survey data. (Moreno *et al.*, 2008) and (Ibarra, 2011) use video of beach occupancy to test meteorological indices for beach tourism. (Gómez-Martín, 2006) tests meteorological indices against visitor numbers and occupancy rates. All four studies find that weather and climate affects tourists, but in a different matter than typically assumed by biometeorologists.

Studies on the supply side often focus on ski tourism. (Abegg and Elsasser, 1996) is one of the earliest papers. Warming of would raise the altitude of snow-reliable resorts, and fewer resorts would be snow-reliable. (Elsasser and Bürki, 2002) point out that artificial snow-making cannot fully offset the loss in natural snowfall in the Swiss Alps. (Hamilton *et al.*, 2007) reaches a similar conclusion for New England. They highlight the importance of "backyard snow" to induce potential skiers to visit ski slopes. (Pickering *et al.*, 2010) find that skiers in Australia prefer natural snow over artificial snow. From a series of interviews, (Hill *et al.*, 2010) find that tourist operators in the Swiss Alps seek to maintain the status quo through adaptation, rather than search for viable alternatives to ski tourism; and argue that better coordination is needed for adaptation to be successful. (Scott and McBoyle, 2007) highlight that there are many options to adapt to a loss of snow for skiing. (Hoffmann *et al.*, 2009) use a survey of ski lift operators in the Swiss Alps. They find that the need for adaptation exceeds the ability to adapt and that adaptation is more prevalent on higher slopes (which are less vulnerable). (Scott *et al.*, 2006) study the impact of climate change on ski areas in eastern North America. Even with snowmaking, climate change could be an existential threat to 3 of the 6 ski areas by 2050; and climate change would lead to a contraction in each area in each scenario. (Dawson *et al.*, 2009) use past analogues to study the impact of future climate change on ski tourism in the Northeastern USA. They find that small and very large resorts will be hit hardest. (Scott *et al.*, 2008a) find that snowmobiling would have disappeared from the Northeastern USA by the end of the 21st century. Artificial snowmaking would halt the decline of ski resorts, but water scarcity and the costs of snowmaking would be increasingly large problems. (Scott *et al.*, 2003) reach the same conclusion for southern Ontario, (Scott *et al.*, 2007) for Quebec, and (Steiger and Mayer, 2008) for Tyrol. (Bicknell and Mcmanus, 2006) study adaptation for ski resorts in Southeastern Australia. They note that resorts may continue to be economically viable in the absence of snow by focusing on alternative activities. (Pickering and Buckley, 2010) note that artificial snow-making may be infeasible and uneconomic at the scale required to offset the loss of natural snow in Australia, and argue for a reorientation towards summer tourism and residential property development. (Moen and Fredman, 2007) find that alpine ski resorts in Sweden would become economically unviable, and that alternative livelihoods need to be developed. (Tervo, 2008) finds that the shortening of the Finnish ski season would be too limited to affect the economic viability of tourist operators. (Serquet and Rebetez, 2011) find that the Swiss Alps attract more tourists during hot summers, and argue that climate change would structurally improve the mountains as a summer tourism destination. (Bourdeau, 2009) argue along the same lines for the French Alps, stressing the importance of non-tourism alternatives as a source of economic development. (Potocka and Zajadacz, 2009) argue that prudent management supplies tourism services suitable for all weather.

Other studies consider beach tourism. (Phillips and Jones, 2006) focuses on beach erosion due to sea level rise, and the various options to prevent that. (Hamilton, 2007) finds that tourists are averse to artificial coastlines, so that hard protection measures against sea level rise would reduce the attractiveness of an area. (Raymond and Brown, 2011) survey tourists on the Southern Fleurieu Peninsula. They conclude that tourists who are there for relaxation worry about climate change, particularly sea level rise, while tourists who are there to enjoy nature (inland) do not share that concern. (Becken, 2005) finds that tourist operators have adapted to weather events, and argues that this helps them to adapt to climate change. (Belle and Bramwell, 2005) find that tourist operators on Barbados are averse to public adaptation policies. (Uyarra *et al.*, 2005) find that tourists on Barbados would consider holidaying elsewhere if there is severe beach erosion. (Buzinde *et al.*, 2010a; Buzinde *et al.*, 2010b) find that there is a discrepancy between the marketing of destinations as pristine and the observations of tourists, at least for Mexican beach resorts subject to erosion. They conclude that, contrary to official preconceptions, tourists are not deterred by environmental change.

Some studies focus on nature tourism. (Wall, 1998) notes the impact of climate change on water-based tourism, on the coast through sea level rise and inland through drought. (Cavan *et al.*, 2006) find that climate change may have a negative effect on the visitor economy of the Scottish uplands as natural beauty deteriorates through increased wild fires. (Saarinen and Tervo, 2006) interviewed nature-based tourism operators in Finland, and found that about half of them do not believe that climate change is real, and that few have considered adaptation options. (Nyaupane and Chhetri, 2009) argue that climate change would increase weather hazards in the Himalayas and that this would endanger tourists. (Uyarra *et al*., 2005) find that tourists on Bonaire would not return if coral was bleached. (Hall, 2006) finds that small tourist operators in New Zealand do not give high priority to climate change, unless they were personally affected by extreme weather in recent times. The interviewed operators generally think that adaptation is a sufficient response to climate change for the tourism sector. (Wang *et al*., 2010) note that glacier tourism is particularly vulnerable to climate change, highlighting the Baishiu Glacier in China.

While the case studies reviewed above provide rich detail, it is hard to draw overarching conclusions. A few studies consider all aspects of the impact of climate change for particular countries or regions. (Ren Guoyu, 1996) shows that domestic tourism in China will shift northwards, that sea level rise would damage some tourist facilities, and that the overall impact of climate change on China's tourist sector would be negative. (Harrison *et al*., 1999) conclude that climate change would make Scotland less attractive to tourists in winter but more attractive in summer. (Ceron and Dubois, 2005) assess the impact of climate change on tourism in France. They argue that the French Riviera may benefit because it is slightly cooler than the competing coastal resorts in Italy and Spain. The Atlantic Coast, although warming, would not become more attractive because of increased rainfall. The increase in summer tourism in the mountains is unlikely to offset the decrease in winter tourism. (Jones *et al*., 2006) study the impact of climate change on three festivals in Ottawa. They argue for heat wave preparedness for Canada Day, find that skating on natural ice may become impossible for Winterlude, and fret that the dates of the Tulip Festival may need to be shifted to reflect changing phenology. (Dawson and Scott, 2010) assess the impacts in the Great Lakes regions, finding reduced tourism potential in winter but increased opportunities in summer. (Turton *et al*., 2010) study Australia. They conclude that tourist operators find the uncertainty about climate change too large for early investment in adaptation.

10.6.3. Market Impacts

There are only two papers that consider the economic impacts of climate-change-induced changes in tourism supply and demand. Both studies use a computable general equilibrium model, assessing the effects on the tourism sector as well as all other markets. (Berrittella *et al*., 2006a) consider the consumption pattern of tourists and their destination choice. They find that the economic impact is qualitatively the same as the impact on tourist flows (discussed above): Colder countries benefit from an expanded tourism sector, and warmer countries lose. They also find a drop in global welfare, because of the redistribution of tourism supply from warmer (and poorer) to colder (and richer) countries. (Bigano *et al*., 2008a) extend the analysis with the implications of sea level rise. The impact on tourism is limited because coastal facilities used by tourists are sufficiently valuable to be protected against sea level rise. The study finds that the economic impacts on the tourism sector are reinforced by the economic impacts on the coastal zone; and that the welfare losses due to the impact of climate change on tourism are larger than the welfare losses due to sea level rise.

10.7. Insurance

10.7.1. Main Results of AR4 and SREX

More intense and/or frequent weather-related disaster would affect property insurance, which is growing with the economic in both developed and developing countries (WG II, 7.4.2.2.4.). Insurability can be preserved through risk-reducing measures, where governments have an important responsibility. Adaptation to climate change can be incentivized through risk-commensurate insurance premiums. Governments' disaster liability would be substantially reduced. Improved risk management would further financial resilience (WG II, 7.4.2.2.4., 7.6.3.). Insurance is linked to disaster risk reduction and climate change adaptation, because it enables recovery, reduces vulnerability and provides knowledge and incentives for reducing risk (SREX 9.2.13., 5.6.3., 6.2.2., 6.4.3., 6.5.3., 7.2.5.2., 7.3.2., 7.4.4., 8.6.2.2.).

10.7.2. Societal Role of Insurance Covering Weather Hazards

Insurance internalizes catastrophe risk costs prior to catastrophic events, reducing the economic impact of weather-related and other disasters to individuals and enterprises, thus stabilizing income and consumption, and decreasing societal vulnerability. Insurance is based on the law of large numbers: the larger the pool of uncorrelated and relatively small risks, the more accurately the average loss per policy can be predicted and charged accordingly, allowing for a lower premium than with a smaller pool. Besides spreading risk over a diversified insured population, insurance spreads risk over time. However, weather-related disasters such as floods violate the principle of uncorrelated risks, because many people are affected simultaneously. Consequently, large losses are much more likely, the loss variance is greater, and the tail risk is higher (e.g., Cummins and Mahul, 2009). If insurance coverage is to be maintained, insurers would need more risk capital to indemnify catastrophic losses and remain financially solvent if frequencies or intensities of weather-related disasters rise. This coverage is purchased in the reinsurance and capital markets. The capital costs account for a substantial portion of premiums and the affordability and viability of weather insurance are subjects of ongoing research given future climate change (e.g., Herweijer et al., 2009; Kunreuther et al., 2009; Charpentier, 2008;).

Increasing volatility and burden of losses in many regions are expected to fundamentally impact on the industry, leading insurers to adapt their business to the changing risk (Phelan *et al.*, 2011; Wilkins, 2010) (Hecht, 2008; Herweijer et al., 2009; Leurig, 2011).

10.7.3. Observed and Projected Losses from Weather Hazards

Direct and insured losses from weather-related disasters have increased substantially in recent decades both globally and regionally (Barthel and Neumayer, 2011; Bouwer *et al.*, 2007; Schwierz *et al.*, 2010; Swiss Re, 2012)(Barrieu and Loubergé, 2009) (SREX 4.5.3.3.; Crompton and McAneney, 2008; Munich Re, 2012; Kunreuther and Michel-Kerjan, 2009). Global insured weather-related losses in the period 1980-2008 increased by US$^{2008}1.4bn per year (Barthel and Neumayer, 2011). As a rule, insured loss figures are more accurate than direct economic loss estimates, because insurance claims and payouts are regulated and monitored; estimates of direct overall losses are often derived from insurance losses (Kron et al., 2012; Changnon, 2009a). Growth, including higher concentrations of people and wealth and rising insurance penetration, is the most prominent driver of the increase in losses.

Growth induced changes in past losses are removed by normalization. So far, there is only one study analyzing global normalized weather-related insured losses (Barthel and Neumayer, 2011), but the period (1990-2008) is too short to infer any reliable trend information. Other studies focus on particular perils and regions, in particular Australia, USA and Germany. Upward trends were found for the USA and Germany but not for Australia (Table 10-4). Trends in normalized insured losses can be influenced not only by changing hazards but also by changing damage sensitivities, prevention measures, different normalization, and changes within the insurance system (Barthel and Neumayer, 2011) (Crompton and McAneney, 2008; SREX 4.5.3.3.). From a risk perspective, prevention measures such as flood defense constructions, or improved building standards over time, would offset an increase in hazard (Kunreuther et al., 2009). Given these confounding factors, it is challenging to estimate to what degree trends in weather losses are due to climate change (SREX FAQ 3.1; 4.5.3.3.). The literature analyzing climate variables and losses in parallel is still relatively small. The number of days that a regional insurer in southwest Germany sustains losses displays an upward trend since 1986, while severe convective storms in that region also show positive trends (Kunz et al., 2009). Corti et al. (2009) found an increase in modeled and partly observed insured subsidence losses in France over the period 1961-2002, consistent with an increase in dryness in central and southern Europe (SREX 3.5.1.). The observed rise in US normalized insured flood losses (Barthel and Neumayer, 2011) corresponds to *likely* increased heavy precipitation events in many parts of the USA (SREX 3.3.2.), but there is no compelling evidence for climate driven changes in the magnitude or frequency of floods (SREX 3.5.2.). The recent upswing in hurricane hazard and losses seems at least partly to be connected to multidecadal climate variability (Schmidt *et al.*, 2009a; Schmidt *et al.*, 2009b) (SREX 3.4.4). Conclusive attribution of losses to anthropogenic climate change has not yet been achieved, also due to missing methodological attribution setup.

[INSERT TABLE 10-4 HERE
Table 10-4: Observed normalized insured losses from weather hazards.]

Most studies concerning climate-change projections for insured weather-related losses relate to the impact of the extratropical storms on homeowners' insurance in Europe. Climate models display a roughly consistent pattern of change: local extreme wind speeds fall in the Mediterranean and increases in central, west and northern Europe. Loss ratios, i.e. insured loss divided by insured value, follow the same pattern (Pinto *et al*., 2007; Pinto *et al*., 2009; Schwierz *et al*., 2010) (Donat et al., 2011; Leckebusch et al., 2007; Dailey et al., 2009; Table 10-5). Accordingly, direct overall losses from winter storms will increase with climate change (SREX 4.5.4.2.; 3.4.5.; 4.4.5.5.) - (Narita *et al*., 2010) also find a worldwide increase in the costs and fatalities due to extratropical storms. Studies calibrated to German data project a 17% - 64% rise in insurance losses from winter storms in the period 2041-2070 (A1B) as against a late 20th century control period (keeping exposures and damage sensitivities constant) (German Insurance Association, 2011 – [scientific publications forthcoming])

[INSERT TABLE 10-5 HERE
Table 10-5: Climate change projections of insured losses.]

Direct flood losses will increase with climate change in many locations (SREX, 4.5.4.2.; 3.5.2.). Mean annual insured flood property losses in the UK and the Netherlands are projected to rise with climate change (Aerts and Botzen, 2011) (Dailey et al., 2009); for the German insurance market an increase of more than 90% in river inundation losses in the period 2041-2070 relative to the late 20th century was projected (keeping exposures and sensitivities constant) (German Insurance Association, 2011).

Direct losses from tropical cyclones will increase with exposure and may increase with the frequency of very intense cyclones in some basins (SREX, 4.5.4.2.; 3.4.4.). Mendelsohn et al. (2011b) project rising climate driven direct losses for Asian coasts along the Northwest Pacific and the Atlantic coasts of North America. (Narita *et al*., 2009) report an increase in damages and fatalities in all parts of the world. Insured typhoon-related property losses in China are projected to increase (Dailey et al., 2009). Studies for the North Atlantic also project a climate-driven loss increase (Pielke, 2007) (Emanuel, 2011; Mendelsohn et al., 2011a; SREX 4.5.4.2.). (Ranger and Niehoerster, 2012) discuss changes in both directions across a broad range of dynamical and statistical models.

Agricultural hailstorm insurance losses in the Netherlands (Botzen *et al*., 2010b) and Germany (German Insurance Association, 2011) are projected to increase. Paddy rice insurance payouts are projected to decrease (Izumi et al., 2008; all examples Table 10-5).

Few impact projections account for future economic growth and inflation (Bouwer, 2011). Increasing insured wealth and inflation will increase both losses and premium income. The ratio of losses to premium income need not change significantly. Opposite to this, adjustments are not automatically made for external drivers of losses such as changing event frequencies or intensities. Hence, projection studies using relative entities such as loss ratios and a frozen spatial distribution of insured property can be justified as a relevant first-order approximation of the climate change impact (e.g. Donat et al., 2011). Research on the projection of insured losses is developing and, for many perils, information on expected future insured losses has to be inferred from studies on direct overall losses, if available (SREX 4.5.4.2.; 4.4).

10.7.4. Supply-Side Challenges and Sensitivities

10.7.4.1. High-Income Countries

The provision of weather hazard insurance is contingent on an insurer's ability to find a balance between affordability of the premiums and costs that have to be covered by the revenue. On the cost side, the expected level of losses, expenses for risk assessment, product development, marketing, operating, and claims processing are included. Moreover, the revenue must provide a fair return on shareholders' equity and, to a substantial proportion, allow for the purchase of external capital needed to cover large loss if a disaster materializes (Kunreuther et al., 2009; Charpentier, 2008).

The balance between affordability and profitability is sensitive to climate change. Increases in large weather-related losses may corrode an insurer's ability to cover the losses (solvability) if it fails to reflect the changes in its risk management, or is hampered in doing so, as was the case with the upswing in Atlantic hurricane activity in the USA since the mid-1990s (Grace and Klein, 2009). Additionally, misguided incentives for development in hazard-prone areas, as involved with, e.g., the US National Flood Insurance Program (Burby, 2006; Zahran *et al*., 2009) (Kousky and Kunreuther, 2010; Michel-Kerjan, 2010; Michel-Kerjan and Kunreuther, 2011; GAO, 2010; GAO, 2011), can aggravate the situation (Table 10-6).

[INSERT TABLE 10-6 HERE
Table 10-6: Supply-side challenges and sensitivities.]

The additional uncertainty brought about by climate change translates into a need for more risk capital (Kunreuther et al., 2009; Charpentier, 2008; Grace and Klein, 2009). This would raise insurance premiums and hence affect the economy (Table 10-6).

Health and life insurance are also affected through the health impacts of climate change (Hecht, 2008; Leurig, 2011). Liability insurance, too, may be susceptible to climate change. So far, no damages have been awarded for greenhouse gas emissions as such, but litigation where damages are sought is pending, especially in the USA (Hecht, 2008; Mills, 2009; Ebert, 2010; Steward and Willard, 2012; Heintz et al., 2009). A decision by the Supreme Court of Virginia in April 2012 denied defense costs under the specific liability insurance policy of an utility company (Supreme Court of Virginia, U.S.A., 2012) (Table 10-6).

10.7.4.2. Middle- and Low-Income Countries

Middle- and low-income countries account for a small share of worldwide non-life insurance: 12% of premiums in 2007. Whereas in high-income countries around 40% of direct economic losses are covered by insurance, only about 13% in middle-income countries and approximately 4% in low-income countries is covered (Bosse and Liedtke, 2009) (Cummins and Mahul, 2009; SREX, 6.2.2.). For instance, insured losses amounted to only about 1% of direct overall losses in the 2010 floods in Pakistan (Munich Re, 2011).

The small share of insurance in risk financing is not deemed economically prudent, because other options, such as external credit or donor assistance, can be unreliable and late. This leaves a risk financing gap in the months immediately following the event, often exacerbated by overstretched tax bases. Pre-disaster financing instruments such as insurance or trigger-based risk-transfer products are a better means of providing prompt liquidity for households, farmers, businesses and governments (Ghesquiere and Mahul, 2007; Linnerooth-Bayer et al., 2009; SREX 6.4.3.; Box 6-3; 6.5.3. ; 7.4.4.; 9.2.13.). These may become more important if disaster incidence increases with climate change (SREX 4.5.4.2.; 4.4.; Hochrainer et al., 2010; Collier et al., 2009), given the high vulnerability condition of these countries (SREX 4.5.2.).

It is challenging to upscale catastrophe insurance because of low business volumes, high transaction costs, and phases of high reinsurance premiums following large disasters. Small-scale insurance schemes in middle- and low-income countries may find it difficult to obtain sufficient risk capital (Cummins and Mahul, 2009; Mahul and Stutley, 2010).

Microinsurance schemes, keeping transaction costs at the lowest operable level, provide health and life cover to individuals, households and small enterprises in low-income markets. Correlated weather risks are one ground that this was not extended to property insurance. Yet, weather coverage is growing, typically with government and NGO assistance or cross-subsiding by local insurers (Qureshi and Reinhard, 2011) (Linnerooth-Bayer and Mechler, 2009). These schemes may be particularly sensitive to a rise in disaster risk due to climate change (Collier et al., 2009).

Adverse selection is another challenge: clients do not always disclose their high risk, e.g. a floodplain site, to the insurer so as to benefit from lower rates. Lower-risk participants are charged too high premiums and leave the scheme, thus increasing overall risk. In low-income countries, where data to establish homogenous risk groups are not available, this can cause catastrophe insurance markets to fail (Barnett *et al.*, 2008) (Mahul and Stutley, 2010). Moral hazard is another issue, where the insured adopt more risky behavior than anticipated by the insurer, particularly in the absence of proper monitoring (e.g. Mahul and Stutley, 2012).

10.7.5. Products and Systems Responding to Changes in Weather Risks

10.7.5.1. High-Income Countries

A rise in weather-related disaster risk may drive the need for more risk capital to cover the losses. There are several options that reduce vulnerability and sustain insurability. Reducing vulnerability often make sense even if expected climate change impacts will not materialize. Premiums conveying the risk incentivize policyholders to reduce their vulnerability (Thieken *et al.*, 2006) (SREX 1.4.3.; Hecht, 2008; Kunreuther et al., 2009; Table 10-7). Premium discounts for loss-prevention further promote this (Ward *et al.*, 2008) (Kunreuther et al., 2009; Table 10-7). Moral hazard can be reversed by involving the policyholder to some extent in the payment of losses (deductibles, upper limits of insurance coverage: (Botzen and van den Bergh, 2008; Botzen and van den Bergh, 2009; Botzen *et al.*, 2009)). Collaborative efforts of insurers and authorities on damage prevention has a long tradition and is crucial for reducing vulnerability (Ward *et al.*, 2008) (Herweijer et al., 2009). For example, new wind-resistant building standards in Florida reduced mean damage per average home by 42% in the period 1996-2004 relative to pre-1996 (Kunreuther et al., 2009).

[INSERT TABLE 10-7 HERE
Table 10-7: Products and systems responding to changes in weather risks.]

Most commercial risk-assessment models only incipiently factor in changes in weather –related hazard conditions, mainly to reflect higher hurricane frequencies (Seo and Mahul, 2009), assuming unchanging conditions for other weather hazards (Leurig, 2011). Ignoring changing hazard conditions results in biased estimates of expected loss, loss volatility and risk capital requirements (Watson and Johnson, 2008) (Charpentier, 2008; Herweijer et al., 2009). Other confounding factors, e.g. systemic economic impacts, in recent large losses (Cooke and Cousky, 2009) have been addressed (e.g. Muir-Wood and Grossi, 2008; Table 10-7). Geospatial risk-assessment tools, e.g. flood-recurrence zoning with premium differentiation, counteract adverse selection (Kunreuther et al., 2009; Mahul and Stutley, 2010). Weather alert systems and seasonal agricultural planning systems have been offered by some insurers to clients (Niesing, 2004). Credit rating agencies and upcoming Solvency II insurance regulation in Europe contribute to enhanced disaster resilience (Michel-Kerjan and Morlaye, 2008; Kunreuther et al., 2009; Grace and Klein, 2009). The insurance associations of Great Britain and of Germany have taken steps to project climate change driven losses to allow for adaptation of the industry (Dailey et al., 2009; German Insurance Association, 2011). The insurance sector is better adaptable that other sectors due to its short-term contracts (Botzen *et al.*, 2010a).

Reinsurers are key to the supply of disaster risk capital. They operate globally to diversify the regional risks of hurricanes and other disasters. Access to reinsurance enhances risk diversification of insurers (Cummins and Mahul, 2009; SREX 7.4.4.2.3.). In 2007, reinsurance products paying for losses above thresholds offered seven times the capacity available in insurance-linked securities (Cummins and Mahul, 2009; Kunreuther and Michel-Kerjan, 2009).

Truly disastrous loss events, say in excess of US$ 100bn, may make additional capacity desirable. These disasters can be diversified across the large global financial securitization market (SREX, 7.4.4.2.4.). Natural catastrophe risks are not correlated with capital market risks and hence are attractive to institutional investors. Catastrophe bonds thus cover disaster losses. The investor in a catastrophe bond gains above-market returns as long as a specified event does not occur, but pays the insurer's loss when the event materializes. The catastrophe bond market reached critical mass after the hurricanes of 2004 and 2005, with some US$ 11bn of risk capital in effect by June 2011 (Cummins, 2012; Cummins and Weiss, 2009; Michel-Kerjan and Morlaye, 2008; Kunreuther and Michel-Kerjan, 2009) (Table 10-7).

10.7.5.2. Middle- and Low-Income Countries

Index-based weather insurance schemes are considered well-suited to the agricultural sector in low- and middle-income countries in the context of climate change (e.g., Collier et al., 2009; SREX 5.6.3.; 6.5.3.; 7.4.4.2.3.; 9.2.13.4.). Payouts depend on a physical trigger, e.g. cumulative rainfall at a nearby weather station, so that costly loss assessments are avoided. Moral hazard is removed (Barnett *et al*., 2008) (Linneroth-Bayer and Mechler, 2009). Risk-based premiums encourage adaptive responses, particularly if combined with access to advanced technologies, e.g. drought-resistant seed (Collier et al., 2009; Hess and Hazell, 2009; Mahul and Stutley, 2010; Table 10-7). Basis risk, where losses occur but no payout is triggered (or vice versa), is a disadvantage of index-based schemes. It may cause the insured to lose confidence in the scheme (Patt *et al*., 2010; Zhu, 2011). Scale problems still have to be overcome. There is, for example, a disincentive to reduce risk by irrigation if rain-fed crops are insured (Fuchs and Wolff, 2011). Improvements can be achieved; currently indemnity-based schemes play a major role (Herbold, 2010; Meze-Hausken et al., 2009; Table 10-7).

Sovereign insurance is deemed appropriate in developing countries suffering from post-disaster financing gaps (see above 10.7.4). Current schemes include government disaster reserve funds (FONDEN, Mexico) and pools of small states' sovereign risks (CCRIF, Caribbean) (SREX Box 6-3; 7.4.4.2.5.; 9.2.13.4.3.). In both cases, peak risk is transferred to reinsurance and the catastrophe bonds (Table 10-7).

10.7.6. Governance, Public-Private Partnerships, and Insurance Market Regulation

10.7.6.1. High-Income Countries

Theory favors an arrangement where individual risk is insured, but the non-diversifiable component of risk (that may rise with climate change) is public (Borch, 1962) (Kunreuther et al., 2009). Accordingly, many high-income states already have public private partnerships involving governmental intervention on peak risk (Aakre *et al*., 2010; Botzen and van den Bergh, 2008; Bruggeman *et al*., 2010; Schwarze and Wagner, 2007; Schwarze *et al*., 2011; Van den Berg and Faure, 2006) (SREX 6.5.3.; Table 10-8). The pro-adaptive, impact-reducing features of insurance are more effective if the price reflects the risk and the pool of insured is larger, e.g. through bundled perils (Bruggeman *et al*., 2010) (Kuhnreuther et al., 2009). Excluded people can be covered by vouchers (Kunreuther et al., 2009) or by premium subsidies (Aakre *et al*., 2010; Van den Berg and Faure, 2006) (Table 10-8). Adapting to climate change challenges in continuation with socio-cultural roots of individual insurance systems is seen key (Schwarze *et al*., 2011). Insurance regulation ensures availability, affordability, and solvency, but often adopts only short- to medium-term views. Because of climate change, regulators have a new role in risk-adequate pricing, risk education and risk-reduction in the long term (Mills, 2009; Hecht, 2008; Grace and Klein, 2009; Leurig, 2011).

[INSERT TABLE 10-8 HERE
Table 10-8: Governance, public-private partnerships, and insurance market regulation.]

10.7.6.2. Middle- and Low-Income Countries

A key element of risk financing is the transfer of private risks to a competitive insurance market. This reduces the governments' fiscal burden and uncertainty due to weather disasters (Cummins and Mahul, 2009; Ghesquiere and Mahul, 2009). Interest in public-private partnerships may evolve, e.g. between government, farmers and insurers, in order to expedite agricultural development and resilience, e.g. by means of subsidies for the uppermost risk portion (Hochrainer et al., 2010; Collier et al., 2009; Mahul and Stutley, 2010; Table 10-8). As such insurance systems suffered from adverse selection and moral hazard in the past (Makki and Somwaru, 2001; Coble et al., 1997; Glauber, 2004), an improved design is needed. Well designed and implemented laws and regulation can encourage purchase of insurance (SREX 6.5.3.). Insurance pools can diversify weather risks across larger regions, reduce premiums and improve access to external risk capital (Hochrainer et al., 2011; Mendoza, 2009; SREX 7.4.4.2.5.).

In the least developed countries, even incipient domestic insurance markets hardly exist. Climate-change-related disaster risk management was proposed for inclusion in the post-2012 adaptation regime of the UNFCCC. Insurance is a central element in these proposals, funded from UNFCCC adaptation processes according to the principles of "common but differentiated responsibilities and respective capabilities" (UNFCCC Art.3.1) and "polluter pays" (AOSIS, 2008; Swiss Confederation, 2008; Warner and Spiegel, 2009) (e.g., Linneroth-Bayer et al., 2009; MCII, 2008; SREX 7.4.4.1; Table 10-8).

Innovative insurance concepts, including greater disaster risk capital, are available in middle- and low-income countries, at least at pilot stage. These can advance adaptation to climate change impacts. Everywhere, risk-based premiums foster risk awareness and risk reduction. Challenges include improved risk assessment, with sufficient detail and appropriate dynamics, and scaling-up of successful pilot schemes. Regulatory requirements for risk capital, and access to reinsurance and securitization market further contribute to a resilient insurance system. These are the provisions of sound risk management, even in the absence of climate change.

10.8. Services Other than Tourism and Insurance

Other service sectors of the economy, not covered elsewhere, include waste management, wholesale and retail trade, engineering services, government including education and defense and health. Contributions to the economy vary substantially by country; however, overall worldwide economic activity related to government accounts for approximately 30% of global expenditures (with military expenditures representing approximately 2.5% of global GDP), while health accounts for approximately 10% of global GDP by expenditures. The literature on climate change impacts on health costs covers both morbidity and mortality impacts (section 10.8.2) and some estimates on the health care industry.

10.8.1 Sectors Other than Health

The literature on the impact of climate change on other sectors of the economy is extremely sparse. Few studies have evaluated the possible impacts of climate change, and particularly the economic impacts, on these sectors. (Tamiotti *et al.*,2009) conducted a qualitative assessment of climate and trade. (Travers and Payne, 1998) and (Subak *et al.*, 2000) find that weather significantly affects retail. (Sabbioni *et al.*, 2009) note that climate change may require a greater effort to protect cultural heritage. Chapter 12 discusses the impact of climate change on violent conflict, which has implications for military expenditures.

10.8.2. Health

The health sector is not a single entity. It can be divided into (1) the public health agencies, institutions, and organizations that focus on improving population health and the quality of life through activities that prevent adverse health conditions, prolong life, and promote health; and (2) individual and family health care diagnosis, treatment, and health management services delivered by medical and other health professions. In many countries, the health sector is comprised of, at the least, a ministry of health, health care services managed separately, and, particularly in low-income countries, non-governmental organizations helping both to achieve their goals.

Climate change could affect the health sector through impacts on the delivery of health care services and through changes in the demands for those services. Health care workers can be providers of services, as well as victims and patients requiring services. Weather impacts on delivery of services, as with other sectors, can occur through increases in the frequency, intensity, and extent of extreme weather events adversely affecting infrastructure and increase the demands for services, placing additional burdens on public health and health care personnel and supplies, with economic consequences. Health care facilities are priority infrastructure that can be damaged by storm surges, floods, wildfires, and other weather and climate events, compromising critical resources required for patient treatment; and physical damage and destruction of equipment and buildings (Carthey et al. 2009). Floods and wildfires can require evacuation of critical care patients, with the attendant risks for the patients. Adverse impacts on transportation (such as flooded roads) can exacerbate the situation. Very large events that affect multiple health care facilities challenge the ability of the community and/or region to properly care for the affected and those with ongoing health issues requiring medication and/or treatment. Areas projected to experience increases in the frequency and intensity of extreme events could consider additional “surge capacity” to increase the ability of health care facilities to manage such events without interruption of service (Banks et al. 2007; Hess et al. 2009).

Extreme weather and climate events can increase demands for health care services. Large numbers of people are affected in weather-related disasters; for example, more than 600,000 people required immediate assistance in hydrological events in 2002 through 2010 (EM-DAT 2011). Although the proportion seeking medical treatment is a small subset, the additional burden on health care facilities can be significant (Hess et al. 2009). Heatwaves and other extreme events can increase hospitalizations (cf. Mayner et al. 2010; Chapter 11) with attendant increased costs. Heatwaves also can increase hospital visits by individuals looking for an air-conditioned location (Carthey et al. 2009). Increases in ambient temperature can increase visits to health care facilities. One trauma center in the U.S. found a 5.25% increase in hourly admissions for each approximately 5°C increase in temperature; and a 60-78% increase in admission for each 2.5 cm increase in precipitation in the previous three hours (Rising et al. 2006). Climate change is projected to increase the burden of major worldwide causes of childhood mortality: malnutrition, diarrheal diseases, and malaria (Chapter 11.5). Any increase in health burdens or risks would increase the demands for public health services (e.g. surveillance and control programs) and the demands for health care and relevant supplies (e.g. oral rehydration for severe cases of diarrheal disease).

Estimates of the costs of additional treating cases of climate sensitive health outcomes are in the range of billions of US dollars annually (Ebi 2008; Pandey 2010). An estimate of the worldwide costs in 2030 of additional cases of malnutrition, diarrheal disease, and malaria due to climate change, assuming no population or economic growth, emissions reductions resulting in stabilization at 750 ppm CO2 equivalent in 2210, and current costs of treatment in developing countries, estimated treatment costs without adaptation could be $4 to 12 billion worldwide, based on costs estimated in 2001 US dollars, and depending on assumptions of the sensitivity of these health outcomes to climate change (Ebi 2008). The costs for additional infrastructure and health care workers were not estimated, nor were the costs of additional public health services, such as surveillance and monitoring. The costs were estimated to be unevenly distributed, with most of the costs borne by developing countries, particularly in South East Asia and Africa, to address the projected additional cases of diarrheal disease and malaria (Markandya and Chiabai 2009). To put these numbers in perspective, the projected additional cases due to climate change were (in thousands) 131,980 for diarrheal diseases; 4,673 for malnutrition; and 21,787 for malaria. This was against (in thousands) 4,513,981 cases of diarrheal disease, 46,352 cases of stunting and wasting, and 408,227 cases of malaria in 2004 (WHO 2004). Development assistance for the health sector in the year 2002 from bilateral and multilateral agencies, the European Commission, the Global Fund to Fight AIDS, Tuberculosis, and Malaria, and the Bill and Melinda Gates Foundation was estimated to be 9.3 billion in US dollars (Hecht and Shah 2003).

A second global estimate assumed UN population projections, strong economic growth, updated projections of the current health burden of diarrheal diseases and malaria, two climate scenarios, and updated estimates of the costs of malaria treatment (Pandey 2010). In 2010, the average annual adaptation costs for treating diarrheal disease and malaria, in 2005 US dollars, were estimated to be $3 to 5 billion, with the costs expected to decline over time with improvement in basic health services. Over the period 2010-2050, the average annual costs were estimated to be around $2 billion, with most of the costs related to treating diarrheal disease; the largest burden is expected to be in Sub-Saharan Africa. The differences in costs from Ebi (2008) are primarily due to a reduction in the baseline burden of disease and lower costs for malaria treatment.

The malaria estimates from the global estimates of the costs of adaptation are comparable with estimates of the additional health care costs in 2025 in Southern Africa due to a climate change-related increase in the incidence of malaria (Van Rensburg and Blignaut 2002). Assuming low (high) cost scenarios in 2000 prices in purchasing power parity in US dollars, additional costs for the prevention and treatment of malaria in South Africa were estimated to be approximately US$279.6 (3,764.2) million; this represented an increase of 0.23% in costs per capita as a percentage of GDP per capita in 2025. Smaller populations resulted in lower estimates for Botswana (US$ 9.3

(124.3) million) and Namibia (US$ 13.2 (177.1) million); for Namibia, the high cost scenario represented an increase of about 4.6% of costs per capita as a percentage of GDP per capita.

Because any additional climate change-related cases are projected to occur primarily in low-income countries, where no or limited health care is provided by the government, the treatment costs will primarily be borne by families (WHO 2004). Time off from work to care for sick children, including in rural areas transportation to health facilities, can be expected to affect productivity, although estimates are few.

(Bosello *et al*., 2006) use a computable general equilibrium model to study the economic impacts of climate-change-induced changes in the mortality and morbidity due to cardiovascular and respiratory diseases, malaria, diarrhea, schistosomiasis, and dengue fever. They consider the effects on labor productivity and demand for health care. They find that health and welfare impacts have the same sign; and that increased health problems are associated with an expansion of the public sector at the expense of the private sector.

The health-related welfare costs and benefits of temperature-related mortality, salmonellosis, and coastal flooding-induced mental health impacts resulting from climate change for Europe, separate from the effects of socioeconomic change, were estimated for the periods 2011–2040 and 2071–2100 (Watkiss and Hunt 2012). Costs were estimated in 2005 prices, with no adjustments for future time periods and no discounting. Increases in heat-related mortality and reductions in cold-related mortality were estimated to cost up to 100 billion Euro annually by the later time-period, with the costs and benefits unevenly distributed across countries. Climate scenario (SRES A2 and B2), impact function (climate dependent and country specific), extent of acclimatization, and the choice of physical and monetary metrics affected the cost estimates, with acclimatization particularly important in determining the magnitude of the temperature impacts. Climate change was projected to increase the number of cases of salmonellosis in 2071-2100 by up to 50% more than would be expected on the basis of population change alone. The associated welfare costs were estimated at potentially several hundred million Euro annually. A scoping assessment of the health costs of climate change from coastal flooding, focusing on mental health problems such as depression, were estimated at up to 1.5 billion Euro annually by the period 2071–2100.

10.9. Impacts on Markets and Development

Prior sections of this chapter present the direct impacts of climate change on the economy sector by sector. There are, however, also indirect impacts. The effects that impacts in one sector may have on the rest of the economy are initially presented, followed by the impacts on economic growth and development.

10.9.1. General Equilibrium Effects

General equilibrium analysis describes how climate change impacts in one sector propagate to the rest of the economy, how impacts in one country influence other countries, and how macroeconomic conditions affect each impact (Ginsburgh and Keyzer, 1997). There are three channels through which impact diffuse. First, outputs of one sector are used as inputs to other sectors. For example, a change in crop yields would affect the food-processing industry. Second, products compete for the consumers' finite budget. If, for example, food becomes more expensive, less money would be spent on other goods and services. Third, sectors compete for the primary factors of production (labor, capital, land, water). If more labor is needed in agriculture to offset a drop in crop yields, less labor is available to produce other goods and services. Firms and households react to changes in relative prices, domestically and internationally.

General equilibrium models can provide a comprehensive and internally consistent analysis of the medium-term impact of climate change on economic activity and welfare. However, these models necessarily make a number of simplifying assumptions, particularly with regard to the rationality of consumers and producers and the absence of market imperfections.

Computable general equilibrium models have long been used to study the wider economic implications of changes in crop yields (Kane *et al*., 1992). (Yates and Strzepek, 1998) show for instance that the impact of a reduced flow of the Nile on the economy of Egypt is much more severe without international trade than with, because trade would allow Egypt to focus on water-extensive production for export and import its food.

Older studies focused on the impact of climate change on patterns of specialization and trade, food prices, food security and welfare (Darwin and Kennedy, 2000; Darwin, 2004; Kane *et al*., 1992; Reilly *et al*., 1994; Winters *et al*., 1998; Yates and Strzepek, 1998). This has been extended to land use (Lee, 2009; Ronneberger *et al*., 2009), water use (Calzadilla *et al*., 2011; Kane *et al*., 1992), and multiple stresses (Reilly *et al*., 2007). General equilibrium models have also been used to estimate the value of improved weather forecasts (Arndt and Bacou, 2000), a form of adaptation to climate change. Computable general equilibrium analysis has also been used to study selected impacts other than agriculture, notably sea level rise (Bosello *et al*., 2007; Darwin and Tol, 2001), tourism (Berrittella *et al*., 2006b; Bigano *et al*., 2008b), human health (Bosello *et al*., 2006) and energy (see 10.2).

(Bigano *et al*., 2008b) study the joint impacts on tourism and coasts, finding that tourism dominates the welfare impacts. (Kemfert, 2002) and (Eboli *et al*., 2010a) estimate the joint effect on the world economy of a range of climate change impacts, but conflate general equilibrium and growth effects. (Aaheim *et al*., 2010) analyze the economic effects of impacts of climate change on agriculture, forestry, fishery, energy demand, hydropower production, and tourism on the Iberian Peninsula. They find positive impacts on output in some sectors (agriculture, electricity) negative impacts in other sectors (forestry, transport) and negligible ones in others (manufacturing, services). (Ciscar *et al*., 2011) study the combined impact on agriculture, coasts, river floods and tourism in the current European economy. They find an average welfare loss of 0.2-1.0% of income but there are large regional differences with losses in Southern Europe and gains in Northern Europe.

The following initial conclusions emerge. First, markets matter. Impacts are transmitted across locations—with local, regional and global impacts-- and across multiple sectors of the economy. For instance, landlocked countries are affected by sea level rise because their agricultural land increases in value as other countries face erosion and floods. Second, consumers and producers are often affected differently. The price increases induced by a reduction in production may leave producers better off while hurting consumers. Third, the distribution of the direct impacts can be very different than the distribution of the indirect effects. For instance, a loss of production may be advantageous to an individual company or country if the competition loses more. Fourth, a loss of productivity or productive assets in one sector leads to further losses in the rest of the economy. Fifth, markets offer options for adaptation, particularly possibilities for substitution. This changes the size, and sometimes the sign of the impact estimate.

10.9.2. Growth Effects

10.9.2.1. The Rate of Economic Growth

Climate change would also affect economic growth and development, but our understanding is limited. (Fankhauser and Tol, 2005) investigate four standard models of economic growth and three transmission mechanisms: economic production, capital depreciation, and the labor force. They find that, in three models, the fall in economic output is slightly larger than the direct impact on markets while the 4th model (which emphasizes human capital accumulation) points to indirect impacts that are 1.5 times as large as the direct impacts. The difference can be understood as follows. In the three models, the impacts of climate change crowd out consumption and investment in physical capital, while in the fourth model investment in human capital too is crowded out; lower investment implies slower growth. (Hallegatte, 2005) reaches a similar conclusion. (Hallegatte and Thery, 2007; Hallegatte and Ghil, 2008; Hallegatte and Dumas, 2009) highlight that the impact of climate change through natural hazards on economic growth can be amplified by market imperfections and the business cycle. (Eboli *et al*., 2010a) use a multi-sector, multi-region growth model. The impact of climate change would lead to a 0.3% reduction of GDP in 2050. Regional impacts are more pronounced, ranging from -1.0% in developing countries to +0.4% in Australia and Canada. Sectoral results are varied too, with output changes ranging from output of +0.5% for power generation (to meet increased demand to air conditioning) to -0.7% for natural gas (as demand for space heating falls) and rice.

Using a biophysical model of the human body's ability to do work, (Kjellstrom *et al*., 2009b) find that by the end of the century climate change may reduce labor productivity by 11-27% in the humid (sub)tropics. Assuming a output elasticity of labor of 0.8, this would reduce economic output in the affected sectors (involving heavy manual labor without air conditioning) by 8-22%. Although structural change in the economy may well reduce the dependence on manual labor and air conditioning would be an effective adaptation, even the ameliorated impact would have a substantial, but as yet unquantified, impact on economic growth.

There are also statistical analyses of the relationship between climate and economic growth. (Dell *et al*., 2009) find that one degree of warming would reduce income by 1.2% in the short run, and by 0.5% in the long run. The difference is due to adaptation. (Horowitz, 2009) finds a much larger effect: a 3.8% drop in income in the long run for one degree of warming. In a yet-unpublished study, (Dell *et al*., 2008) find that climate (change) has no effect on economic growth in countries with an income above the global median ($\$^{PPP,2000}$3170) but a large impact on countries below the median. If companies can fully adapt to a new climate in 10 years time, economic growth in the 21st century would be 0.6% slower if climate changes according to the A2 scenario than in the case without climate change. If economic growth is 2.6% per year without climate change, and 2.0% with, then a century of climate change would reduce income by 44%.

10.9.2.2. Poverty Traps

Poverty is concentrated in the tropics and subtropics. This has led some analysts to the conclusion that a tropical climate is one of the causes of poverty. (Gallup *et al*., 1999) emphasize the link between climate, disease, and poverty while (Masters and McMillan, 2001) focus on climate, agricultural pests, and poverty. Other studies (Acemoglu *et al*., 2001; Acemoglu *et al*., 2002; Easterly and Levine, 2003) argue that climatic influence on development disappears if differences in human institutions (the rule of law, education, etc) are accounted for. However, (Van der Vliert, 2008) demonstrates that climate affects human culture and thus institutions, but this has yet to be explored in the economic growth literature. (Brown *et al*., 2011) find that weather affects economic growth in Sub-Saharan Africa – particularly, drought decelerates growth. (Jones and Olken, 2010) find that exports from poor countries fall during hot years. (Bloom *et al*., 2003) find limited support for an impact of climate (rather than weather) on past growth in a single-equilibrium model, but strong support in a multiple-equilibrium model: Hot and wet conditions and large variability in rainfall reduce long-term growth in poor countries (but not in hot ones) and increase the probability of being poor.

(Galor and Weil, 1996) speculate about the existence of a climate-health-poverty trap. (Bonds *et al*., 2010) and (Strulik, 2008) posit theoretical models and offer limited empirical support, while (Tang *et al*., 2009) offers more rigorous empirical evidence. This is further supported by yet-to-be-published analyses (Bretscher and Valente, 2010; Gollin and Zimmermann, 2008; Gollin and Zimmermann, 2010; Ikefuji *et al*., 2010). Climate-related diseases such as malaria and diarrhea impair children's cognitive and physical development. This leads to poverty in their later life so that there are limited means to protect their own children against these diseases. Furthermore, high infant mortality may induce parents to have many children so that the investment in education is spread thin. An increase in infant and child mortality and morbidity due to climate change would thus trap more people in poverty.

(Zimmerman and Carter, 2003) build a model in which the risk of natural disasters causes a poverty trap: At higher risk levels, households prefer assets with a safe but low return. (Carter *et al*., 2007) find empirical support for this model at the household level, but (van den Berg, 2010) concludes the natural disaster itself has no discernible impact on investment choices. At the macro-economic level, natural disasters disproportionally affect the growth rate of poor countries (Noy, 2009).

(Bougheas *et al*., 1999; Bougheas *et al*., 2000) show that more expensive infrastructure, for example because of frequent repairs after natural disasters, slows down economic growth and that there is a threshold infrastructure cost above which trade and specialization do not occur, suggesting another mechanism through which climate could cause a poverty trap. The implications of climate change have yet to be assessed.

10.9.2.3. Conclusion

In sum, the literature on the impact of climate and climate change on economic growth and development has yet to reach firm conclusions. There is agreement that climate change would slow economic growth, by a little according to some studies and by a lot according to other studies. There is disagreement whether climate change would affect the nature of economic development, with some studies suggesting that more people may be trapped in poverty and fewer people enjoying exponential growth.

10.10. Research Needs and Priorities

Evaluating the economic aspects of the impacts has emerged as an active research area. Initial work has developed in a few key economic sectors and through economy wide economic assessments. Data, tools and methods continue to evolve to address additional sectors and more complex interactions among the sectors in the economic systems and a changing climate.

Based on a comprehensive assessment across economic sectors, few key sectors have been subject to detailed research. Multiple aspects of energy impacts have been assessed, but others remain to be evaluated, particularly economic impact assessments of adaptation both on existing and future infrastructure, but also the costs and benefits for future systems under differing climatic conditions. Studies focused on the impacts of climate change on the energy sector indicate both potential benefits and detrimental impacts across developed and developing countries. In energy supply, the deployment of extraction, transport and processing infrastructure, power plants and other installations are expected to proceed rapidly in developing countries in the coming decades to satisfy fast growing demand for energy. Designing newly deployed facilities with a view to projected changes in climate attributes and extreme weather patterns would require targeted inquiries into the impacts of climate change on the energy related resource base, conversion and transport technologies.

The economics of transportation systems and their role in overall economic activity have yet to be well understood. For water related sectors, improved estimation of flood damages to economic sectors, research on economic impacts of ecosystems, rivers, lakes and wetlands, ecosystems service, and tourism and recreation are needed. Economic assessments of adaptation strategies such as water savings technologies, particularly for semi-arid and arid developing countries, are also needed. Further, detailed studies are needed of the integrated impact of climate change on all water-dependent economic sectors, as existing studies do not examine competitiveness between water uses among sectors and economic productivity.

Although both tourism and recreation are sensitive to climate change, the literature on tourism is far more extensive. Current studies either have a rudimentary representation of the effect of weather and climate but a detailed representation of substitution between holiday destination and activities, or a detailed representation of the immediate impact of climate change but a rudimentary representation of alternatives to the affected destinations or activities.

Considerable research has been developed related to climate change and associated weather risk to insurance; however, limited research has been published on observed trends in normalized insured climate-related losses as compared to trends in direct economic climate-related losses, including insured property and agriculture losses as compared to direct economic losses. Additionally, no quantitative study could be found for projected impacts on health and life insurance, or regional markets including scenarios on hazard, exposure, vulnerability and adaption status, regulation, risk capital availability. Furthermore, little is known regarding the temporal changes of vulnerability for insured risk such as how susceptibilities of structures to damage changed in the past and can be projected to change in the future.

Little literature exists on potential climate impacts on other economic sectors, such as mining, manufacturing, and services (apart from health, insurance and tourism); in particular assessments of whether these sectors are indeed sensitive to climate and climate change.

The spillover effects of the impacts of climate change in one sector on other markets are understood in principle, but the number of quantitative studies is too few to place much confidence in the numerical results. Similarly, the impact of climate and climate change on economic growth and development is not well understood, with some studies pointing to a small or negligible effect and other studies arguing for a large or dominant effect.

Frequently Asked Questions

FAQ 10.1: How complete is the assessment of the economics of impacts of, vulnerability to and adaptation to climate change?
Initial work has developed in a few key economic sectors and through economy wide economic assessments. Data, tools and methods continue to evolve to address additional sectors and more complex interactions among the sectors in the economic systems and a changing climate.

FAQ 10.2: What is the effect of climate change on energy demand?
Climate change will reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors; the balance of the two depends on the geographic, socioeconomic and technological conditions. (10.2)

FAQ 10.3: What is the effect of climate change on energy supply?
Climate change will affect different energy sources and technologies differently, depending on the resources (water flow, wind, insolation), the technological processes (cooling) or the locations (coastal regions, floodplains) involved. Climate change may influence the integrity and reliability of pipelines and electricity grids. (10.2)

FAQ 10.4: What is the effect of climate change on water resources?
Flooding can have major economic cost both in term of impacts and adaptation costs with major sectoral and economy wide impacts due to capital destruction. Competition for water, driven by institutional, economic or social factors, many time means that water assumed to available for sector is not. (10.3)

FAQ 10.5: What is the effect of climate change on transport?
Climate change may degrade road infrastructure. Multi-modal transportation is vulnerable to changes in precipitation and temperature, thus threatening key logistics links in both commercial and passenger transportation schedules. (10.4)

FAQ 10.6: What is the effect of climate change on manufacturing and industry?
Literature on the impact of climate and climate change on industry, manufacturing and services is very scarce and no conclusion can be drawn based on the existing studies. (10.5)

FAQ 10.7: What is the effect of climate change on tourism and recreation?
There are only a few anecdotal estimates of the impact of climate change on outdoor recreation. Because of climate change, tourists are likely to spend their holidays at higher altitudes and latitudes. Climate change would affect tourism resorts, particularly ski, beach, and nature resorts. The economic implications may be substantial, with gains for countries closer to the poles and losses for countries closer to the equator. (10.6)

FAQ 10.8: What is the effect of climate change on insurance?
Through the expected increase losses and loss volatility in various regions through more frequent and/or intensive weather disasters, insurance systems are challenged to offer coverage for premiums that are still affordable, while at the same time allow for generating more risk-based capital. The latter is due to higher risk volatility necessitating more risk-based capital to compensate for large losses, with the greatest challenge in low- and middle-income countries. Solutions suggested include, first, assessing risk in a way that allows for temporal changes in hazard conditions, and second, transmitting the risk information to policyholders and stakeholders through premiums calibrated to existing risk, thereby encouraging them to reduce vulnerability through cost-effective measures. Reduction of vulnerability can be further incentivized through various insurance conditions. Besides efforts to

decrease vulnerability and the foresight of governments for large-scale prevention and the non-diversifiable disaster portion of risk, highly efficient sources of risk capital such as commercial reinsurance and maybe increasingly risk-linked securitization markets have a role in ensuring financially healthy insurance systems. (10.7)

FAQ 10.9: What is the effect of climate change on the health sector?
Increases in the frequency, intensity, and extent of extreme weather events adversely affect infrastructure and increase the demands for services, placing additional burdens on public health and health care personnel and supplies. (10.8)

FAQ 10.10: What is the effect on other services?
Few studies have evaluated the possible (economic) impacts of climate change on other economics sectors including waste management, wholesale and retail trade, engineering services and government. (10.8)

FAQ 10.11: Do the economic impacts of climate change interact with one another?
The impacts of climate change on one sector of the economy of one country in turn affect other sectors and other countries through product and input markets. For an individual sector or country, 'the market' provides an additional mechanism for adaptation and thus reduces negative impacts and increases positive ones. However, as sectoral or national studies omit market spillovers, such estimates tend to understate the total economic impact. (10.9)

FAQ 10.12: What is the effect of climate change on economic development?
The impacts of climate change would affect economic growth, but the magnitude of this effect is not well understood. Climate could be one of the causes why some countries are trapped in poverty, and climate change may make it harder to escape poverty traps. (10.9)

FAQ 10.13: What are the research priorities?
Further research, collection and access to more detailed economic data and the advancement of analytic methods and tools will be required to further assess the potential impacts of climate on key economic systems and sectors. (10.10)

APPENDIX 10.A1. Industrial Classification and Chapter Outline

Table 10.A1.1. International Standard Industrial Classification (ISIC) of All Economic Activities, Rev.4, and the outline of Chapter 10.

- A - Agriculture, forestry and fishing (10.5)
    - 01 - Crop and animal production, hunting and related service activities
    - 02 - Forestry and logging
    - 03 - Fishing and aquaculture
- B - Mining and quarrying (10.5)
    - 05 - Mining of coal and lignite
    - 06 - Extraction of crude petroleum and natural gas
    - 07 - Mining of metal ores
    - 08 - Other mining and quarrying
    - 09 - Mining support service activities
- C – Manufacturing (10.5, except C19)
    - 10 - Manufacture of food products
    - 11 - Manufacture of beverages
    - 12 - Manufacture of tobacco products
    - 13 - Manufacture of textiles
    - 14 - Manufacture of wearing apparel
    - 15 - Manufacture of leather and related products
    - 16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
    - 17 - Manufacture of paper and paper products
    - 18 - Printing and reproduction of recorded media

    - 19 - Manufacture of coke and refined petroleum products (10.2)
    - 20 - Manufacture of chemicals and chemical products
    - 21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations
    - 22 - Manufacture of rubber and plastics products
    - 23 - Manufacture of other non-metallic mineral products
    - 24 - Manufacture of basic metals
    - 25 - Manufacture of fabricated metal products, except machinery and equipment
    - 26 - Manufacture of computer, electronic and optical products
    - 27 - Manufacture of electrical equipment
    - 28 - Manufacture of machinery and equipment n.e.c.
    - 29 - Manufacture of motor vehicles, trailers and semi-trailers
    - 30 - Manufacture of other transport equipment
    - 31 - Manufacture of furniture
    - 32 - Other manufacturing
    - 33 - Repair and installation of machinery and equipment
- D - Electricity, gas, steam and air conditioning supply (10.2)
    - 35 - Electricity, gas, steam and air conditioning supply
- E - Water supply; sewerage, waste management and remediation activities
    - 36 - Water collection, treatment and supply (10.3)
    - 37 – Sewerage (10.3)
    - 38 - Waste collection, treatment and disposal activities; materials recovery (10.8)
    - 39 - Remediation activities and other waste management services (10.8)
- F – Construction (10.5)
    - 41 - Construction of buildings
    - 42 - Civil engineering
    - 43 - Specialized construction activities
- G - Wholesale and retail trade; repair of motor vehicles and motorcycles (10.8)
    - 45 - Wholesale and retail trade and repair of motor vehicles and motorcycles
    - 46 - Wholesale trade, except of motor vehicles and motorcycles
    - 47 - Retail trade, except of motor vehicles and motorcycles
- H - Transportation and storage (10.4)
    - 49 - Land transport and transport via pipelines
    - 50 - Water transport
    - 51 - Air transport
    - 52 - Warehousing and support activities for transportation
    - 53 - Postal and courier activities
- I - Accommodation and food service activities (10.6)
    - 55 - Accommodation
    - 56 - Food and beverage service activities
- J - Information and communication (10.8)
    - 58 - Publishing activities
    - 59 - Motion picture, video and television programme production, sound recording and music publishing activities
    - 60 - Programming and broadcasting activities
    - 61 - Telecommunications
    - 62 - Computer programming, consultancy and related activities
    - 63 - Information service activities
- K - Financial and insurance activities (10.7)
    - 64 - Financial service activities, except insurance and pension funding
    - 65 - Insurance, reinsurance and pension funding, except compulsory social security
    - 66 - Activities auxiliary to financial service and insurance activities
- L - Real estate activities (10.8)
    - 68 - Real estate activities
- M - Professional, scientific and technical activities (10.8)

  - 69 - Legal and accounting activities
  - 70 - Activities of head offices; management consultancy activities
  - 71 - Architectural and engineering activities; technical testing and analysis
  - 72 - Scientific research and development
  - 73 - Advertising and market research
  - 74 - Other professional, scientific and technical activities
  - 75 - Veterinary activities
- N - Administrative and support service activities (10.8 except N79)
  - 77 - Rental and leasing activities
  - 78 - Employment activities
  - 79 - Travel agency, tour operator, reservation service and related activities (10.6)
  - 80 - Security and investigation activities
  - 81 - Services to buildings and landscape activities
  - 82 - Office administrative, office support and other business support activities
- O - Public administration and defence; compulsory social security (10.8)
  - 84 - Public administration and defence; compulsory social security
- P – Education (10.8)
  - 85 - Education
- Q - Human health and social work activities (10.8)
  - 86 - Human health activities
  - 87 - Residential care activities
  - 88 - Social work activities without accommodation
- R - Arts, entertainment and recreation (10.6)
  - 90 - Creative, arts and entertainment activities
  - 91 - Libraries, archives, museums and other cultural activities
  - 92 - Gambling and betting activities
  - 93 - Sports activities and amusement and recreation activities
- S - Other service activities (10.8)
  - 94 - Activities of membership organizations
  - 95 - Repair of computers and personal and household goods
  - 96 - Other personal service activities
- T - Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use (10.8)
  - 97 - Activities of households as employers of domestic personnel
  - 98 - Undifferentiated goods- and services-producing activities of private households for own use
- U - Activities of extraterritorial organizations and bodies (10.8)
  - 99 - Activities of extraterritorial organizations and bodies

APPENDIX 10.B. Industrial Classification and Literature Search

Table 10.B.1 International Standard Industrial Classification (ISIC) of All Economic Activities, Rev.4, and nil returns in a literature search on Scopus.

- A - Agriculture, forestry and fishing
  - 01 - Crop and animal production, hunting and related service activities
  - 02 - Forestry and logging
  - 03 - Fishing and aquaculture
- B - Mining and quarrying
  - 05 - Mining of coal and lignite
  - 06 - Extraction of crude petroleum and natural gas
  - 07 - Mining of metal ores
  - 08 - Other mining and quarrying
    - Climate change impact & quarrying: No results*
  - 09 - Mining support service activities

- C – Manufacturing
  - 10 - Manufacture of food products
    - Climate change impact & food products: No results*
    - Climate change impact & food processing: No results*
  - 11 - Manufacture of beverages
    - Climate change impact & beverages: No results*
  - 12 - Manufacture of tobacco products
    - Climate change impact & tobacco: No results*
  - 13 - Manufacture of textiles
    - Climate change impact & textiles: No results*
  - 14 - Manufacture of wearing apparel
    - Climate change impact & apparel: No results*
  - 15 - Manufacture of leather and related products
    - Climate change impact & leather: No results*
  - 16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
    - Climate change impact & wood: No results*
  - 17 - Manufacture of paper and paper products
    - Climate change impact & pulp paper: No results*
  - 18 - Printing and reproduction of recorded media
    - Climate change impact & printing: No results*
    - Climate change impact & recorded media: No results*
  - 19 - Manufacture of coke and refined petroleum products
  - 20 - Manufacture of chemicals and chemical products
    - Climate change impact & chemical production: No results*
  - 21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations
    - Climate change impact & pharmaceutical: No results*
  - 22 - Manufacture of rubber and plastics products
    - Climate change impact & rubber: No results*
    - Climate change impact & plastic: No results*
  - 23 - Manufacture of other non-metallic mineral products
    - Climate change impact & cement: No results*
    - Climate change impact & glass: No results*
  - 24 - Manufacture of basic metals
    - Climate change impact & steel: No results*
    - Climate change impact & iron: No results*
    - Climate change impact & alumina: No results*
    - Climate change impact & aluminum: No results*
  - 25 - Manufacture of fabricated metal products, except machinery and equipment
    - Climate change impact & metal: No results*
  - 26 - Manufacture of computer, electronic and optical products
    - Climate change impact & equipment: No results*
  - 27 - Manufacture of electrical equipment
    - Climate change impact & equipment: No results*
  - 28 - Manufacture of machinery and equipment n.e.c.
    - Climate change impact & equipment: No results*
    - Climate change impact & machinery: No results*
  - 29 - Manufacture of motor vehicles, trailers and semi-trailers
    - Climate change impact & vehicle: No results*
  - 30 - Manufacture of other transport equipment
    - Climate change impact & equipment: No results*
  - 31 - Manufacture of furniture
    - Climate change impact & furniture: No results*
  - 32 - Other manufacturing

    - 33 - Repair and installation of machinery and equipment
        - Climate change impact & equipment: No results*
        - Climate change impact & machinery: No results*
- D - Electricity, gas, steam and air conditioning supply
    - 35 - Electricity, gas, steam and air conditioning supply
- E - Water supply; sewerage, waste management and remediation activities
    - 36 - Water collection, treatment and supply
    - 37 - Sewerage
    - 38 - Waste collection, treatment and disposal activities; materials recovery
    - 39 - Remediation activities and other waste management services
- F – Construction
    - 41 - Construction of buildings
    - 42 - Civil engineering
    - 43 - Specialized construction activities
- G - Wholesale and retail trade; repair of motor vehicles and motorcycles
    - 45 - Wholesale and retail trade and repair of motor vehicles and motorcycles
    - 46 - Wholesale trade, except of motor vehicles and motorcycles
    - 47 - Retail trade, except of motor vehicles and motorcycles
- H - Transportation and storage
    - 49 - Land transport and transport via pipelines
    - 50 - Water transport
    - 51 - Air transport
    - 52 - Warehousing and support activities for transportation
    - 53 - Postal and courier activities
- I - Accommodation and food service activities
    - 55 - Accommodation
    - 56 - Food and beverage service activities
- J - Information and communication
    - 58 - Publishing activities
    - 59 - Motion picture, video and television programme production, sound recording and music publishing activities
    - 60 - Programming and broadcasting activities
    - 61 - Telecommunications
    - 62 - Computer programming, consultancy and related activities
    - 63 - Information service activities
- K - Financial and insurance activities
    - 64 - Financial service activities, except insurance and pension funding
    - 65 - Insurance, reinsurance and pension funding, except compulsory social security
    - 66 - Activities auxiliary to financial service and insurance activities
- L - Real estate activities
    - 68 - Real estate activities
- M - Professional, scientific and technical activities
    - 69 - Legal and accounting activities
    - 70 - Activities of head offices; management consultancy activities
    - 71 - Architectural and engineering activities; technical testing and analysis
    - 72 - Scientific research and development
    - 73 - Advertising and market research
    - 74 - Other professional, scientific and technical activities
    - 75 - Veterinary activities
- N - Administrative and support service activities
    - 77 - Rental and leasing activities
    - 78 - Employment activities
    - 79 - Travel agency, tour operator, reservation service and related activities
    - 80 - Security and investigation activities

  - 81 - Services to buildings and landscape activities
  - 82 - Office administrative, office support and other business support activities
- O - Public administration and defence; compulsory social security
  - 84 - Public administration and defence; compulsory social security
- P – Education
  - 85 - Education
- Q - Human health and social work activities
  - 86 - Human health activities
  - 87 - Residential care activities
  - 88 - Social work activities without accommodation
- R - Arts, entertainment and recreation
  - 90 - Creative, arts and entertainment activities
  - 91 - Libraries, archives, museums and other cultural activities
  - 92 - Gambling and betting activities
  - 93 - Sports activities and amusement and recreation activities
- S - Other service activities
  - 94 - Activities of membership organizations
  - 95 - Repair of computers and personal and household goods
  - 96 - Other personal service activities
- T - Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
  - 97 - Activities of households as employers of domestic personnel
  - 98 - Undifferentiated goods- and services-producing activities of private households for own use
- U - Activities of extraterritorial organizations and bodies
  - 99 - Activities of extraterritorial organizations and bodies

*No results = no results for the impact of climate change on this particular economic activity. There may be results for the impact of climate change on a related activity, or for the impact of the activity on climate change.

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Table 10-1. Main impacts of CC and EWEs on energy supply.

Tech	Changes in climatic or related attributes	Impacts	Adaptation options
Thermal and nuclear power plants	Increasing air temperature	Reduces efficiency of thermal conversion by 0.1-0.2% in the USA; by 0.1-0.5% in Europe where the capacity loss is estimated in the range of 1-2%/1°C temperature increase, accounting for decreasing cooling efficiency and reduced operation level/shutdown	Siting at locations with cooler local climates where possible
	Changing (lower) precipitation and increasing air temperature increases temperature and reduces the availability of water for cooling	Less power generation; annual average load reduction by 0.1-5.6% depending on scenario	Use of non-traditional water sources (e.g., water from oil and gas fields, coal mines and treatment, treated sewage); Re-use of process water from flue gases (can cover 25-37% of the power plants cooling needs), coal drying, condensers (dryer coal has higher heating value, cooler water enters cooling tower),, flue-gas desulphurization; Using ice to cool air before entering the gas turbine increases efficiency and output, melted ice used in cooling tower; Condenser mounted at the outlet of cooling tower to reduce evaporation losses (by up to 20%). Alternative cooling technologies: dry cooling towers, regenerative cooling, heat pipe exchangers; Costs of retrofitting cooling options depend on depend on features of existing systems, distance to water, required additional equipment, estimated at US$250,000-500,000/MW
	Increasing frequency of extreme hot temperatures	Exacerbating impacts of warmer conditions: reduced thermal and cooling efficiency; limited cooling water discharge; overheating buildings; self-ignition of coal stockpiles	Cooling of buildings (air conditioning) and of coal stockpiles (water spraying)
	Drought: reduced water availability	Exacerbating impacts of warmer conditions, reduced operation and output, shutdown	Same as reduced water availability under gradual CC
Hydropower	Increase/decrease in average water availability	Increased/reduced power output	Schedule release to optimize income
	Changes in seasonal and inter-annual variation in inflows (water availability)	Shifts in seasonal and annual power output; floods and lost output in the case of higher peak flows	Soft: adjust water management Hard: build additional storage capacity, improve turbine runner capacity
	Extreme precipitation causing floods	Direct and indirect (by debris carried from flooded areas) damage to dams and turbines, lost output due to releasing water through by-pass channels	Soft: adjust water management Debris removal Hard: increase storage capacity
Solar energy	Increasing mean temperature	Improving performance of TH (especially in colder regions), reducing efficiency of PV and CSP with water cooling; PV efficiency drops by ~0.5%/1°C temperature increase for crystalline Si and thin-film modules as well, but performance varies across types of modules, with thin film modules performing better; Long-term exposure to heat causes faster aging	

	Changing cloudiness	Increasing unfavourable (reduced output), decreasing beneficial (increased output) for all types, but evacuated tube collectors for TH can use diffuse insolation. CSP more vulnerable (cannot use diffuse light)	Apply rougher surface for PV panels that use diffuse light better; optimize fixed mounting angle for using diffuse light, apply tracking system to adjust angle for diffuse light conditions; Install/increase storage capacity
	Hot spells	Material damage for PV, reduced output for PV and CSP; CSP efficiency decreases by 3-9% as ambient temperature increases from 30 to 50°C and drops by 6% (tower) to 18% (trough) during the hottest 1% of time	Cooling PV panels passively by natural ail flows or actively by forced air or liquid coolants
	Hail	Material damage to TH: evacuated tube collectors are more vulnerable than flat plate collectors; Fracturing as glass plate cover, damage to photoactive material	Flat plate collectors: using reinforced glass to withstand hailstones of 35mm (all of 15 tested) or even 45 mm (10 of 15 tested); only 1 in 26 evacuated tube collectors withstood 45mm hailstones Increase protection to current standards or beyond them
Wind power	Windiness: total wind resource (multi-year annual mean wind power densities); likely to remain within ±50% of current values in Europe and North America; within ±25% of 1979-2000 historical values in contiguous USA	Change in wind power potential	Site selection
	Wind speed extremes: gust, direction change, shear	Structural integrity from high structural loads; fatigue, damage to turbine components; reduced output	Turbine design, lidar-based protection

Sources: (Nee Schulz, 2012),(Parkpoom *et al*., 2005), (ADAM-Project, 2009),(Ott and Richter, 2008)(Feeley III *et al*., 2008; Förster and Lilliestam, 2009; Hoffmann *et al*., 2010; Laboratory *et al*., 2007; Linnerud *et al*., 2011)(Mukheibir, ; Williams and Toth, 2012), (Schaefli *et al*., 2007)(Markoff and Cullen, 2008),(Droogers, 2009). Sources: [1] (Bloom *et al*., 2008; Bradsher, 2009; DOE, 2007; Honeyborne, 2009; Kurtz *et al*., 2009a; Kurtz *et al*., 2009b; Norton, 2006; Patt *et al*., 2011; Pryor *et al*., 2006; Pryor and Barthelmie, 2010; Pryor and Schoof, 2010; Sailor *et al*., 2008; Walter *et al*., 2006)(Christensen and Busuioc, 2007; Haugen and Iversen, 2008; Leckebusch *et al*., 2008; Pryor and Barthelmie, 2011(b)) (Pryor and Barthelmie, 2012)(EPA , 2001; SPF, 2009).

Table 10-2: Main impacts of CC and EWEs on pipelines and the electricity grid.

Tech	Changes in climatic or related attribute	Impacts	Adaptation options
Pipelines	Melting permafrost	Destabilizing pillars, obstructing access for maintenance and repair	Adjust design code and planning criteria, install disaster mitigation plans
	Increasing high wind, storms, hurricanes	Damage to offshore and onshore pipelines and related equipment, spills; lift and blow heavy objects against pipelines, damage equipment	Enhance design criteria, update disaster preparedness
	Flooding caused by heavy rain, storm surge or sea-level rise	Damage to pipelines, spills	Siting (exclude flood plains), water proofing
Electricity grid	Increasing average temperature	Increased transmission line losses	Include increasing temperature in the design calculation for maximum temperature/rating
	Increasing high wind, storms, hurricanes	Direct mechanical damage to overhead lines, towers, poles, substations, flashover caused by live cables galloping and thus touching or getting too close to each other; indirect mechanical damage and short circuit by trees blown over or debris blown against overhead lines	Adjust wind loading standards, reroute lines alongside roads or across open fields, vegetation management, improved storm and hurricane forecasting
	Extreme high temperatures	Lines and transformers may overheat and trip off; flashover to trees underneath expanding cable	Increase system capacity, increase tension in the line to reduce sag, add external coolers to transformers
	Combination of low temperature, wind and rain, ice storm	Physical damage (including collapse) of overhead lines and towers caused by ice build-up on them	Enhance design standard to withstand larger ice and wind loading, reroute lines alongside roads or across open fields, improve forecasting of ice storms impacts on overhead lines and on transmission circuits

Sources: (Bayliss, 2007; Hines *et al*., 2009; Krausmann and Mushtaq, 2008; Reed, 2008; Winkler *et al*., 2010)Cruz and Krausmann (2012),(Vlasova and Rakitina, 2010), (Ward, 2012), (McColl, 2012).

Table 10-3: Summary of recent literature on the economic impacts of climate change and extreme weather on the energy sector.

Study	Model Type	Climate Impacts Modelled	Energy/Economic Impacts	Regions	Sectors Studied
(Bosello *et al*., 2009)	IAM	Rising temperatures/ changing demand for energy; impacts from 4 other sectors/events (Global, 2001 - 2050)	Change in GDP in 2050 due to rising temperatures and changing energy demand: 0% to 0.75% (+1.2°C); -0.1% to 1.2% (+3.1°C)	14	4
(Jorgenson and Goettle, 2004)	CGE	Rising temperatures/ changing demand for energy; climate impacts from 3 other sectors (USA, 2000 - 2100)	Optimistic adaptation: 4% to 6.7% higher energy productivity per year (2000 – 2100); Output from electricity: -6% in 2050; GDP is +0.7% (aggregate all sectors, avg annual 2000 – 2100) Pessimistic adaptation: 0.5% to 2.2% lower energy productivity per year; Output from electricity: +2% in 2050; GDP is -0.6% (aggregate impact all sectors)	1	35
(Bosello *et al*., 2007)	CGE	Rising temperatures/ changing demand for energy (Global, 2050)	Change in GDP in 2050 (perfect competition): -0.297% to 0.027%; Change in GDP in 2050 (imperfect competition): -0.303% to 0.027%	8	1
(Aaheim *et al*., 2009)	CGE	Change in precipitation -> share of hydro power; rising temperatures/ changing demand for energy ; impacts from 4 other sectors (Western Europe, 2071 – 2100)	Impact from all sectors in 2100: GDP in cooler regions: -1% to -0.25% GDP in warmer regions: -3% to -0.5% Adaptation can mitigate 80% to 85% of economic impact	8	11
(Boyd and Ibarraran, 2009)	CGE	Drought scenario affecting hydro plus 3 other sectors (Mexico, 2005 - 2026)	Generation output in 2026: -2.1% Refining output: -10.1% Coal output: -7.8% NG output: -2% Crude oil output: +1.7% GDP: -3% With adaptation: Generation output in 2026: 0.24%% Refining output: 1.36%% Coal output: 1.09%% NG output: 0.34%% Crude oil output: 0.22% GDP: 0.33%	1	2
(Jochem *et al*., 2009)	PE/ CGE	Rising temperatures/ changing demand for energy; Change in technical potential of renewables; Change in rainfall -> change in hydro; High temperatures -> water temperatures exceeding regulatory limits (Europe); High temperatures -> greater electric grid losses and lower thermal efficiency; generic extreme events -> reduced capital stock in CGE model (EU27+2, 2005 – 2050)	GDP (Europe): -50 billion € p.a. in 2035 GDP (Europe): -240 billion € p.a. in 2050 GDP (EU regions): -0.1% to -0.4% in 2035 GDP (EU regions): -0.6% to -1.3% in 2050 Jobs (Europe): -380K in 2035 Jobs (Europe): -1 million in 2050	25	1
(Eboli *et al*., 2010b)	CGE	Rising temperatures/ changing demand for energy; climate impacts	By 2100, change in GDP due to climate impacts on energy	8	17

		in 4 other sectors modelled (Global, 2002 - 2100)	demand vary by country between ~ -0.15% and 0.7%. USA and Japan were negative and all other countries positive. Overall economic impact from all sectors is neutral to positive for developed countries and negative for developing.		
(Golombek *et al.*, 2011)	PE	Rising temperatures/ changing demand for energy; Rising temp/ reduced thermal efficiency; change in water inflow (Western Europe, 2030)	Net impact on the price of electricity is a 1% increase. Generation decreases by 4%	13	4
(Bye *et al.*, 2006)	PE	Water shortages (Nordic countries, hypothetical 2 year period)	Water shortage scenarios can lead to a 100% increase in electricity prices at peak demand over a 2 year period. Higher prices lead to marginal reductions in demand (~ 1% - 2.25%).	4	1
(Koch *et al.*, 2012)	PE	High temperatures -> water temperatures exceeding regulatory limits (Berlin, 2010 - 2050)	Thermal plant outages amounting to 60 million EURO for plants in Berlin through 2050	1	1
(Gabrielsen *et al.*, 2005)	Econo metric	Rising temperatures/ changing demand for energy; change in water inflow; change in wind speeds (Nordic countries, 2000 - 2040)	Net change in electricity supply in 2040: 1.8%. Change in electricity demand: 1.4%. Change in electricity price: -1.0%	4	1
(DOE, 2009)	PE	Drought scenario (Western Electric Coordinating Council, USA, 2010 – 2020)	In 2020, 3.7% reduction in coal generation; 43.4% increase in NG gen; 29.3% reduction in hydro gen. Production cost increase of $3.5 billion. Average monthly electricity prices up 8.1% (Nov) to 24.1% (Jul).	1	1

Table 10-4: Observed normalized insured losses from weather hazards.

Region / peril accounted for in normalized insured losses	Observation period	Trend (aggregation mode)	References
Australia / aggregate of bushfire, flood, hailstorm, thunderstorm, tropical cyclone	1967 – 2006	No trend (annual aggregates)	[6]
USA / winter storms (ice storms, blizzards and snow storms)	1949 – 2003	Positive trend (pentade totals) Positive trend (average loss per state, pentade totals)	[2]
USA / all flood ("flood only" and floods specifically caused by convective storms, tropical cyclones, snow-melt)	1972 - 2006	Positive trend (annual aggregates)	[3]
USA / tropical cyclones	1949 - 2004	No statistical trend assessment. Observation: Increase (7-year totals)	[4]
USA / hail storm	1951 – 2006	No statistical trend assessment. Observation within top-ten major hail storm losses: Increase in frequency and loss in the 1992 – 2006 period as compared to 1951 – 1990	[5]
World / all weather-related USA / all weather-related USA / floods USA / convective events USA / winter storms USA / tropical cyclones USA / heat episodes USA / cold spells Germany / all weather-related Germany / floods Germany / convective events Germany / winter storms	1990 – 2008 1973 – 2008 1973 – 2008 1973 – 2008 1973 – 2008 1973 – 2008 1973 – 2008 1973 – 2008 1980 – 2008 1980 – 2008 1980 – 2008 1980 – 2008	No trend (annual aggregates) Positive trend (annual aggregates) Positive trend (annual aggregates) Positive trend (annual aggregates) Positive trend (annual aggregates) Positive trend (annual aggregates) Positive trend (annual aggregates) No trend (annual aggregates) Positive trend (annual aggregates) No trend (annual aggregates) No trend (annual aggregates) Positive trend (annual aggregates)	[1]

References: [1] (Barthel and Neumayer, 2011) [2] Changnon, 2007; [3] Changnon, 2008; [4] Changnon, 2009a; [5] Changnon, 2009b; [6] Crompton and McAneney, 2008.

Table 10-5: Climate change projections of insured losses.

Hazard / insurance line	Region	2021-2050 (2050s) relative to current climate	End of 21st century relative to current climate	References
Extratropical storm, Homeowners' insurance*	Portugal/Spain France Switzerland UK/Ireland Germany North Rhine-Westphalia Belgium/Netherlands Sweden/Norway Poland Europe in general	-4% to -2% A1B [1] +2% to +9% A1B [1] - +6% to +13% A1B [1] +5% to +18% A1B [1] - +4% to +7% A1B [1] - +2% to +12% A1B [1] -	-10% to -5% A1B, A2 [1;3] +6% to +47% A1B, A2 [1;3;5] +19% A2 [5] +17% to +43% A1B, A2 [1;2;3;5;6] +15% to +114% A1B, A2 [1;2;3;5] +8% to +19% A1B, A2 [4] +8% to +80% A1B, A2 [1;5] +7% to +95% A1B, A2 [3;5] -23% to +12% A1B, A2 [1;5] +44% A2 [5]	[1] Donat et al., 2011; [2] Leckebusch et al., 2007; [3] (Pinto *et al.*, 2007) [4] (Pinto *et al.*, 2009) [5] (Schwierz *et al.*, 2010) [6] Dailey et al., 2009.
Extratropical storm, Homeowners' insurance*	Germany	+17% to +64% A1B (2041-2070)		German Insurance Association, 2011 [scientific publications forthcoming]
Hail storm, Agricultural insurances*	Netherlands	+1°C (+2°C) global mean temperature by 2050s: Outdoor farming insurance: +25% to +29% (+49% to +58%) Greenhouse horticulture insurance: +116% to +134% (+219% to +269%)		(Botzen *et al.*, 2010b)
Hail storm, Homeowners' insurance*	Germany	+61% A1B (2041-2070 relative to 1984-2008)		German Insurance Association, 2011 [scientific studies forthcoming]
Flood, Homeowners' flood insurance*	Germany	+91% (mean of seven member ensemble comprising B1, A1B, A2 scenarios) (2041-2070 relative to 1961-2000)	+114% (mean of seven member ensemble comprising B1, A1B, A2 scenarios) (2071-2100 relative to 1961-2000)	German Insurance Association, 2011 [scientific studies forthcoming]
Flood, Property insurance*	The Netherlands	Expected value of loss higher by 125% by 2040 (+ 24cm SLR) relative to 2015	Expected value of loss higher by 1,784% by 2100 (+85cm SLR) relative to 2015	(Aerts and Botzen, 2011)
Flood, Property insurance*	United Kingdom	+2° global mean temperature (approx. 2040s	+4° global mean temperature (approx. 2070s according to A1FI) Mean annual loss +14%	Dailey et al., 2009

		according to A1B or A2) Mean annual loss +8% 100-year loss +18% 200-year loss +14%	100-year loss +30% 200-year loss +32%	
Typhoon, Property insurance*	China	+2° global mean temperature (approx. 2040s according to A1B or A2) Mean annual loss +20% 100-year loss +7% 200-year loss +14%	+4° global mean temperature (approx. 2070s according to A1FI) Mean annual loss +32% 100-year loss +9% 200-year loss +17%	Dailey et al., 2009
Storms, pests, diseases driven by climate, Paddy rice insurance*	Japan		Decrease in rice yield in central and western Japan, increase in northern Japan. Paddy rice insurance payouts will decrease by 13%, caused by changed standard yield.	Iizumi et al., 2008

*Spatial distribution and damage susceptibility of insured values assumed to be unchanged over time.

Table 10-6: Supply-side challenges and sensitivities.

Challenges that increase in the climate change context	Example / Explanation
Failure to reflect temporal changes in hazard condition in risk management	Following the devastating 2004 and 2005 hurricane seasons, the losses of Florida's homeowners' insurance accumulated since 1985 exceeded the cumulative direct premiums earned by 31%. Consequence of the upswing and peak in hurricane activity: One insurer liquidated, two seized by regulation due to insolvency; reduced coverage availability in high-risk areas [9].
Misguided incentives additionally increasing risk	US National Flood Insurance Program (NFIP) allows for a vicious circle of built-up areas already existing within flood plains pressing authorities to construct or improve protecting levees which in turn lead to even more development attracted by NFIP premium discounts, although exposed to extreme flooding events [11; 17; SREX 1.4.3.]. Additionally, older properties situated within flood plains and accounting for 16% of losses in the period 1978-2008 pay premiums substantially below the risk-adequate level [1;6;7;12;11;13]. These features represent incentives to not reduce individual flood risk adequately. Finally, policy holders residing in flood plains where flood cover was made precondition for mortgage drop the cover after only two to four years, accounting for missing insurance penetration and insufficient built-up of NFIP risk capital [12; 11;13]. All these features, together with some others, account for the fact that NFIP has continuously been running a cumulative operating deficit, reaching more than US$ 20bn after the big hurricane catastrophes by 2006 [12;13;6;7].
Non-quantifiable uncertainties increasing risk	Ambiguity as to what degree climate change may modify regional weather hazards – model projections are not unequivocal [2; 3]. Uncertainty about prospects of post-disaster regulatory/jurisdictional pressures, e.g. to extend claims payments beyond the original coverage [9].
Liability insurance impacted by new climate risk	Chances for success of litigation in the U.S. where damages from greenhouse gas emissions are sought seem small, due to legal obstacles [4;5;8;15]. But defense costs can be high and may be covered by liability insurance. As CO_2 emissions were declared pollution (US Supreme Court/EPA), regulation on limits for CO_2 emissions is ongoing and non-compliance could impose liability for CO_2 emissions in the near future, which will be covered by liability insurance. This pending risk has not yet been adequately taken into account, as was the case with escalating environmental liability claims in the late twentieth century [10; 14]. The Supreme Court of Virginia ruled on 20 April 2012 that the emissions of greenhouse gases by a specific energy company according to a "clear scientific consensus" had global warming and the damages suffered by the Inupiat village of Kivalina as consequences. Hence, the damage cannot be viewed as accident, i.e. it is excluded from liability insurance coverage in this case [16].

References: [1] (Burby, 2006) [2] Charpentier, 2008; [3] Collier et al., 2009; [4] Ebert, 2010; [5] Faure and Peeters, 2011; [6] GAO, 2010; [7] GAO, 2011; [8] Gerrard, 2007; [9] Grace and Klein, 2009; [10] Hecht, 2008; [11] Kousky and Kunreuther, 2010; [12] Michel-Kerjan, 2010; [13] Michel-Kerjan and Kunreuther, 2011; [14] Mills, 2009; [15] Steward and Willard, 2010; [16] (Supreme Court of Virginia, U.S.A., 2012) [17] (Zahran *et al.*, 2009).

Table 10-7: Products and systems responding to changes in weather risks.

Response option	Example/Explanation
Risk-adjusted premiums convey the risk to the insureds, encouraging them to adaptive measures	According to an investigation, prior to Germany's disastrous River Elbe flood in 2002, 48.5% of insured households had obtained information on flood mitigation or were involved in emergency networks and 28.5% implemented one of several mitigation measures compared with 33.9% and 20.5%, respectively, of uninsured households [32].
Conditions of insurance policies incentivizing vulnerability reduction	Premium discounts for compliance with local building codes or other prevention options [33;21]; long-term natural-hazard insurance tied to the property and linked to mortgages and loans granted for prevention measures [21;22;28]; share of the insured in claims payment payments by deductibles or upper coverage limits; exclusion of systematically affected property [1;5;6;7;8;10;16;32].
Amplifying factors in large disaster losses included in risk models	Evacuation and systemic economic catastrophe impacts, adversely affecting regional workforce and repair capacity, or knock-on catastrophes following initial catastrophes, e.g. long-term flooding following hurricane landfall [30].
Diversifying large disaster risk across securitization markets	Following the hurricane disasters of 2004 and 2005, securitisation instruments, e.g. catastrophe bonds, industry loss warranties and sidecars acquired greater prominence and have been recovering again from the market break of the financial crisis [15; 11; 13]. Catastrophe bonds, covering part of the exposure to disaster losses, are designed so that in the absence of a large catastrophe the investor receives an above-market return. If a parametric trigger point is exceeded, e.g. an index based on observed gust wind speeds, the (re)insurer's obligation to pay the interest and/or principal is waived. The (re)insurer can use the funds to cover the corresponding losses. Weather derivatives are further instruments used to transfer risks to the capital markets [12;23;29]. There are also multiple-trigger "hybrid" products available, combining a parametric trigger-based catastrophe bond with a trigger-based protection against a simultaneous drop in stock market prices, thereby hedging against a double hit from direct disaster loss and losses incurred by the asset management side [13;4;31].
Index-based weather crop insurance products	Index-based crop insurance is available in 40% of middle-income countries, with enlarged systems beyond pilot implementation only in India and Mexico [26;19]. There are schemes coupled with access to advanced technology [3;10;19;26]. Various schemes exist – often in pilot form – or have been proposed for cumulative rainfall, cumulative temperature, vegetation index, livestock mortality per region, or cumulative reservoir inflow for irrigation purposes [3;23;25]. Pooling local schemes across climate regions can reduce risk capital requirements [9;27]. The disaster risk layer and high start-up costs (weather-data collection, risk modelling, education) necessitate subsidies from the state or donors [10;26].
Improvements to basis risk coupled to index-based weather insurance	Basis risk can be strongly reduced if the index scheme is applied to an area-yield trigger in a region with homogeneous production potential and/or to the uppermost disaster risk layer only. Further on, it can be absorbed if the index insurance works at aggregate level, e.g. to cover crop-credit portfolios or cooperatives, and if once satellite-based remote-sensing technology can be used to establish plot identification, vegetation status, yield estimation and loss assessment [17].
Sovereign insurance schemes	Economic theory about the public sector's risk neutrality argues (i) that risks borne publicly render the social cost of risk-bearing insignificant and (ii) that disaster loss is seen small in comparison with a government's portfolio of diversified assets [2]. This theory proved inadequate if applied to relatively vulnerable small-sized middle to low-income countries [14], thereby rehabilitating sovereign insurance. For the Caribbean scheme CCRIF, that pools states, the reduction in premium cost per country is estimated to be 45–50% [25]. Pooling natural catastrophe risks across an array of megacities has also been proposed, but not yet implemented [20].

References: [1] (Aakre *et al.*, 2010) [2] (Arrow and Lind, 1970) [3] (Barnett *et al.*, 2008) [4] (Barrieu and Loubergé, 2009) [5] (Botzen and van den Bergh, 2008) [6] (Botzen and van den Bergh, 2009) [7] (Botzen *et al.*, 2009) [8] (Botzen *et al.*, 2010a) [9] Candel, 2007; [10] Collier et al., 2009; [11] Cummins, 2012; [12] Cummins and Mahul, 2009; [13] Cummins and Weiss, 2009; [14] Ghesquiere and Mahul, 2007; [15] Guy Carpenter, 2011; [16] Hecht, 2008; [17] Herbold, 2010; [18] Herweijer et al., 2009; [19] Hess and Hazell, 2009; [20] Hochrainer and Mechler, 2011; [21] Kunreuther et al., 2009; [22] Kunreuther and Michel-Kerjan, 2009; [23] Leiva and Skees, 2008; [24] Linnerooth-Bayer et al., 2009; [25] Linnerooth-Bayer and Mechler, 2009; [26] Mahul and Stutley, 2010; [27] Meze-Hausken et al., 2009; [28] Michel-Kerjan and Kunreuther, 2011; [29] Michel-Kerjan and Morlaye, 2008; [30] Muir-Wood and Grossi, 2008; [31] Scheurig , 2011; [32] (Thieken *et al.*, 2006) [33] (Ward *et al.*, 2008)

Table 10.8: Governance, public-private partnerships, and insurance market regulation.

Structural element	Example/Explanation
Public-private partnerships involving government intervention on the non-diversifiable disaster risk portion	Systems with government intervention range from ex ante risk financing design, such as public monopoly natural hazard insurance (e.g. Switzerland, with inter-cantonal pool) or compulsory forms of coverage to maximize the pool of insureds (e.g. Spain, France, with unlimited state guarantee on top), to ex post financing design, such as taxation-based governmental relief funds (e.g. Austria, Netherlands). In between these boundaries rank predominantly private insurance markets, in several countries combined with governmental post-disaster ad hoc relief (e.g. Germany, Italy, UK, Poland, USA). For all of these systems, pros and cons are discussed [12;11;14;5;1;4].
Care for people who cannot afford insurance (any more)	Either by funds outside the insurance system, e.g. insurance vouchers [7], or by premium subsidies for the catastrophic risk portion [1;14].
Public-private partnership to expedite agricultural development	Insurance improve the farmers' creditworthiness that in turn strengthens their adaptive capacity. For instance, by means of loans farmers can step from low-yield to higher-yield cropping systems [3;8;9].
Proposals for adaptation oriented climate change risk management frameworks to UNFCCC	Risk prevention and risk reduction is the starting point (AOSIS, Switzerland and MCII) that can absorb many of the smaller weather risks, and various forms of insurance are meant to cover all of the remaining risks [2;6;8;10;13].

References: [1] (Aakre *et al*., 2010) [2] (AOSIS, 2008) [3] (Barnett *et al*., 2008) [4] (Botzen and van den Bergh, 2008) [5] (Bruggeman *et al*., 2010) [6] (The Geneva Association, 2009) [7] Kunreuther et al., 2009; [8] Linnerooth-Bayer et al., 2009; [9] Mahul and Stutley, 2010; [10] MCII, 2008; [11] (Schwarze and Wagner, 2007) [12] (Schwarze *et al*., 2011) [13] (Swiss Confederation, 2008) [14] (Van den Berg and Faure, 2006)

Figure 10-1.
Source: (Williams and Toth, 2012)