10. Key Economic Sectors and Services

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Executive Summary

This chapter assesses the implications of climate change on economic activity in key economic sectors and services, on economic welfare, and on economic development.

For most economic sectors, the impact of climate change will be small relative to the impacts of other drivers (*high agreement, medium evidence*). Changes in population, age, income, technology, relative prices, lifestyle, regulation, governance and many other aspects of socio-economic development will have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change [10.10].

Climate change will 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 a 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 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. Several options are available to cope with reduced water availability but at higher cost; however, decreased efficiency of thermal conversion remains a primary concern. 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 may influence the integrity and reliability of pipelines and electricity grids (*medium agreement, medium evidence*). Pipelines and electric transmission lines have been designed and operated for over a century in diverse and often extreme climatic conditions on land from hot deserts to permafrost areas and increasingly at sea. Due to the private nature and high economic value to the energy sector, they have been designed to higher tolerance levels than most transportation infrastructure. Climate change may require changes in design standards for the construction and operation of pipelines and power transmission and distribution lines. Adopting existing technology from other geographical and climatic conditions may reduce the cost of adapting new infrastructure as well as the cost of retrofitting existing pipelines and grids to the changing climate, sea-level and weather conditions which is likely to become more intense over time. [10.2]

Climate change will have impacts, positive and negative and varying in scale and intensity, on water supply infrastructure and water demand (*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 is not available in sufficient quantity or quality for some uses or locations. [10.3]

Climate change may negatively affect transport infrastructure (*high agreement, limited evidence*). Transport infrastructure malfunctions if the weather is outside the design range, which would happen more frequently as the climate continues to change. All infrastructure is vulnerable to freeze-thaw cycles. Paved roads are particularly vulnerable to temperature extremes; unpaved roads and bridges to precipitation extremes. Transport infrastructure on ice or permafrost is especially vulnerable. [10.4]

Climate change will affect tourism resorts, particularly ski resorts, beach resorts, and nature resorts (*high agreement, robust evidence*) and tourists may 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 entail gains for countries closer to the poles and higher up the mountains and losses for other countries. The demand for outdoor recreation is affected by weather and climate, and impacts will vary geographically and seasonally. [10.6]

Climate change will affect insurance systems (*high agreement, robust evidence*). More frequent and/or intensive weather disasters as projected for some regions/hazards will increase losses and loss variability in various regions and challenge insurance systems to offer affordable coverage while raising more risk-based capital, particularly in low- and middle-income countries. Economic-vulnerability reduction through insurance has proven effective. Large-scale public-private risk prevention initiatives and government insurance of the non-diversifiable portion of risk offer example mechanisms for adaptation. Commercial reinsurance and risk-linked securitization markets also have a role in ensuring financially resilient insurance and risk transfer systems. [10.7]

Climate change will affect the health sector (*high agreement, medium evidence*) through increases in the frequency, intensity, and extent of extreme weather events as well as increasing demands for health care services and facilities, including public health programs, disease prevention activities, health care personnel, infrastructure, and supplies related to treatment of infectious deceases and temperature related events. [10.8]

Well-functioning markets provide an additional mechanism for adaptation and thus tend to reduce negative impacts and increase positive ones for any specific sector or country (*high agreement, medium evidence*). The impacts of climate on one sector of the economy of one country in turn affect other sectors and other countries though product and input markets. Markets increase overall welfare, but not necessarily welfare in every sector and country. [10.9]

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

Globally aggregated economic impacts of global warming are a small fraction of income up until 3°C [10.9.2, *medium evidence, high agreement*]. A global mean average temperature rise of 2.5C may lead to global aggregated economic losses between 0.2 and 2.0% of income (*medium evidence, medium agreement*) and losses increase with greater warming. Little is known about aggregate economics impacts above 3°C. Impact estimates are incomplete and depend on a large number of assumptions, many of which are disputable. Aggregate impacts hide large differences between and within countries. **The incremental impact of emitting a tonne of carbon dioxide lies between a few dollars and several hundreds of dollars per tonne of carbon [10.9.3, *robust evidence, medium agreement*]. Estimates vary strongly with the assumed discount rate.** The uncertainty about the marginal impacts is large, and more so for lower discount rates. [10.9]

Not all key economic sectors and services 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; e.g., 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 chapter. 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? What is the effect on the overall economy, and on welfare?

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. 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. 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. Section 10.10 discusses whether there may be vulnerable sectors that have yet to be studied.

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 demand as reported in the SAR (Acosta *et al.*, 1995) and reinforced by the TAR (Scott *et al.*, 2001) and AR4 (Wilbanks *et al.*, 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. Earlier IPCC assessments did not write much about energy supply, but an increasing number of studies now explore its vulnerability, impacts and the adaptation options (Ebinger and Vergara, 2011; Troccoli, 2010; USGCRP, 2009). The energy sector will be transformed by climate policy (IPCC WG3 AR5 Chapter 7) but impacts of climate changes too will be important for secure and reliable energy supply.

10.2.1. Energy Demand

Most studies conducted since AR4 explore the impacts of climate change on residential energy demand, particularly electricity (Mideksa and Kallbekken, 2010). 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 (Olonscheck *et al.*, 2011; Zachariadis, 2010), rely on improved methods (more advanced statistical techniques) (de Cian *et al.*, 2013) and data (both historical and regional climate projections), and many of them explicitly include non-climatic drivers of energy demand (e.g., sources). A few studies consider changes in demand together with changes in climate-dependent energy sources, like hydropower (Hamlet *et al.*, 2010).

Sorting the assessed studies according to the present climate (represented by mean annual temperature based on 1971-2000 climatology) and current income (represented by GDP per capita in 2009), the general patterns are as follows. In countries and regions with already high incomes, climate related changes in energy demand will be primarily driven by increasing temperatures. In countries/regions with high incomes and warm climates, increasing temperatures will be associated with heavier use of air conditioning. In countries/regions with high incomes and temperate and cold climates, increasing temperatures will result in lower demands for various energy forms (electricity, gas, coal, oil). Increasing incomes will play a marginal role in these countries and regions. In contrast, changes in income will be the main driver of increasing demand for energy (mainly electricity for air conditioning and transportation fuels) in present-day low-income countries in warm climates. Neither indicator is ideal because 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 finding.

At the global scale, energy demand for residential air conditioning in summer is projected to increase rapidly in the 21st century under the reference climate change scenario (medium population and economic growth globally, but faster economic growth in developing countries; no mitigation policies in addition to those in place in 2008) by the TIMER/IMAGE model (Isaac and Van Vuuren, 2009). The increase is from nearly 300 TWh in 2000, to about 4,000 TWh in 2050 and more than 10,000 TWh in 2100, about 75% of which is due to increasing income in emerging market countries and 25% is due to climate change. Energy demand for heating in winter 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). In these regions, energy demand for heating will decrease.

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, mixed effects from urbanization), lifestyles (upwards by larger floor area of dwellings), building codes and regulations for the design and insulation 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.

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 the operation of energy installations and infrastructure over time. Possible changes in the frequency and intensity of extreme weather events (EWEs) as a result of CC represent a different kind of hazard forthem.. (EWEs are weather events that are rare at a particular place and time of the year; usually defined as rare or rarer than the 10th and 90th percentile of a probability density function estimated from observations – see the Glossary in this report). (Rummukainen, 2013) and (Mika, 2013) summarize recent trends and prospects relevant for the energy sector. 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 projected impacts of climate change and extreme weather events on energy supply and the related adaptation options.]

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 can be designed to operate under diverse climatic conditions from the cold Arctic to the hot tropical regions and are normally 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.

A general impact of CC on thermal power generation (including combined heat and power) is the decreasing efficiency of thermal conversion as a result of rising temperature that 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 (operating at much higher pressure and temperature conditions than conventional power 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 due to CC. Another problem facing thermal power generation in many regions 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 (Hoffmann *et al.*, 2010; IEA, 2012; Ott and Richter, 2008; Sieber, 2013). Both problems will be exacerbated if CO_2 capture and handling equipment is added to fossil-fired power plants: energy efficiency declines by 8-14 % and water requirement per MWh electricity generated can double (IPCC, 2005). Using partial equilibrium river basin models, (Hurd *et al.*, 2004; Strzepek *et al.*, 2013) estimate USA welfare loses due to thermal cooling water changes at $622 million per year up to 2100, a 6.5 % welfare loss in the energy sector. (Van Vliet *et al.*, 2012) find that the southeastern United States, Europe, eastern China, southern Africa and southern Australia could potentially be affected by reduced water available for thermoelectric power and drinking water, inducing changes to dry or hybrid cooling (with concomitant loss in electric output), or plant shut downs, with associated impacts on local and regional economic activity.

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. Water use regulation, heat discharge restrictions and occasional exemptions might be an institutional adaptation (Eisenack and Stecker, 2012). While it is easier to plan for changing climatic conditions and select the site and 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 as well but the safety regulations are stricter than for fossil-fired plants (Williams and Toth, 2013). A range of alternative cooling options are available 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 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, 2013).

Hydropower is by far the largest of renewable energy sources in the current electricity mix. It is 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 topology. 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, 2013).

Assessing the impacts of climate change on hydropower generation is a highly complex. 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, and the climate response of glaciers make resource estimates difficult (see Chapters 2 and 3) 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 regimes. For hydropower locations, adaption to climate change to maintain output has been reported; in Ethiopia, (Block and Strzepek, 2012) report that capital expenditures through 2050 may either decrease by ~3% under extreme wet scenarios, or increase by up to 4% under a severe dry scenario. In the Zambezi river basin, hydropower may fall by 10% by 2030, and by 35% by 2050 under the driest scenario (Strzepek *et al.*, 2012). Lower generation is *likely* in the upstream powerstations of the Zambezi basin and increases are *likely* downstream (Fant *et al.*, 2012).

Focusing on the possible impacts of CC on hydroelectricity and the adaptation options in the sector in response to the changes in the amount, the seasonal and inter-annual variations of available water, and in other demands, the conclusion from the literature is that the overall impacts of CC and EWEs on hydropower generation by 2050 is expected to be slightly positive in most regions (e.g., in Asia, by 0.27%) and negative in some (e.g., in Europe, by -0.16%), with diverging patterns across regions, watersheds within regions and even river basins within watersheds (IPCC, 2011). Adaptation responses and planning tools for long-term hydrogeneration may need to be enhanced to cope with slow but persistent shifts in water availability. Short-term management models may need to be enhanced to deal with the impacts of EWEs. A series of hard (raising dam walls, adding bypass channels) and soft (adjusting 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, 2013).

Solar energy is expected to increase from its currently small share in the global energy balance across a wide range of mitigation scenarios (IEA, 2008; 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 and unglazed collectors), photovoltaic (PV) cells (crystalline silicon 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 *et al.*, 2013).

All types of solar energy are sensitive to changes in climatic attributes that directly or indirectly influence the amount of insolation reaching them. If cloudiness increases under climate change (see Chapters 11 and 12 of the WGI report), the intensity of solar radiation and hence the output of heat or electricity would be reduced. 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 solar technologies towards new designs, models and materials. An objective of these development efforts is to make the next generation of solar technologies less vulnerable to existing physical challenges, changing climatic conditions and the impacts of 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 and identifying possible adaptation responses for wind energy is complicated by the complex dynamics characterizing this generation source. 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 to 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. 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 mean values over the past 20 years in Europe and North America (Pryor and Barthelmie, 2010). The wide range of the estimates results from the circulation and flow regimes in different General Circulation Models (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, 2013; Pryor *et al.*, 2011). 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. 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, 2013). In summary, the wind energy sector does not face insurmountable challenges resulting from climate change.

In the coal fuel cycle, vulnerability in mining depends on the mining method. Surface mining might be particularly affected by high precipitation extremes and related floods and erosion, and temperature extremes, especially extreme cold that might encumber extraction for some time, whereas impacts on coal cleaning and operation of underground mines will probably be less severe (Ekman, 2013). Changes in drainage and run-off regulation for on-site coal storage as well as in coal handling might be required due to the increased moisture content of coal and more energy might be required for coal drying before transportation (CCSP, 2007). At the back end of the fuel cycle, the management of fly-ash, bottom ash and boiler slag may need to be modified in response to changes in some EWE patterns like wind, precipitation and floods. Impacts on biomass-based energy sources are discussed in Chapter 7 of this report.

Climate and weather related hazards in the oil and gas sector include tropical cyclones with potentially severe effects on off-shore platforms and on-shore infrastructure as well, leading to more frequent production interruptions and evacuation (Cruz and Krausmann, 2013). Gradual changes in air temperature and precipitation are projected to generate risk and opportunities for the oil and gas industry. For example, new areas for oil and gas exploration could open in the Arctic, potentially increasing the technically recoverable resource base (Cruz and Krausmann, 2013). Reduced sea ice thickness and coverage might open new shipping routes, thus reducing shipping costs, while ice scour and ice pack loading on marine structures would increase. However, most changes involve increased risks, such as thawing permafrost would increase construction costs on unstable ground relative to ice-based construction, while thaw subsidence would trigger increased maintenance costs. Sea level rise and coastal erosion would degrade coastal barriers, damage facilities and trigger relocation (Dell and Pasteris, 2010).

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 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 climate change and extreme weather events 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 potential spread of CO_2 capture and storage (CCS) technology, another important function will be to deliver CO_2 from the capture site (typically fossil power plants) to the storage 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.

In addition to reduced line-heating and dilution needs due to reduced viscosity of liquid fuels under warmer temperatures, pipelines will be mainly affected by secondary impacts of climate change: sea-level rise in coastal regions, melting permafrost in cold regions, floods washing away infrastructure, landslides triggered by heavy rainfall and bushfires caused by heat waves or extreme temperatures in hot regions. A proposed way to reduce vulnerability to these events is to amend land zoning codes, risk based design and construction standards for new pipelines, and structural upgrades to existing infrastructure (Antonioni *et al.*, 2009; Cruz and Krausmann, 2013).

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 EWE. The power industry has developed numerous technical solutions and related standards to protect assets and provide reliable electricity supply under existing climate and weather conditions worldwide. However, these assets and the reliability of supply may be vulnerable to changes in the frequency and intensity of EWEs under changing climate conditions (DOE, 2013).

Higher average temperatures increase transmission efficiency and reduce current carrying capacity, but this effect is relatively small compared to the physical and monetary damages that can be caused by EWEs (Ward, 2013). 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). Other impacts include freezing precipitation, ice and winter storms, wildfires caused by higher temperatures, less precipitation and increased tree death caused by pests. If the frequency and power of high wind conditions, as well as extreme precipitation events, will increase in the future, vegetation management along existing power lines, rerouting new transmission lines along roads or across open fields or moving them underground might help reduce related risks. An important institutional option is to redefine technical standards to provide incentives for grid operators to implement appropriate adaptation measures. Such measures are cheaper to implement as part of the maintenance-renewal cycle than as independent retrofit measures.

The economic importance of a reliable transmission and distribution network is highlighted by the fact that the damage to customers tends to be much higher than the price of electricity not delivered (lost production, electricity enabled commerce, service delivery, food spoilage, lost or restricted water availability). Losses can be minimized through efficient rationing of electricity (de Nooij *et al.*, 2009) if generation is the limiting factor. Designing and building climate-resilient infrastructure will depend on technical standards, market governance, and the type and degree of liberalization and deregulation of grid services.

10.2.4. Macroeconomic Impacts

Most economic research related to climate change impacts on the energy sector 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: Economy-wide implications of impacts of climate change and extreme weather on the energy sector.]

Assessing across a broad array of studies that 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 leads to the overall conclusion that the macroeconomic impact of climate change on energy demand is *likely* to be minimal in developed countries (Aaheim *et al.*, 2009; Bosello *et al.*, 2007a; Bosello *et al.*, 2009; Eboli *et al.*, 2010a; 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 beyond those related to changes in energy demand. Europe is the focus of most of the literature so far. Only two studies focus on developing countries: Mexico and Brazil (Boyd and Ibarraran, 2009; de Lucena *et al.*, 2010). Asia and Africa are not well represented, appearing as aggregated regions in only three global studies (Bosello *et al.*, 2007a; Bosello *et al.*, 2009; Eboli *et al.*, 2010a; Eboli *et al.*, 2010b). The limited results indicate that developing countries *likely* face a greater negative GDP impact with respect to climate change implications for the energy sector than developed countries, largely because of higher expected temperature changes (Aaheim *et al.*, 2009; Boyd and Ibarraran, 2009; Eboli *et al.*, 2010a; Eboli *et al.*, 2010b).

Despite the considerable number of potential climate change and extreme weather phenomena – 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, fire, and sea-level rise – and their potential impacts on electricity generation and transmission systems, fuel infrastructure and transport systems, and energy demand (Williams, 2013) – the range of impacts modeled in the literature (Table 10-3) is quite limited. Most studies consider changing energy demand (specifically, changes in electricity and fuel consumption for space heating/cooling) 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 (Eskeland and Mideksa, 2010; Gabrielsen *et al.*, 2005; Kirkinen *et al.*, 2005; Mansur *et al.*, 2005; Mideksa and Kallbekken, 2010; Rübbelke and Vögele, 2010).

Studies using a computable general equilibrium (CGE) model that consider only climate impacts in the energy sector find that the effect on GDP in 2050 is in the range of -0.3% to 0.03% (Bosello *et al.*, 2007a) and -1.3% to -0.6% (Jochem *et al.*, 2009). These findings are largely consistent despite the fact that (Bosello *et al.*, 2007a; Bosello *et al.*, 2009) are global studies that model only the change in demand due to rising temperatures, whereas (Jochem *et al.*, 2009) focus on the EU and model the change in demand plus six other climate impacts.

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 similar 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.*, 2009). Roughly consistent with each other, (Aaheim *et al.*, 2009; Eboli *et al.*, 2010a; Eboli *et al.*, 2010b) find 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 *et al.*, 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; Eboli *et al.*, 2010b) 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 *et al.*, 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 rarely report changes in GDP. 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). For example, (Rübbelke and Vögele, 2013) conclude that the short-term effects of climate-related problems affecting water cooling and hydropower production can have negative distributional effects. (de Lucena *et al.*, 2010) find that rising temperature and changing precipitation lead to the need for an additional 153 – 162 TWh per year by 2035 with a capital investment of $48 to $51 billion.

(Golombek *et al.*, 2011) 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. (UNDP, 2011) finds between a 0.06% and 1.74% increase in electricity system costs for Macedonia resulting from temperature changes. (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%. (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 $80 million 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 $0.1 per MWh. The magnitude of change in electricity price is small in each of the previously mentioned studies that evaluate gradual temperature increases.

In contrast, studies that consider shorter-term heat waves and water shortages find considerably higher price impacts. (Bye *et al.*, 2008) consider a hypothetical water shortage scenario – 25% lower inflow over 2 years – in Nordic countries and conclude that the price of electricity can double over a 2 year period and then return to normal as water flow returns. (McDermott and Nilsen, 2013) find more generally that electricity prices in Germany increase by 1% for every degree that water temperatures rise above 25°C and by 1% for every 1% that river levels fall. (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. (Pechan and Eisenack, 2013) find that an equivalent of the 2006 German heat wave can result in an increase in electricity prices of 11% or even 24% (affected plants running at minimum output) and 50% (affected plants at zero output).

10.2.5. Summary

The balance of evidence emerging from the literature assessed in this section suggests that climate change per se will *likely* 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, biomass, and solar power generation technologies (Mideksa and Kallbekken, 2010). However, gradual temperature-induced impacts on energy supply will probably make a relatively small contribution to the cost of energy and electricity. Acute heat waves and droughts can have a much greater, albeit short-term, impact on electricity prices. Additionally, many other potential climate impacts on energy supply are possible but have not been fully studied, leading to cost estimates to date, based only on temperature change, that underestimate the full cost of climate change on energy supply. Pre-existing subsidies may distort signals for adaptation. 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 as well as mitigation and adaptation response pathways.

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 – range from -3% to 1.2%. (Jochem *et al.*, 2009) is the most detailed and comprehensive study, and report only a 1.3% drop in GDP in 2050 in Europe 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. Energy related economic impact for developing countries is anticipated to be negative, and positive in developed countries. Adaptation within the energy sector can lower the cost of climate change, but these results may be driven largely by assumption since specific policies have not been modeled in these macroeconomic impact studies. 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 (see, e.g., Box CC-WE), which, if modeled, may lead to greater GDP losses 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 for all aspects of energy infrastructure is needed. This information will lead improved assessment of climate impacts due to the use of better, empirically-based assumptions about the relationship of climate impacts and the economy, as well as about the effectiveness of adaptation options.

10.3. Water Services

This section focuses on economic aspects of climate change in water-intensive sectors and infrastructure to provide water services. The climate change impacts on biophysical water system, including the engineering aspects of water infrastructure, are assessed in Chapter 3. There is limited set of studies published in this area and conclusions are limited by the scope of information to date.

10.3.1. Water Infrastructure and Economy-wide Impacts

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 Berz, 2007). In 1990-1996 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). SREX Chapter 4 provides a comprehensive look at the impacts of extreme events on water supply (IPCC, 2012) and flooding at wide range of spatial scales.

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 (Chen *et al.*, 2001; Choi and Fisher, 2003; Hall *et al.*, 2005; Hurd and Rouhi-Rad, 2013; 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. These studies address climate variability; climate change may impact both mean and variability of the hydro-climatic system. The floods associated with the 1997-1998 El Niño and the drought associated with the 1998-2000 La Niña, show a cost to Kenya of 11% and 16% of GDP, respectively (Mogaka *et al.*, 2006). Floods and droughts are estimated to cost Kenya about 2.4% of GDP annually at mid-century, and water resources degradation a further 0.5% (Mogaka *et al.*, 2006). 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 (World Bank, 2006). Syria is projected to experience reduction in economy-wide growth and incomes of urban households (Breisinger *et al.*, 2013). However, it is not hydrological variability per se that causes the problem, but rather 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 (Changnon, 2005; Pielke and Downton, 2000; Ward *et al.*, 2008). 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.

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, annual costs could increase by up to $120-150 billion, for the same high emission scenarios (ABI, 2005). (Feyen *et al.*, 2012) project average annual damage in the EU to increase to $18-28 billion by 2100 depending on the scenario, compared to $8.5 billion today. Continental US mean annual flood damages may increase by $5 billion and $12 billion in 2050 and 2100, respectively (Wobus *et al.*, 2013). (Ntelekos *et al.*, 2010) estimate a range of $7-19 billion, depending on the economic growth rate and the emissions scenarios. (Dasgupta *et al.*, 2010) report that by 2050 Bangladesh will face incremental cost to flood protection (against both sea and river floods) of $2.6 billion initial costs and $54 million annual recurring costs. (Ward *et al.*, 2008) found that the average annual costs to adapt to a 1in 50 year river flood to range from $3.5 to $6.0 billion per year for low- to upper-middle-income countries over the period 2010–50 for the A2 scenario.

10.3.2. Municipal and Industrial Water Supply

Municipal and industrial water supply economic systems are also impacted through changes in precipitation patterns and quantities. These impacts are evaluated as current costs of building in resiliency to the system to adapt to anticipated future changes. For example, the costs of adaptation to maintain supply and quality of water for municipal and industrial uses have been reported for the Assabet River near Boston (Kirshen *et al.*, 2006), Toronto (Dore and Burton, 2001) and Quito (Vergara *et al.*, 2007). Initial analysis indicates that adapatation measures may be beneficial for water infrastructure with an economic and engineering life of more than 25 years. (Nassopoulos *et al.*, 2012) suggest that neglecting to account for future climate change while designing water supply reservoirs can cost 0.2 to 2.8% of the net present value, based on analysis for Greece. For sub-Saharan Africa, adapting urban water infrastructure (storage facilities, wastewater, and additional supply infrastructure) to a 30% reduction in runoff could be $2-5 billion per year (Muller, 2007). Climate change impacts on the Berg River in South Africa are estimated to account for 15% revenue loss for the water supply provider (Callaway *et al.*, 2012). For the OECD, the cost of adaption in the water supply sector is 1-2% of base costs and would save $6-12 billion per year (Hughes *et al.*, 2010). U.S. impacts are estimated to be less than 1% of municipal and industrial welfare (Hurd *et al.*, 2004; Strzepek *et al.*, 2013). In Colorado, a 30% decrease in annual runoff will result in a 12% treatment cost increase and a 22% rise in residential costs (Towler *et al.*, 2011).

(Ward *et al.*, 2010) estimate the costs of adaptation to climate change to ensure enough raw water to meet future industrial and municipal water demand for each country 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 (0.04-0.06% of GDP), 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 as 16% of the global total. Adding adaptive measures to water infrastructure adds 10-20% to the total costs of developing countries meeting the water related millennium goals (Ward *et al.*, 2010).

10.3.3. Wastewater and Urban Stormwater

More frequent heavy rainfall events may overload the capacity of sewer systems and water and wastewater treatment plants more often, and increased occurrences of low flows will lead to higher pollutant concentrations. It is projected for USA in 2100 that national wastewater treatment costs will increase by $0.6-8 billion per year (Henderson *et al.*, 2013). The annual costs of urban stormwater system adaptation , averaged costs over17 climate models simulating the A2 emissions scenario, is $3.0 billion per year in low- to upper-middle-income nations over the period 2010–50 (Hughes *et al.*, 2010). Adaptation costs estimates (for a 10-year, 24-hour storm in 2100) for various locations in the USA are relatively low; e.g., $135 million for Los Angeles, $7 million for Boston and $40 million for Chicago (Neumann *et al.*, 2013). Adapting bridges to altered urban floods could cost $140-250 billion in the USA through the 21st century (Wright *et al.*, 2012).

10.3.4. Inland Navigation

See 10.4.4.

10.3.5. Irrigation

Climate change impacts on the economics of irrigation reflect the anticipated change in temperature, precipitation, and agricultural demand and practices. Assessments of surface, ground and grey water irrigation supplies are addressed in Chapter 3; implications for food production are covered in Chapter 7. By 2080, the global annual costs of additional irrigation water withdrawals for currently existing irrigated land are estimated at $24-27 billion (Fischer *et al.*, 2007). The global cost of improved irrigation efficiency to maintain yields is $1.5-2.0 billion dollar per year for the A2 scenario in developing countries in 2050 (Nelson *et al.*, 2009). Adaptation to maintain agricultural production in Ethiopia would be best achieved by better soil water management with the application of integrated irrigation and drainage systems, improved irrigation efficiency and research related to on-farm practices; adaptation costs range from $68 million per year for the dry scenario dominated by irrigation, to $71 million per year under the wet scenario dominated by drainage (Strzepek *et al.*, 2010).

10.3.6. 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, 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.

10.3.7. Recreation and Tourism

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. See Section 10.6.

10.3.8. Water Management and Allocation

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 and thus economic analyses at the sectoral level are crucial, inter-sectoral and economy-wide assessments are needed for comprehensive economic impacts of water services. Changes in water availability, demand and quality due to climate change would 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). Under a changing climate, existing allocations may no longer be appropriate. (Arndt *et al.*, 2012) examine the implications of alternative development paths and water allocations to suggest climate-smart development strategies in Africa; under stress situations, allocations of water to energy-generation and irrigation may have economy-wide welfare implications. Water resource related climate change impacts on the USA economy measured as cumulative undiscounted welfare changes over the 21st century range from plus (2000US$) $3 trillion for wet scenarios to minus $13 trillion under dry scenarios (Henderson *et al.*, 2013).

10.3.9. Summary

Globally, greenhouse gas induced increases in flooding and droughts may have substantial economic impacts (capital destruction, sectoral disruption) while estimates of adaptation costs (construction, defensive investment) range from relatively modest to relative high levels (see Box CC-WE).

10.4. Transport

The impact of climate change and sea level rise (SLR) on transport has received qualitative, but limited quantitative, focus in the published literature. The impact depends greatly on the climatic zone the infrastructure is in and how climate change will be manifest. There are three major zones:

Geographic Zone	Changes in Climate Expected to Impact Vulnerability
Freezing/Frost Zone	Permafrost, freeze-thaw cycles, precipitation, flooding, SLR and storms (coastal)
Temperate Zone	Precipitation intensity, flooding, maximum daily precipitation, SLR and storms (coastal)
Tropical Zone	Precipitation intensity, flooding, maximum daily precipitation, SLR and storms (coastal)

As detailed below, several studies have explored the potential impacts of climate change on the transport sector, focusing for example on safety or disruptions of service. Quantitative, economic analyses of the impact on physical infrastructure include (Chinowsky *et al.*, 2010; Chinowsky *et al.*, 2011; Hunt and Watkiss, 2010; Larsen *et al.*, 2008) and on wider economic implications (Arndt *et al.*, 2012).

Adaptation options for each sub-sector of transport infrastructure have been studied. Existing literature includes (Chinowsky *et al.*, 2011; Savonis *et al.*, 2008) with proposed strategies ranging from technical to political, including focus on upgraded design specifications during new construction, retrofitting structures, and modified land-use planning in coastal area. Adaptation and resiliency to extreme events is of particular interest as they may have a cascading impact, in that the loss of critical infrastructure assets will negatively affect the recovery and resiliency of a community (Kirshen *et al.*, 2008a; Kirshen *et al.*, 2008b).

10.4.1. Roads

Studies on the direct effects of climate change on road networks are primarily focused on qualitative predictions and surveys concerning impacts on road durability (Eisenack *et al.*, 2012; Koetse and Rietveld, 2009; Ryley and Chapman, 2012; TRB, 2008); with some studies of the quantitative effects (Chinowsky *et al.*, 2013; Nemry and Demirel, 2012). Noted impacts from changes in precipitation and temperature include changes in required road maintenance. These quantitative studies focus on specific impacts such as maintenance in an effort to quantify the long-term costs that need to be assumed by national and regional road agencies. Examples of the metrics used include kilometers of roads lost over time, redistribution requirements of transport funds and benefits from adaptation on long-term maintenance. Chapter 8 addresses the indirect effects of climate change on roads in the areas of congestion and safety. As an example, increases in heavy precipitation events will negatively affect driving safety through decreased driver visibility and changing surface conditions (Qiu and Nixon, 2008).

Paved road degradation is directly related to heat stress 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). The melting of permafrost in northern climates, as well as increased precipitation and flooding, threaten the integrity of road base and sub-bases (Qin *et al.*, 2005). Drainage presents a specific problem for urban areas that experience rainfall above their built capacity and will influence new design standards and costs for urban transport (CCTF, 2008; Hunt and Watkiss, 2010; Lemmen and Warren, 2010). Increased fire danger from droughts could also pose a threat to roads.

Unpaved roads are vulnerable to a number of climate-based factors especially to increasingly intense precipitation, leading to wash out and disruption of service (Chinowsky and Arndt, 2012). Increased precipitation may agricultural areas may have negative economic impacts in addition to the direct impact on infrastructure. 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 could imply that ice roads can no longer be maintained.

Bridges form a core component of any nation’s infrastructure. However, highway bridges that cross water, ubiquitous to most highway networks, are exposed to climate changes via flood events and associated changes in long-term flow regimes. The potential disruptions that could occur due to the loss of or damage to these bridges are numerous. Estimates in the United States range from $140 to $250 billion to address adaptation requirements for bridge infrastructure over the next 50 years (Wright *et al.*, 2012). Similarly, European estimates range from $350-500 million per year to adapt bridge infrastructure (Nemry and Demirel, 2012). Once again, the potential cascading effects of these failures will affect the economic conditions of multiple sectors.

10.4.2. Rail

Rail beds are susceptible to increases in precipitation, flooding and subsidence, sea level rise, extreme events and incidence of freeze-thaw cycles (Nemry and Demirel, 2012). In Northern climates, the melting of permafrost (URS, 2010) may lead to ground settlement, undermining stability (Larsen *et al.*, 2008). Increased temperatures pose a threat to rail through thermal expansion. 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). For example, $290 million has been allocated to finding a workable solution for increasing the capacity of London's underground cooling system (Arkell and Darch, 2006). The complexity of addressing rail infrastructure is increased through differences in design specifications, multiple types of rail and materials used, and uncertainty about the changes in future temperatures.

10.4.3. Pipeline

Increases in precipitation and temperature affect pipelines through scouring of base areas and unearthing of buried pipelines (URS, 2010), compromised stability of bases built on permafrost, and increases in necessary maintenance (TRB, 2008; URS, 2010). Temperature increase can result in thermal expansion of the pipelines, causing cracking at material connection points. In tropical areas, increased precipitation may lead to landslides that can compromise pipeline infrastructure (Sweeney *et al.*, 2005). There has been no economic assessment of the impacts.

10.4.4. Shipping

Impacts of inland navigation 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.

Increased frequency of flood periods will stop ship traffic on the Rhine 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; channel improvements can only partly alleviate these problems (Middelkoop *et al.*, 2001). Economic impact could be substantial given the value of navigation on the Rhine (Krekt *et al.*, 2011). See Chapter 23 for more detail.

Virtually all scenarios of future climate change project reduced Great Lakes water levels and connecting channel flows, mainly because of increased evaporation resulting from higher temperatures. The potential economic impact may result in reductions in vessel cargo capacities and increases in shipping costs. The lower water levels predicted as a result of a doubling of the atmospheric carbon dioxide could increase annual transportation costs by 29%, while more moderate climate change could result in a 13 percent increase in annual shipping costs. The impacts vary across commodities and routes (Millerd, 2010).

Warming leads to increased ice-free navigation and longer shipping season, but also to lower water levels from reduced runoff (Lemmen and Warren, 2010). In cold regions, increased days of ice-free navigation and a longer shipping season could impact shipping and reduce transportation costs (Koetse and Rietveld, 2009; TRB, 2008; UNCTAD, 2009; UNECE and UNCTAD, 2010), although movement in ice waters as the Canada Arctic sea more become more difficult (Stewart *et al.*, 2007; Wilson *et al.*, 2004).

Ports will be affected by climate changes including higher temperatures, sea level rise, increasingly severe storms, and increased precipitation (Becker *et al.*, 2011; Nursey-Bray and Miller, 2012). However, (the need to prioritize) adaptation of ports has been overshadowed by a focus on potential impacts. Training of port personnel is needed to begin the adaptation process. Over $3 trillion in port infrastructure assets in 136 of the world's largest port cities are vulnerable to weather events (Potter *et al.*, 2008; UNCTAD, 2009; UNECE and UNCTAD, 2010).

Increased storminess in certain routes may raise cost of shipping through additional safety measures or longer routes that are less storm-prone (UNCTAD, 2009; UNECE and UNCTAD, 2010). Transport costs would increase or new routes sought if storms disrupt supply chains by destroying port infrastructure connecting road or rail (Becker *et al.*, 2011). Increased storminess may also affect passage through lock systems (Potter *et al.*, 2008; UNCTAD, 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, this may result in limitations for freight capacity, safety, and weather-related delays, unless runways are lengthened (Pejovic *et al.*, 2009; TRB, 2008). (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 (Lemmen and Warren, 2010; Pejovic *et al.*, 2009) and increase maintenance and repair costs (Gusmao, 2010). Clear-air turbulence will increase in the Atlantic corridor leading to longer and bumpier trips (Williams and Joshi, 2013). The impact of climate change on airport pavement is very similar to paved roads (DOT, 2002; Fortier *et al.*, 2007). The effect of temperature and increase precipitation intensity on airports imposes a risk to the entire facility if pavements are not adapted to these increases (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

Chapters 7 and 9 assess 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. Including adaptation in forest management, climate change will accelerate tree growth. This will reduce prices to the benefit of consumers everywhere. Low to mid latitude producers will benefit too as they switch to short-rotation forest plantations. Mid to high latitude producers will be hurt by lower prices while their productivity increases only modestly (*Adaptation of Forests and*

*People to Climate Change -- A Global Assessment Report.*2009; Lee and Lyon, 2004; Perez-Garcia *et al.*, 2002; Sohngen and Mendelsohn, 1997; Sohngen and Mendelsohn, 1998; Sohngen *et al.*, 2001). The value of the forest land in Europe would fall between 14 and 50 percent by 2100 (Hanewinkel *et al.*, 2013). Different trees will be affected differently (Aaheim *et al.*, 2011a; Aaheim *et al.*, 2011b). Higher biomass prices differentially impact different forest-based industries (Moiseyev *et al.*, 2011).

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. Adaptation and markets will substantially change the effect of climate change on fisheries (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 sign and size of climate-driven change for particular fish stocks and fisheries are uncertain but are expected to lead to either increased economic hardship or missed opportunities for development in countries that depend upon fisheries but lack the capacity to adapt. A major part of the gross turnover of nine key fish and cephalopod species in the Bay of Biscay remains potentially unaffected by climate change (Floc'h *et al.*, 2008). In contrast, Iberian-Atlantic sardine biomass and profitability declines due to climate change (Garza-Gil *et al.*, 2011). 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).

Ocean acidification has a range of impacts on the biological systems (Doney *et al.*, 2009), but the studies on the economic impacts of ocean acidification are rare (Cooley and Doney, 2009; Hilmi *et al.*, 2013). Using a partial equilibrium model, (Narita *et al.*, 2012) estimate the economic impact of ocean acidification on shellfish. By the turn of this century the aggregate cost could be over $100 billion.

10.5.1.4. Mining and Quarrying

Climate change will affect exploration, extraction, production, and shipping in the mining and quarrying industry (Pearce *et al.*, 2011). An increase in climate-related hazards (such as forest fires, flooding, windstorm) 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). (Damigos, 2012) estimates the damages due to climate change under IPCC A1B scenarios for the period 2021-2050 of the extent of 0.8 billion US dollars for the Mediterranean Region. Note that other factors such as research and development might influence the viability of mining operations by lowering the cost of adaptation.

10.5.2. Secondary Economic Activities

10.5.2.1. Manufacturing

Climate change will 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 supply chain 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.*, 2009) project labour productivity to fall, particularly of manual labour in humid climates. Labour productivity losses will be accentuated by increased incidences of malaria and vector borne diseases. Note that the loss in labour productivity can be offset by the technological progress. (Hübler *et al.*, 2008) uphold the finding with a German case study, and (Hsiang, 2010) corroborate it 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 for manufactures that supply primary sectors (Kingwell and Farré, 2009) and construction material (see below). Unfortunately, there are only a few studies that quantify these effects (see Appendix A).

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 will 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) show 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 will 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. This requires increased airflow in facilities such as hospitals, schools, and office buildings; that is, upgrades to air conditioning and fan units and perhaps further renovations that may be significant in scope and cost. Third, a change in the pattern of natural disasters will imply a change in the demand for rebuilding and repair. Unfortunately, these impacts have yet to be quantified (Hertin *et al.*, 2003). Note that the direction and magnitude of the effect on construction and housing costs will possibly vary geographically. Cost impacts due to changing precipitation and storms patterns (magnitude, frequency, and/or variation) will vary as these changes are expected to vary by region as well. Air to air heat exchangers, heat recovery ventilators, and dehumidifiers and other technologies may be useful in adapting indoor air quality.

10.6. Recreation and Tourism

Recreation and tourism is one of the largest sectors of the world economy. In 2011, it accounted for 9% of global expenditure, and employed 260 million people (WTTC, 2011). 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 (Gössling *et al.*, 2012; Pang *et al.*, 2013; Scott *et al.*, 2012a). 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 tourist operators and destinations, 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 region, timing and activities of their holidays; recreationists would adapt only timing and activities (Becken and Hay, 2007).

10.6.1.1. Recreation

There has been no research on systematic differences of recreational behaviour due to differences in climate at large spatial scales. The impact of climate change on recreation is therefore largely unknown. The economic impact is probably limited, as people will tend to change the composition rather than the level of their time and money spent on recreation. For instance, (Shaw and Loomis, 2008) argue that climate change would increase boating, golfing and beach recreation at the expense of skiing.

There are case studies that indicate the impact of climate change on recreation. (Buckley and Foushee, 2012) find that a trend toward earlier visits to US national parks between 1979 and 2008. They argue this is due to climate change, but do not rigorously test this hypothesis nor control for other explanations. (Whitehead *et al.*, 2009) find a substantial decrease in the recreational value of sea shore fishing in North Carolina due to sea level rise. (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. (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. (Hamilton *et al.*, 2007) highlight the importance of “backyard snow” to induce potential skiers to visit ski slopes. One could expect people to adopt other ways of enjoying themselves but such alternatives were excluded from these studies. There are positive effects too (Richardson and Loomis, 2005). (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 recreation on the Canadian Prairies, and (Coombes *et al.*, 2009) predict an increase in beach tourism in East Anglia. (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. (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 that the dates of the Tulip Festival may need to be shifted to reflect changing phenology.

10.6.1.2. Tourism

Climate (Becken and Hay, 2007; WTO and UNEP, 2008) and weather (Day *et al.*, 2013; Falk, 2013; Førland *et al.*, 2012; Rossello, 2011; Rosselló-Nadal *et al.*, 2010; Álvarez-Díaz and Rosselló-Nadal, 2010) are important factors in tourist destination choice, and the tourist sector is susceptible to extreme weather (Forster *et al.*, 2012; Forster *et al.*, 2012; Hamzah *et al.*, 2012; Tsai *et al.*, 2012). (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; Prideaux and Mcnamara, 2012) use a similar mechanism to explain the rise in popularity of Tuvalu as a destination choice. (Huebner, 2012) find no impact of future climate change on current travel choices. (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. (Denstadli *et al.*, 2011) 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; and (Moreno, 2010) for tourists in the Mediterranean.

There are a number of biometeorological studies of the impact of climate change on tourism. (Yu *et al.*, 2009a) find that Alaska has become more attractive over the last 50 years, and Florida less attractive to tourists. (Yu *et al.*, 2009b) conclude that the climate for sightseeing has improved in Alaska, while the climate for skiing has deteriorated. (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, 2008; Lin and Matzarakis, 2011) apply the index to Taiwan POC and Eastern China. (Endler and Matzarakis, 2010a; Endler and Matzarakis, 2010b; Endler and Matzarakis, 2011) use an index to study the Black Forest in Germany in detail, highlighting the differences between summer and winter tourism, and between high and low altitudes (Endler *et al.*, 2010). (Matzarakis and Endler, 2010; Zaninović and Matzarakis, 2009) use this method to study Freiburg and Hvar. (Matzarakis *et al.*, 2007) project this potential into the future, finding that the Mediterranean will probably become less attractive to tourists. (Amelung and Moreno, 2012; Amengual *et al.*, 2012; Giannakopoulos *et al.*, 2011; Hein *et al.*, 2009; Perch-Nielsen *et al.*, 2009) 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 (Moreno, 2010; Rutty and Scott, 2010). (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, and 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 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 way than typically assumed by biometeorologists.

(Maddison, 2001) estimates a statistical model of the holiday destinations of British tourists, (Lise and Tol, 2002) for Dutch tourists, (Bujosa and Rosselló, 2012) for Spanish tourists in Spain, and (Bigano *et al.*, 2006) for international tourists from 45 countries. These models control for as many other variables as possible; their focus on the average tourist may be misleading, and their representation of climate may be oversimplified (Gössling and Hall, 2006). 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 the climate in which they spend their holidays than people from cool climates. Whereas (Bigano *et al.*, 2006) find regularity in *revealed* preferences, (Scott *et al.*, 2008b) find pronounced differences in *stated* preferences between types of people.

(Bigano *et al.*, 2007; Hamilton *et al.*, 2005a; Hamilton *et al.*, 2005b) construct a simulation model of domestic and international tourism and climate change (but not sea level rise), considering the simultaneous change in the attractiveness of all potential holiday destinations (Dawson and Scott, 2013); (Hamilton and Tol, 2007) downscale these national results to the regions of selected countries. 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

Studies on the supply side often focus on ski tourism. Warming is expected to raise the altitude of snow-reliable ski resorts, and fewer resorts will be snow-reliable (Hendrikx *et al.*, 2012; Hendrikx *et al.*, 2013; Steger *et al.*, 2012)(Dawson *et al.*, 2009). Snowmobiling will be negatively affected too (Scott *et al.*, 2008a)(Mcboyle *et al.*, 2007). Artificial snow-making cannot fully offset the loss in natural snowfall (Elsasser and Bürki, 2002; Scott *et al.*, 2006)(Hoffmann *et al.*, 2009), particularly in lower areas (Schmidt *et al.*, 2012)(Morrison and Pickering, 2012; Wolfsegger *et al.*, 2008), and water scarcity and the costs of snowmaking will be increasingly large problems (Matzarakis *et al.*, 2012)(Scott *et al.*, 2003)(Scott *et al.*, 2007)(Hendrikx and Hreinsson, 2012)(Steiger and Mayer, 2008)(Pons-Pons *et al.*, 2012); skiers prefer natural over artificial snow (Pickering *et al.*, 2010). Tourism alternatives to skiing or non-tourism alternatives need to be considered as a source of economic development (Hill *et al.*, 2010)(Scott and McBoyle, 2007)(Bicknell and Mcmanus, 2006)(Pickering and Buckley, 2010)(Moen and Fredman, 2007)(Tervo, 2008)(Serquet and Rebetez, 2011)(Landauer *et al.*, 2012)(Matzarakis *et al.*, 2012)(Bourdeau, 2009)(Steiger, 2010)(Potocka and Zajadacz, 2009). Other socio-economic trends dominate the impact of climate change (Steiger, 2012)(Hopkins *et al.*, 2012).

Other studies consider beach tourism. (Scott *et al.*, 2012b) highlight the vulnerability of coastal tourism facilities to sea level rise. (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 tourists have a mixed response to environmental change, contrary to the officials' view that tourists respond negatively. (Jopp *et al.*, 2013) find that an increase in tourism in the shoulder season may offset losses in the peak season in Victoria.

Some studies focus on nature tourism. (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 were 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. (Klint *et al.*, 2012) find that tourist operators in Vanuatu give low priority to adaptation to climate change and (Jiang *et al.*, 2012) find Fiji poorly prepared. (Saarinen *et al.*, 2012) find that tourist operators in Botswana think that climate change would not affect them. (Wang *et al.*, 2010) note that glacier tourism is particularly vulnerable to climate change, highlighting the Baishiu Glacier in China. (Brander *et al.*, 2012) estimate the economic impacts of ocean acidification on coral reefs under four IPCC marker scenarios using value transfer function approach and find that the annual economic impacts increase rapidly overtime, though it remains a small fraction of total income.

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)(Harrison *et al.*, 1999). In France, the 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; it is not probable that the increase in summer tourism in the mountains would offset the decrease in winter tourism (Ceron and Dubois, 2005). In the Great Lakes regions, there is a reduced tourism potential in winter but increased opportunities in summer (Dawson and Scott, 2010). Tourist operators in Australia find the uncertainty about climate change too large for early investment in adaptation (Turton *et al.*, 2010).

10.6.3. Market Impacts

There are only two papers that consider the economic impacts of rather stylized climate-change-induced changes in tourism supply and demand. Both studies use a global computable general equilibrium model, assessing the effects on the tourism sector as well as all other markets. (Berrittella *et al.*, 2006) 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.*, 2008) extend the analysis with the implications of sea level rise. The impact on tourism is limited because coastal facilities used by tourists typically are sufficiently valuable to be protected against sea level rise. The economic impacts on the tourism sector are reinforced by the economic impacts on the coastal zone; 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 and Financial Services

10.7.1. Main Results on insurance of AR4 and SREX

More intense or frequent weather-related disaster would affect property insurance, of which coverage is expanding with economic growth (WG II, 7.4.2.2.4). Insurability can be preserved through risk-reducing measures. Adaptation to climate change can be incentivized through risk-commensurate insurance premiums. 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 (IPCC, 2012).

10.7.2. Fundamentals of Insurance Covering Weather Hazards

Insurance is organized either through private markets, publicly or public-private partnerships. It internalizes catastrophe risk costs prior to catastrophic events, reducing the economic impact of weather-related and other disasters to individuals, enterprises,and governments, thus stabilizing income and consumption, and decreasing societal vulnerability (Melecky and Raddatz, 2011) (17.5.1). Insurance is based on the law of large numbers: the larger the portfolio 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 ensemble. Besides spreading risk over a diversified insured population, insurance spreads risk over time. However, weather-related disasters such as floods simultaneously affect many, and thus violate the principle of uncorrelated risks. Consequently, large losses are much more probable, the loss variance is greater, and the tail risk is higher (Kousky and Cooke, 2012). If insurance coverage is to be maintained, insurers would need more risk-based capital to indemnify catastrophic losses and remain financially solvent. 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 (Charpentier, 2008); (Maynard and Ranger, 2012); (Clarke and Grenham, 2012).

Increasing volatility and burden of losses in many regions are expected to fundamentally impact the industry, leading insurers to adapt their business to the changing risk (Herweijer *et al.*, 2009); (Phelan *et al.*, 2011); (Mills, 2012); (Paudel, 2012), including the use of short-term contracts to adapt to changing cirumstances (Botzen *et al.*, 2010a).

10.7.3. Observed and Projected Insured Losses from Weather Hazards

Direct and insured losses from weather-related disasters have increased substantially in recent decades both globally and regionally (IPCC, 2012); (Bouwer *et al.*, 2007); (Swiss Re, 2013c); (Munich Re, 2013); (Crompton and McAneney, 2008); (Smith and Katz, 2013). Global insured weather-related losses in the period 1980-2008 increased by US$^{2008}1.4bn per year on average (Barthel and Neumayer, 2012). As a rule, insured loss figures are more accurate than direct economic loss estimates, because insurance payouts are closely monitored. Often they are the basis for estimates of direct overall losses (Kron *et al.*, 2012); (Smith and Katz, 2013). Economic growth, including greater concentrations of people and wealth in periled areas and rising insurance penetration, is the most important driver of increasing losses.

Growth induced changes in past losses are removed by normalizing to current levels of destructible wealth. So far, only one study analyzes normalized global weather-related insured losses (Barthel and Neumayer, 2012), but the period is too short (1990-2008) to support a meaningful analysis oftrends. A few studies focus on specific perils and regions, in particular Australia, USA and Europe. Trends were detected for the USA and Germany, but not for Australia and Spain (Table 10-4). Such trends can be influenced by changing damage sensitivities, adaptive measures, different normalization, and changes in insurance – besides changing hazards (Barthel and Neumayer, 2012); (Crompton and McAneney, 2008); (Bouwer, 2011); (IPCC, 2012). Prevention measures such as flood control structures, or improved building standards, would offset an increase in hazard (Kunreuther *et al.*, 2009); (Kunreuther *et al.*, 2012). Given such confounding factors, it can be challenging to estimate to what degree developments in losses convey a climate signal (Kron, 2012); (IPCC, 2012). Nonetheless, normalized direct natural disaster losses have already been demonstrated to properly reflect climate variability on various time scales (Pielke and Landsea, 1999); (Welker and Faust, 2013).

Studies analyzing changes in climate variables and insured losses in parallel are still rare. Variability and mean level of thunderstorm-related insured losses in the USA in the period 1970-2009 have substantially increased, while meteorological thunderstorm forcing has risen in parallel (Sander *et al.*, 2013). The number of days that a regional insurer in southwest Germany sustains hail losses displays an upward trend since 1986, while meteorological severe storm indicators also show upward trends (Kunz *et al.*, 2009). Although more studies find increases of large hail in Europe, general data and monitoring issues hindered assessing more than low confidence in observed meteorological trends (WG1-2.6.2.4). (Corti *et al.*, 2009) found an increase in modeled and partly observed insured subsidence losses in France over the period 1961-2002, consistent with a *likely* increase in dryness in Mediterranean regions (WG1-2.6.2.3). The observed rise in US normalized insured flood losses (Barthel and Neumayer, 2012) may partly correspond to *very likely* increased heavy precipitation events in central North America (WG1-2.6.2.1), while the evidence for climate driven changes in river floods is not compelling (WG1-2.6.2.2). Declining anthropogenic aerosol emissions may partly explain the recent upswing in hurricane hazard and losses (WG1-14.6; WG1-2.6.3; Table 10-4). Apart from detection, loss trends have not been conclusively attributed to anthropogenic climate change; most such claims are not based on scientific attribution methods.

[INSERT TABLE 10-4 HERE
Table 10-4: Observed normalized insured losses from weather hazards (trends significant at the 10% level are indicated as a trend).]

Many GCM-based projection studies agree that extreme winter storm wind speeds fall in the Mediterranean and increase in west, central, and northern Europe (WG1-14.6.2.2). Loss ratios, i.e. insured loss divided by insured value, follow the same pattern (Schwierz *et al.*, 2010); (Donat *et al.*, 2011); (Pinto *et al.*, 2012) (Table 10-5). Return periods per loss level are projected to shorten in large parts of Europe, indicating more frequent high losses (Pinto *et al.*, 2012) (Table 10-5). Projected overall losses and fatalities develop accordingly (IPCC, 2012); (Narita *et al.*, 2010). Across three modeling approaches calibrated to German insurance data, the 25-year loss is projected (A1B) to change by –10% to +18% (2011-2040), +5% to +41% (2041-2070), and +45% to +58% (2071-2100) against 1971-2000, keeping exposures and damage sensitivities constant (Held *et al.*, 2013). Although it is *unlikely* that the North Atlantic response to climate change is just a simple poleward shift of the stormtrack, overall confidence in the magnitude of regional storm track changes is low (WG1-14.6.3).

[INSERT TABLE 10-5 HERE
Table 10-5: Climate change projections of insured losses and/or insurance prices.]

Direct losses and fatalities from flooding will increase with climate change in various locations in the absence of adequate adaptation, given *very likely* wide-spread increases in heavy precipitation (WG1-12.4.5.4; 11.3.2.5.2) (IPCC, 2012). This is selectively reflected in studies projecting mean annual insured heavy rainfall and flood losses will rise with climate change in the UK, the Netherlands, Germany, southern Norway and the Canadian province of Ontario (Table 10-5).

Direct losses and fatalities from tropical cyclones will increase with exposure and may increase with the frequency of very intense cyclones in some basins (WG1-14.6); (IPCC, 2012); (Nordhaus, 2010); (Peduzzi *et al.*, 2012). (Ranger and Niehoerster, 2012), (Kunreuther *et al.*, 2012), and (Raible *et al.*, 2012) found insured hurricane losses change in opposite directions across a range of dynamical and statistical model projections, whereas a high-resolution approach tends to support a long-term increase (Emanuel, 2011). Here, increased probabilities of upward shifted accumulated loss might be detectable by 2025 at earliest, whereas a significant loss trend might emerge much later (Emanuel, 2011); (Crompton *et al.*, 2011). Insured typhoon-related property losses in China are projected to increase (Dailey *et al.*, 2009). Averaged across four GCMs, (Mendelsohn *et al.*, 2012) project rising direct losses for Central America, the Caribbean, North America, and East Asia. (Narita *et al.*, 2009) report an increase in damages and fatalities in all parts of the world.

Hailstorm insurance losses in the Netherlands (Botzen *et al.*, 2010b) and Germany (Gerstengarbe *et al.*, 2013) are projected to increase, consistent with more severe thunderstorms (WG1-12.4.5.5). Paddy rice insurance payouts in Japan are projected to decrease (Iizumi *et al.*, 2008) (Table 10-5).

Rising insured wealth will increase both losses and premium income, not necessarily altering the ratio of both. Such automatic compensation is not effective for changing hazards. Hence, projected ratios of losses to premiums or sums insured (while assuming constant insured property) are an approximation of the climate change impact (Donat *et al.*, 2011). Additional impact factors such as future economic growth (Aerts and Botzen, 2011) or changing vulnerability are rarely projected.

10.7.4. Fundamental 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. Costs include, the expected level of losses, expenses for risk assessment, product development, marketing, operating, and claims processing. Moreover, the revenue must provide a return on shareholders’ equity and allow for the purchase of external capital to cover large losses (Charpentier, 2008); (Kunreuther *et al.*, 2009).

The balance between affordability and profitability is sensitive to climate change. Increases in large weather-related losses may corrode an insurer’s solvency if it fails to adjust its risk management, or is hampered in doing so by price regulation (Grace and Klein, 2009). Additionally, misguided incentives for development in hazard-prone areas, as with the US National Flood Insurance Program (Kousky and Cooke, 2012)); (Michel-Kerjan, 2010); (GAO, 2011), can aggravate the situation (Table 10-6).

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

The additional uncertainty induced by climate change translates into a need for more risk capital (Charpentier, 2008); (Kunreuther *et al.*, 2009); (Grace and Klein, 2009). This raises insurance premiums and affects the economy (Table 10-6). Health and life insurance may also be affected through the health impacts of climate change (Hecht, 2008). 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 (Mills, 2009); (Heintz *et al.*, 2009); (Patton, 2011). Defense cost coverage under liability insurance in such cases depends on the specific contractual wording (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: approximately 14% of premiums in 2012 (Swiss Re, 2013b). In high-income countries, some 35% of direct natural disaster losses have been covered by insurance in the period 1980-2011, about 5% in middle-income countries, and less than 1% in low-income countries (Wirtz *et al.*, 2013). For instance, only about 1% of direct overall losses in the 2010 floods in Pakistan were insured (Munich Re., 2011).

The small share of insurance in risk financing in middle and low income countries may be insufficient because other options, such as external credit or donor assistance, can be unreliable and late. This leaves a financial gap in the months immediately following an EWE, often exacerbated by overstretched public finances. Pre-disaster financing instruments such as insurance or trigger-based risk-transfer products have proven to be effective means of providing prompt liquidity for households, businesses, and governments (Ghesquiere and Mahul, 2007); (Linnerooth-Bayer *et al.*, 2011); (Melecky and Raddatz, 2011; von Peter *et al.*, 2012); (IPCC, 2012); Table 10-6). These may become more important if disaster incidence increases with climate change (IPCC, 2012); (Collier *et al.*, 2009); (Hochrainer *et al.*, 2010).

It is challenging to increase catastrophe insurance coverage because of low business volumes, high transaction costs, and 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, mainly provide health and life insuracne to households and small enterprises in low-income markets. Supply of property insurance suffers from correlated weather risks, although weather-related agricultural damages are covered. Such weather coverage is growing, typically with government and NGO assistance or cross-subsidies from local insurers (Linnerooth-Bayer *et al.*, 2011; Qureshi and Reinhard, 2011). These schemes may be particularly sensitive to a rise in disaster risk due to climate change (Collier *et al.*, 2009); (Leblois and Quirion, 2011); (Clarke and Grenham, 2012).

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

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-based capital to cover the losses. There are several options that sustain insurability. Reducing vulnerability often makes sense even if expected climate change impacts will not materialize. Theoretically, risk-based premiums incentivize policyholders to reduce their vulnerability (IPCC, 2012); (Hecht, 2008); (Kunreuther *et al.*, 2009) (Table 10-7). Premium discounts for loss-prevention can further promote this (Ward *et al.*, 2008); (Kunreuther *et al.*, 2009) (Table 10-7). Moral hazard can be reduced by involving the policyholder in the payment of losses, e.g. via deductibles or upper limits of insurance coverage (Botzen and van den Bergh, 2009); (Botzen *et al.*, 2009). Coordinated efforts of insurers and governments on damage prevention decrease risk (Ward *et al.*, 2008); (Reinhold *et al.*, 2012). For example, new building standards in Florida reduced mean damage per house by 42% in the period 1996-2004 relative to pre-1996; risks can be further reduced, and premium discounts contingent on building standard are offered (Kunreuther *et al.*, 2009); (Kunreuther *et al.*, 2012). However, risk-based premiums required to incentivize vulnerability reduction are often hampered (see also 15.4.4, 17.5.1). Price regulation, subsidies, competitive pressures, and bundling of perils in one product (implying cross-subsidies) have fostered underpricing. Also, availability of sufficient on-site risk information limits price adequacy, e.g. for flood insurance (Maynard and Ranger, 2012).

[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 hazards, mainly to reflect higher hurricane frequencies (Seo and Mahul, 2009), assuming unchanging conditions for other weather hazards. Ignoring changing hazard conditions results in biased estimates of expected loss, loss variability and risk capital requirements (Charpentier, 2008); (Herweijer *et al.*, 2009) (10.7.3). Other confounding factors, e.g. systemic economic impact, in recent large losses have been addressed (Muir-Wood and Grossi, 2008) (Table 10-7). For example, geospatial risk-assessment tools, e.g. flood-recurrence zoning with premium differentiation, counteract adverse selection (Kunreuther *et al.*, 2009); (Mahul and Stutley, 2010). Some insurers have offered weather alert systems to clients (Niesing, 2004). Further, credit rating agencies and Solvency II insurance regulations in Europe contribute to enhanced disaster resilience (Michel-Kerjan and Morlaye, 2008); (Kunreuther *et al.*, 2009); (Grace and Klein, 2009). Finally, insurers and researchers have projected climate change driven losses to allow for adaptation of the industry (10.7.3).

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. Periodic shortages in reinsurance capacity following major disasters have moderated over the last two decades because of easier new capital inflow (Cummins and Mahul, 2009).

Global diversification potential of large losses has fallen over recent decades because of increasing dependence between major insurance markets. For instance, the floods in Thailand in 2011 disrupted industrial hubs and global supply chains (Courbage *et al.*, 2012). This process may continue with climate change (Sherement and Lucas, 2009); (Kousky and Cooke, 2012). However, global diversification potential can be increased by developing insurance markets in middle- and low-income countries (Cummins and Mahul, 2009).

Very large loss events, say in excess of US$ 100bn, may make additional capacity desirable. These disasters can be diversified in the financial securitization market (IPCC, 2012). Natural catastrophe risks are not correlated with capital market risks and hence are attractive to institutional investors. For instance, a catastrophe bond assures the investor above-market returns as long as a parametric index (e.g., wind-based) does not exceed a threshold, but pays the insurer’s loss otherwise. 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 is often considered well-suited to the agricultural sector in developing countries (Collier *et al.*, 2009); (IPCC, 2012). Payouts depend on a physical trigger, e.g. cumulative rainfall at a nearby weather station, instead of the policyholder’s condition. Thus, they can be timely; costly loss assessments and moral hazard are avoided, and adverse selection reduced (Barnett *et al.*, 2008). Risk-based premiums can encourage adaptive responses (Mahul and Stutley, 2010) (Table 10-7). However, basis risk, where losses occur but no payout is triggered, provokes distrust. Misunderstanding and scaling up of pilots pose further difficulties (Patt *et al.*, 2010); (Leblois and Quirion, 2011); (Clarke and Grenham, 2012). Suggested improvements include area-yield indices and coverage at aggregate levels to reduce basis risk, and a cooperative design (Clarke and Grenham, 2012); (Biener and Eling, 2012) (Table 10-7). Application of indemnity-based insurance and index-based concepts depend on the insured’s characteristics and the market setting ((Herbold, 2013a); (Swiss Re, 2013a)). Insurance-linked services can strengthen farmers’ resilience by seasonal-forecast-based agricultural guidance (*AgroClima. Informática Avanzada SA de CV.*2013).

Improved building standards at high-risk sites in the Caribbean ubstantially reduce damages from tropical cyclones and increase benefits twofold over costs over a twenty year period, assuming scenarios of changing hazard inferred from past decades (Ou-Yang *et al.*, 2013); (Michel-Kerjan *et al.*, 2013). Insurance coverage linked to credit for retrofitting could improve adaptation (Mechler *et al.*, 2006).

Sovereign insurance is deemed appropriate in developing countries suffering from post-disaster financing gaps (see 10.7.4). Current schemes include government disaster reserve funds (FONDEN, Mexico) and pools of developing states’ sovereign risks (e.g., CCRIF, Caribbean) (IPCC, 2012). In both cases, peak risk is transferred to reinsurance and 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 have public-private arrangements involving government intervention on peak risk (Aakre *et al.*, 2010); (Bruggeman *et al.*, 2010); (Schwarze *et al.*, 2011); (Paudel, 2012), or even public statutory insurance systems (Quinto, 2011) (Table 10-8). Expected post-disaster relief has been shown to counteract insurance uptake (Raschky *et al.*, 2013). The pro-adaptive, risk-reducing features of insurance are more effective if the price reflects the risk and the pool of insureds is larger, e.g. through bundled perils (Bruggeman *et al.*, 2010); (Paudel, 2012). People who cannot afford premiums can be covered by vouchers, leaving the price signal undistorted, or by subsidies (Kunreuther *et al.*, 2009); (Aakre *et al.*, 2010) (Table 10-8). Insurance regulation ensures availability, affordability, and solvency, but often adopts only short- to medium-term views. Because of climate change, the role of regulators has changed to include risk-adequate pricing, risk education, and risk-reduction in the long term (Hecht, 2008); (Grace and Klein, 2009); (Mills, 2009).

[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 an insurance system. This reduces the governments' burden and uncertainty due to weather disasters (Ghesquiere and Mahul, 2007); (Melecky and Raddatz, 2011). Interest in public-private partnerships may evolve, e.g. between government, farmers, rural banks and insurers, in order to expedite agricultural development and resilience, e.g. by means of subsidies for start-up costs and peak risk (Collier *et al.*, 2009); (Mahul and Stutley, 2010) (Table 10-8). Previously implemented systems have suffered from adverse selection and moral hazard (Makki and Somwaru, 2001); (Glauber, 2004), suggesting an improved design is needed. For instance, group policies that foster mutual monitoring, programs or legislative actions that encourage purchase of insurance may increase participation rates. Further, insurance pools can diversify weather risks across larger regions, reduce premiums and improve access to external risk capital (Mendoza, 2009); (Hochrainer and Mechler, 2011); (Biener and Eling, 2012); (IPCC, 2012).

In least developed countries, domestic insurance markets are rare. Climate change-related disaster risk management was proposed for inclusion in the adaptation regime of the UNFCCC. Besides prevention, insurance is a central element in these concepts, partly funded from an UNFCCC adaptation fund according to the principles of "equity and […] common but differentiated responsibilities and respective capabilities" (UNFCCC Art.3.1); (Warner and Spiegel, 2009); (Linnerooth-Bayer *et al.*, 2009); (IPCC, 2012) (Table 10-8).

For insurance systems in developing markets, challenges include adequate public-privated partnership framing, improved risk assessment, with sufficient detail and appropriate dynamics, development of markets and regulation, and scaling-up of successful schemes. Regulatory requirements for risk-based capital, and access to reinsurance and securitization markets further contribute to a resilient insurance system.

10.7.7. Financial Services

The financial industry apart from insurance is vulnerable to both slow-onset changes and to more frequent and/or intensive weather-related disasters. Equity investors potentially face a higher exposure than debt investors, due to exit conditions and a focus on longer-term returns in equity markets, but ultimately the impact on debt investors depends on the exposure of credit collateral to climate change (Stenek *et al.*, 2010). In the short-to medium term, the financial sector is better sheltered from climate change due to high capital mobility, an ability to hedge against a range of business risks, an aptitude for the development of new products to cater for changing demand in particular with respect to risk transfers and invest in growing markets (Oliver Wyman, 2007); (Whalley and Yuan, 2009). In the longer-term, some risks associated with climate change will be more difficult to diversify in particular for financial institutions with local reach.

There are few papers on the impact of climate change on the financial sector (other than insurance). Surveys agree with earlier views (AR3, WGII, 8.4.) that climate change is perceived as a material threat by few bankers and asset managers. There is growing awareness of climate change impacts, as illustrated by increasing membership of sector initiatives such as the Carbon Disclosure Project, the UN Principles for Responsible Investment or the Global Reporting Initiative, potentially influencing the responsiveness of the sector to climate change (Brimble and Stewart, 2009). However, only a few financial institutions have systematically factored in climate change into their risk management and analytical framework (Cogan, 2008); (Furrer *et al.*, 2012).

While direct physical impact (i.e. damage to financial infrastructure) is not seen to be a material issue, this may change in the future in light of the exposure of major financial centres to rising sea levels and the reliance on complex IT infrastructure. Moreover, there is an increasing share of equity allocated to infrastructure and real estate that is more long-term oriented and could face higher maintenance and adaptation requirements (Stenek *et al.*, 2010); (Mercer, 2011).

Indirect impacts may become material over the next few decades, for example, value losses of assets/loan portfolios as a result of physical damage. Regulatory and reputational effects, together with liability and litigation risks linked to climate change are of concern too (Cogan, 2008); (Mercer, 2011); (Furrer *et al.*, 2012). However, legitimacy concerns linked to climate change (as reflected by clients) are insufficient, overshadowed by the financial crisis, or mitigated by the size and influence of the financial sector (Brimble and Stewart, 2009).

It is difficult to quantify how significant the impact of climate change will be for the industry. While it is not probable that climate change alone will affect the liquidity or financial capacity of an institution, the financial performance of both equity and debt markets could be weakened by a variety of factors including changes in market conditions through climate driven price variations, higher capital and operating expenditure or aggravation of country risk but also regulatory drivers, e.g. higher capital reserve requirements to cover higher on-and off-balance-sheet exposures (Stenek *et al.*, 2010).

10.7.8. Summary

More frequent or more severe extreme weather events, and increased uncertainty about such hazards, would lead to higher insurance premiums and reduced cover in several regions, to the detriment of the insured, and perhaps to reduced profitability of insurers, and to the detriment of their shareholders. Improvements in risk management, product innovation, financial innovation and better regulation would partially alleviate these impacts.

10.8. Services Other than Tourism and Insurance

Other service sectors of the economy include waste management, wholesale and retail trade, engineering, government, education, 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.

10.8.1. Sectors Other than Health

The literature on the impact of climate change on other sectors of the economy is sparse (see Appendix A). 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 affects retail, mostly through transfers in the economy. (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

Climate change-related alterations in weather patterns, particularly extreme weather and climate events, have the potential to affect the health sector through impacts on infrastructure and the delivery of health care services from changing demand. Increased demands for services put additional burdens on public health and health care personnel and supplies, with potential economic consequences. For example, hydrologic disasters (floods and wet mass movements) in 2011 were associated with 20% (140 million) of all reported disaster deaths and 19% of total damages (Guha - Sapir *et al.*, 2012).

Health care facilities are priority infrastructure that can be damaged by weather and climate events, compromising critical resources required for patient treatment; physical damage and destruction of equipment and buildings; and possibly requiring evacuation of critical care patients, with attendant risks for the patients (Carthey *et al.*, 2009). Adverse impacts on transportation (such as flooded roads) can further affect access and evacuation. The ability of health care facilities to properly care for the affected and for those with ongoing health issues requiring medication or treatment may be compromised by very large events that affect multiple health care facilities. Areas projected to experience increases in extreme events could consider additional “surge capacity” to manage such events without interruption of service (Banks *et al.*, 2007; Hess *et al.*, 2009).

Although the proportion of individuals seeking medical treatment during a disaster is typically a small subset of the total number of those affected, the additional burden on health care facilities can be significant (Hess *et al.*, 2009). Six weather and climate events that struck the US between 2000 and 2009 were estimated to have increased health care costs by US$740 million, reflecting more than 760,000 encounters with the health care system (Knowlton *et al.*, 2011). Hospitalizations, with attendant costs, can increase from cases of heat stress, heat stroke, and acerbations of cardiorespiratory diseases and other health conditions during heatwaves (e.g. (Astrom *et al.*, 2013; Lin *et al.*, 2012), and from the adverse health impacts of other extreme events (Chapter 11.4.1; 11.4.2). For example, one trauma center in the U.S. found a 5% increase in hourly admissions for each approximately 5°C increase in temperature (Rising *et al.*, 2006). Individuals looking for an air-conditioned location during high ambient temperatures can further increase hospital visits (Carthey *et al.*, 2009).

Climate change is projected to increase the burden of major worldwide causes of childhood mortality, including malnutrition, diarrheal diseases, and malaria (Chapter 11.5.1; 11.5.2; 11.6.1). 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. antimalarials, insecticide treated bednets, oral rehydration). Studies estimating the costs of additional cases of climate-sensitive health outcomes focus on the costs of treatment, typically omitting the costs of providing additional health services, implementing new policies, and health actions in other sectors (Hutton, 2011). Because most climate change-related cases of adverse health outcomes are projected to occur in low-income countries, treatment costs will primarily be borne by families where governments provide limited health care (WHO, 2004). Time off from work to care for sick children could affect productivity.

Public and private health expenditures account for approximately 10% of global GDP (http://data.worldbank.org/indicator/SH.XPD.TOTL.ZS). A systematic analysis of developing country government expenditures on health from domestic sources estimated that from 1995 to 2006, public financing of health in constant US$ increased nearly 100%; this was a product of rising GDP, slight decreases in the share of GDP spent by government, and increases in the share of government spending on health (Lu *et al.*, 2010). The results varied by region, with shares of government expenditures on health increasing in many regions but decreasing in many sub-Saharan African countries. Development assistance for health rose from about US$8 billion (in constant 2007 US$) in 1995 to nearly $19 billion in 2005 (Ravishankar *et al.*, 2009). Domestic government spending on health was negatively affected by development assistance to governments and positively effect when assistance was to the non-governmental sector (Lu *et al.*, 2010).

Estimates of the costs of treating future cases of adverse health outcomes from climate change are in the range of billions of US$ 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 CO_2 equivalent in 2210, and current costs of treatment in developing countries, estimated treatment costs without adaptation could be $4-12 billion worldwide, 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 approximately 3-5% increase in the number of cases of diarrheal disease and malaria from the 2002 baseline (Markandya and Chaibai, 2009). The prevalence of these diseases have since declined (http://apps.who.int/gho/data/node.main.14?lang=en; Chapter 11.1.1), although there is considerable uncertainty in mortality data from many low-income countries because of the low proportion of deaths covered by vital registration programs (Byass *et al.*, 2013).

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 were estimated to be $3-5 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.

(Watkiss and Hunt, 2012) estimated the health impacts of climate change in Europe in 2071-2100 using physical and monetary metrics, taking socioeconomic change into consideration. Temperature-related mortality during winter and summer due to climate change included positive and negative effects, with welfare costs (and benefits) of up to $130 billion annually, with impacts unevenly distributed across countries. Assumptions about acclimatization influenced the size of the health impacts. The welfare costs for salmonellosis were estimated at potentially several hundred million Euro annually, and those for the mental health impacts associated with coastal flooding due to climate change were up to approximately $2 billion annually.

Estimated additional health care costs for climate change-related cases of malaria are similar in Southern Africa (van Rensburg and Blignaut, 2002). Ranges for (low-high) additional cost scenarios for the prevention and treatment of malaria in South Africa in 2025 were estimated to be approximately $280 - $3,764 million. Estimates for Botswana and Namibia are $9- $124 million and $13- $177 million, respectively. The high cost scenario for Namibia is about 4.6% of GDP. The climate change-related malaria inpatient and outpatient treatments costs at the end of the century (2080-2100) in 25 African countries[1] indicated that even marginal changes in temperature and precipitation could affect the number of malaria cases, with increases in most countries and decreases in others (Egbendewe-Mondzozo et al. 2011). The end of century treatment costs as a proportion of annual 2000 health expenditures per 1,000 people would increase in the vast majority of countries, with increases of more than 20% in inpatient treatment costs for Burundi, Cote D’Ivoire, Malawi, Rwanda, and Sudan.

[FOOTNOTE 1: Algeria, Benin, Botswana, Burkina, Burundi, Central African Republic, Chad, Cote D’Ivoire, Djibouti, Egypt, Ethiopia, Ghana, Guinea, Malawi, Mali, Mauritania, Morocco, Niger, Rwanda, South Africa, Sudan, Togo, Uganda, Tanzania, Zimbabwe.]

The costs of treating cases of cholera in Tanzania due to climate change in 2030 were estimated to be in the range of 0.32 – 1.4 % of GDP (Trærup *et al.*, 2011), and there would be costs for treating additional cases of diarrhea and malaria in India in 2030, depending on the emission scenario (Ramakrishnan, 2011).

(Bosello *et al.*, 2006) used a computable general equilibrium model to study the economic impacts of climate-change-induced changes in mortality and morbidity due to cardiovascular and respiratory diseases, malaria, diarrhea, schistosomiasis, and dengue fever. They considered the effects on labor productivity and demand for health care, and found that health and welfare impacts have the same sign. The economy-wide health impacts were greater than simple aggregation of the costs of the individual health outcomes. Increased health problems were associated with an expansion of the public sector at the expense of the private sector.

Estimates of the impacts of climate change on worker productivity, assuming current work practices, primarily through heat stress, indicate that productivity has already declined during the hottest and wettest seasons in parts of Africa and Asia, with more than half of afternoon hours projected to be lost to the need for rest breaks in 2050 in South East Asia and up to a 20% loss in global productivity in 2100 under RCP4.5 (Chapter 11.6.2; (Dunne *et al.*, 2013; Kjellstrom *et al.*, 2013; Kjellstrom *et al.*, 2009). Alternate workpractices may offer some relief from a health perspective, but would *likely* lead to significantly decreased productivity (Chapter 11).

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, from the one sector on the rest of the economy (10.9.1) and on economic growth and development (10.9.2).

10.9.1. Effects of Markets

There are three channels through which economic 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, consumer would shift to cheaper food but also spend less money on other goods and services. Third, sectors compete for the primary factors of production (labor, capital, land, water). If, besides more fertilizers and irrigation, 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. Ignoring these effects would lead to biased estimates of the impacts of climate change.

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). 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. Other types of economic models have yet to be applied to the estimation of indirect economic effects of climate change.

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.*, 2007b; Darwin and Tol, 2001), tourism (Berrittella *et al.*, 2006; Bigano *et al.*, 2008), human health (Bosello *et al.*, 2006) and energy (see 10.2).

(Bigano *et al.*, 2008) study the joint, global impact on tourism and coasts in the 21st century, finding that changes in tourist demand dominate the welfare impacts of sea level rise. (Kemfert, 2002) and (Eboli *et al.*, 2010a; Eboli *et al.*, 2010b) estimate the joint, global effect on the world economy(Eboli *et al.*, 2010b) of a range of climate change impacts in the 21st century, 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% (depending on the SRES scenario) 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. Aggregate Impacts

Since AR4, four new estimates of the global aggregate impact on human welfare of moderate climate change were published (Bosello *et al.*, 2012; Maddison and Rehdanz, 2011; Roson and van der Mensbrugghe, 2012), including two estimates for warming greater than 3°C. Estimates agree on the size of the impact (small relative to economic growth) but disagree on the sign (Figure 10-1). Climate change may be beneficial for moderate climate change but turn negative for greater warming. Impacts worsen for larger warming, and estimates diverge. The new estimates have slightly widened the uncertainty about the economic impacts of climate.

Welfare impacts have been estimated with different methods, ranging from expert elicitation to econometric studies and simulation models. Different studies include different aspects of the impacts of climate change, but no estimate is complete; most experts speculate that excluded impacts are on balance negative (Füssel, 2010; Tol, 2008; Yohe, 2008). Estimates across the studies reflect different assumptions about intersectoral, interregional and intertemporal interactions, about adaptation, and about the monetary values of impacts. Aggregate estimates of costs mask significant differences in impacts across sectors, regions, countries and populations. Relative to their income, economic impacts are higher for poorer people.

[INSERT FIGURE 10-1 HERE
Figure 10-1: Estimates of the total impact of climate change plotted against the assumed climate change (proxied by the increase in the global mean surface air temperature); studies published since IPCC AR5 are highlighted as diamonds; see Table 10.B.1.]

10.9.3. Social Cost of Carbon

The social cost of carbon (SCC) monetizes the expected welfare impacts of a marginal increase in carbon dioxide emissions in a given year (i.e., the welfare loss associated with an additional tonne of CO_2 emitted), aggregated across space, time, and probability (Tol, 2011). Figure 10-2 shows estimates published before AR4 and since, using the kernel density estimator by (Tol, 2013), extending the data with new estimates by (Anthoff and Tol, 2013b; Hope and Hope, 2013; Hope, 2013; Interagency Working Group on the Social Cost of Carbon, 2013). Central estimates of the social cost of carbon have fallen slightly for all pure rates of time preference and the uncertainty has tightened, particularly for studies that use a pure rate of time preference of zero. See Table 10-9. For comparison, the EU ETS price in July 2013 was about $21/tC.

[INSERT TABLE 10-9 HERE
Table 10-9: Selected statistical characteristics of the social cost of carbon: average (Avg) and standard deviation (SD), both in dollar per tonne of carbon, and number of estimates (N; number of studies in brackets).]

Uncertainty in SCC estimates is high due to the uncertainty in underlying total damage estimates (see 10.9.2), uncertainty about future emissions, future climate change, future vulnerability and future valuation. The spread in estimates is also high due to disagreement regarding the appropriate framework for aggregating impacts over time (discounting), regions (equity weighing), and states of the world (risk aversion).

Quantitative analyses have shown that SCC estimates can vary by at least ~2x depending on assumptions about future demographic conditions (Interagency Working Group on the Social Cost of Carbon, 2010), at least ~3x due to the incorporation of uncertainty (Kopp *et al.*, 2012), and at least ~4x due to differences in discounting (Tol, 2011) or alternative damage functions (Ackerman and Stanton, 2012).

Concerns have been raised that the uncertainty about climate change is so large that the SCC would be unbounded (Weitzman, 2009), but this result is sensitive to assumptions about the utility function (Buchholz and Schymura, 2012; Millner, 2013; Nordhaus, 2011) and disappears when climate policy is formulated as balancing the risks of climate change against those of mitigation policy (Anthoff and Tol, 2013a; Hwang *et al.*, 2013).

[INSERT FIGURE 10-2 HERE
Figure 10-2: Kernel densities of the social cost of carbon for all studies and studies before or after AR4 for three alternative pure rates of time preference (PRTP).]

10.9.4. Effects on Growth

10.9.4.1. The Rate of Economic Growth

Climate change will 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 in the 4th model (which emphasizes human capital accumulation) indirect impacts are 1.5 times as large. 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 is also 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. Additionally, (Eboli *et al.*, 2010a; Eboli *et al.*, 2010b) use a multi-sector, multi-region growth model, and find that the impact of climate change would lead to a 0.3% reduction of global GDP in 2050. Regional impacts are more pronounced, ranging from -1.0% in developing countries to +0.4% in Australia and Canada. In contrast, (Garnaut, 2008) finds -2.1% for Australia; the difference is mainly due to impacts on infrastructure (cf. Section 10.4). Sectoral results are varied too, with output changes ranging from +0.5% for power generation (to meet increased demand to air conditioning) to -0.7% for natural gas (as demand for space heating falls).

Using a biophysical model of the human body's ability to do work, (Kjellstrom *et al.*, 2009) find that by the end of the century climate change may reduce labor productivity by 11-27% in the humid (sub)tropics (depending on the SRES scenario; see Chapter 11 for further discussion). Assuming an 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 changes 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. (Barrios *et al.*, 2010) find that the decline in rainfall in the 20th century partly explains the economies of Sub-Saharan Africa have grown more slowly than those of other developing regions. (Brown *et al.*, 2011) corroborate this. (Dell *et al.*, 2012) find that, in the second half of the 20th century, anomalously hot weather slowed down economic growth in poor countries, in both the agricultural and the industrial sectors. (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. The impact of natural disasters on economic growth in the long-term is disputed, with studies reporting positive effects (Skidmore and Toya, 2002), negative effects (Raddatz, 2009), and no discernible effects (Cavallo *et al.*, 2013).

10.9.4.2. Poverty Traps

Poverty is concentrated in the tropics and subtropics. This has led some analysts to the conclusion that a tropical climate is one in a complex of causes of poverty (which itself is a cause of poverty). We here focus on national economies, while Chapter 13 discusses groups of people in 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; Bretschger and Valente, 2011; Gollin and Zimmermann, 2012; Ikefuji and Horii, 2012; 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 (Gollin and Zimmermann, 2008; Ikefuji *et al.*, 2010). Climate-related diseases such as malaria and diarrhea impair children’s cognitive and physical development. This contributes 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 could thus trap more people in poverty.

(Ikefuji and Horii, 2012; 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).

(Devitt and Tol, 2012) construct a model with a conflict-poverty trap, and show that climate change may exacerbate this. (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.

10.9.5. Summary

In sum, estimates of the aggregate economic impact of climate change are relative small but with a large downside risk. Estimates of the incremental damage per tonne of carbon dioxide emitted vary by two orders of magnitude, with the assumed discount rate the main driver of the differences between estimates. 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. Different economies will be affected differently. Some studies suggest that climate change may trap more people in poverty.

10.10. Summary; Research Needs and Priorities

Table 10-10 summarizes the main findings. For each of the sectors discussed above, it gives the main climate drivers, the relationship between climate and impact (limited to less than linear, linear, and more than linear), the sign of the impacts (where needed split by economic actor), drivers other than climate change, and the relative importance of climate change.

[INSERT TABLE 10-10 HERE
Table 10-10: Summary of findings.]

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 climate change impacts on 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 impacts on insurance; however, only limited research is available on observed and projected changes in insured climate-related losses. To advance such research, climate science and risk research communities need to be better integrated. Additionally, only few quantitative projection studies exist on regional markets including scenarios of changing hazard properties, exposure, vulnerability and adaption status, regulation, and availability of risk-based capital to indemnify disaster losses. Little research is available on the implications of climate change for banking/investment activities, in particular regarding the direct exposure of financial infrastructure. But also indirect effects through value losses in loan portfolios and assets as a result of physical damage and regulatory/reputational effects, together with liability and litigation risks, are underinvestigated.

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. A limited set of studies have evaluated the aggregate economic impact of climate change up to 3°C annual mean temperature rise, while only one study has evaluated larger temperature scenarios; suggesting considerable new analysis is warranted to improved confidence in the conclusions and investigation of a broader suite of RCPs.

Frequently Asked Questions

FAQ 10.1: Why are key economic sectors vulnerable to climate change? *[to be placed after Section 10.1]*
Many key economic sectors are affected by long-term changes in temperature, precipitation, sea level rise, and extreme events, all of which are impacts of climate change. For example, energy is used to keep buildings warm in winter and cool in summer. Changes in temperature would thus affect energy demand. Climate change also affects energy supply through the cooling of thermal plants, through wind, solar and water resources for power, and through transport and transmission infrastructure. Water demand increases with temperature but falls with rising carbon dioxide concentrations as carbon dioxide fertilization improves the water use efficiency plant respiration. Water supply depends on precipitation patterns and temperature, and water infrastructure is vulnerable to extreme weather, while transport infrastructure is designed to withstand a particular range of weather conditions, and climate change would expose this infrastructure to weather outside historical design criteria. Recreation and tourism are weather-dependent. As holidays are typically planned in advance, tourism depends on the *expected* weather and will thus be affected by climate change. Health care systems are also impacted, as climate change affects a number of diseases and thus the demand for and supply of health care.

FAQ 10.2: How does climate change impact insurance and financial services? *[to be placed in Section 10.7]*
Insurance buys financial security against, among other perils, weather hazards. Climate change, including changed weather variability, is anticipated to increase losses and loss variability in various regions through more frequent and/or intensive weather disasters. This will challenge insurance systems to offer coverage for premiums that are still affordable, while at the same time requiring more risk-based capital. Adequate insurance coverage will be challenging in low and middle-income countries. Other financial service activities can be affected depending on the exposure of invested assets/loan portfolios to climate change. This exposure includes not only physical damage but also regulatory/reputational effects, liability and litigation risks.

FAQ 10.3: Are other economic sectors vulnerable to climate change too? *[to be placed in Section 10.8]*
Economic activities such as agriculture, forestry, fisheries and mining are exposed to the weather and thus vulnerable to climate change. Other economic activities, such as manufacturing and services, largely take place in controlled environments and are not really exposed to climate change. However, markets connect sectors so that the impacts of climate change spill over from one activity to all others. The impact of climate change on economic development and growth also affects all sectors.

Cross-Chapter Box

Box CC-WE: The Water-Energy-Food/Feed/Fiber Nexus as Linked to Climate Change

[Douglas J. Arent (USA), Petra Döll (Germany), Kenneth M. Strzepek (UNU / USA), Blanca Elena Jimenez Cisneros (Mexico), Andy Reisinger (New Zealand), FerencToth (IAEA / Hungary), Taikan Oki (Japan)]

Water, energy, and food/feed/fiber are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure WE-1. The depth and intensity of those linkages vary enormously between countries, regions and production systems. Energy technologies (e.g. biofuels, hydropower, thermal power plants), transportation fuels and modes, and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops and forages) may require significant amounts of water (Sections 3.7.2, 7.3.2, 10.2, 10.3.4, 22.3.3, 25.7.2; Allan, 2003; King and Weber 2008; McMahon and Price, 2011; Macknick *et al*., 2012a). In irrigated agriculture, climate, irrigating procedure, crop choice and yields determine water requirements per unit of produced crop. In areas where water (and wastewater) must be pumped and/or treated, energy must be provided (Asano et al., 2006; Khan and Hanjra, 2009; USEPA, 2010; Gerten et al., 2011). While food production, refrigeration, transport and processing require large amounts of energy (Pelletier et al., 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (Section 7.3.2, Box 25-10; Diffenbaugh et al., 2012; Skaggs et al., 2012) *(robust evidence, high agreement)*. Food and crop wastes, and wastewater, may be used as sources of energy, saving not only the consumption of conventional non-renewable fuels used in their traditional processes, but also the consumption of the water and energy employed for processing or treatment and disposal (Schievano et al., 2009; Sung et al., 2010; Olson, 2012). Examples of this can be found in several countries across all income ranges. For example, sugar cane by-products are increasingly used to produce electricity or for cogeneration (McKendry, 2002; Kim and Dale 2004) for economic benefits, and increasingly as an option for greenhouse gas mitigation.

[INSERT FIGURE WE-1 HERE
Figure WE-1: The water-energy-food nexus as related to climate change. The interlinkages of supply/demand, quality and quantity of water, energy and food/feed/fiber with changing climatic conditions have implications for both adaptation and mitigation strategies.]

Most energy production methods require significant amounts of water, either directly (e.g., crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (Sections 10.2.2 10.3.4, 25.7.4; van Vliet et al., 2012; Davies et al., 2013) *(robust evidence, high agreement)*. Water for biofuels, for example, under the IEA Alternative Policy Scenario, which has biofuels production increasing to 71 EJ in 2030, has been reported by Gerbens-Leenes et al. (2012) to drive global consumptive irrigation water use from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water is also required for mining (Section 25.7.3), processing, and residue disposal of fossil and nuclear fuels or their byproducts. Water for energy currently ranges from a few percent in most developing countries to more than 50% of freshwater withdrawals in some developed countries, depending on the country (Kenny et al., 2009; WEC, 2010). Future water requirements will depend on electricity demand growth, the portfolio of generation technologies and water management options employed (WEC, 2010; Sattler et al., 2012) *(medium evidence, high agreement)*. Future water availability for energy production will change due to climate change (Sections 3.4, 3.5.1, 3.5.2.2) *(robust evidence, high agreement).*

Water may require significant amounts of energy for lifting, transport and distribution and for its treatment either to use it or to depollute it. Wastewater and even excess rainfall in cities requires energy to be treated or disposed. Some non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, e.g. locally produced potable water from ground/surface water sources vs. desalinated seawater (Box 25-2, Tables 25-6 and 25-7; Macknick et al., 2012b; Plappally and Lienhard, 2012). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user; Döll et al., 2012) is generally more energy intensive than surface water. In India, for example, 19% of total electricity use in 2012 was for agricultural purposes (Central Statistics Office, 2013), with a large share for groundwater pumping. Pumping from greater depth increases energy demand significantly– electricity use ($kWhr/m^3$ of water) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard, 2012).

The reuse of appropriate wastewater for irrigation (reclaiming both water and energy-intense nutrients) may increase agricultural yields, save energy, and prevent soil erosion (Smit and Nasr, 1992; Jimenez, 1996; Wichelns et al., 2007; Raschid-Sally and Jayakody, 2008) *(medium confidence)*. More energy efficient treatment methods enable poor quality ("black") wastewater to be treated to quality levels suitable for discharge into water courses, avoiding additional fresh water and associated energy demands (Keraita et al, 2008). If properly treated to retain nutrients, such treated water may increase soil productivity, contributing to increased crop yields/food security in regions unable to afford high power bills or expensive fertilizer (Oron, 1996; Lazarova and Bahri, 2005; Redwood and Huibers, 2008; Jimenez, 2009) *(high confidence)*.

Linkages among water, energy, food/feed/fiber and climate are also strongly related to land use and management (Section 4.4.4, Box 25-10) *(robust evidence, high agreement)*. Land degradation often reduces efficiency of water and energy use (e.g. resulting in higher fertilizer demand and surface runoff), and compromises food security (Sections 3.7.2, 4.4.4). On the other hand, afforestation activities to sequester carbon have important co-benefits of reducing soil erosion and providing additional (even if only temporary) habitat (see Box 25-10) but may reduce renewable water resources. Water abstraction for energy, food or biofuel production or carbon sequestration can also compete with minimal environmental flows needed to maintain riverine habitats and wetlands, implying a potential conflict between economic and other valuations and uses of water (Sections 25.4.3 and 25.6.2, Box 25-10) *(medium evidence, high agreement)*. Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water and climate (McCornick et al., 2008; Bazilian et al., 2011; Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy and water demand, bioproductivity and other factors (see Figure WE-1 and Wise et al., 2009), and has implications for security of supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the implications for health and economic impacts as described throughout this report.

The interconnectivity of food/fiber, water, land use, energy and climate change, including the perhaps not yet well understood cross-sector impacts, are increasingly important in assessing the implications for adaptation/mitigation policy decisions. Fuel-food-land use-water-GHG mitigation strategy interactions, particularly related to bioresources for food/feed, power, or fuel, suggest that combined assessment of water, land type and use requirements, energy requirements and potential uses and GHG impacts often epitomize the interlinkages. For example, mitigation scenarios described in the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011) indicate up to 300EJ of biomass primary energy by 2050 under increasingly stringent mitigation scenarios. Such high levels of biomass production, in the absence of technology and process/management/operations change, would have significant implications for land use, water and energy, as well as food production and pricing. Consideration of the interlinkages of energy, food/feed/fiber, water, land use and climate change is increasingly recognized as critical to effective climate resilient pathway decision making *(medium evidence, high agreement)*, although tools to support local- and regional-scale assessments and decision-support remain very limited.

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APPENDICES

Appendix 10.A. Industrial Classification

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

- 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
        - Climate change impact & quarrying: No results*
    - 09 - Mining support service activities
- C – Manufacturing (10.5, except C19)
    - 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 (10.2)
    - 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 (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

*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.

Appendix 10.B. Estimates of the Total and Marginal Economic Impact of Climate Change

Table 10.B.1: Estimates of the welfare loss due to climate change (as equivalent income loss in percent); estimates of the uncertainty are given in bracket as standard deviations or 95% confidence intervals.
[NB: See tables file for content.]

Table 10-1: Main projected impacts of climate change and extreme weather events on energy supply and the related adaptation options.

Tech	Changes in climatic or related attributes	Possible 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: (Sieber, 2013), (Parkpoom *et al.*, 2005), (Feeley III *et al.*, 2008; Förster and Lilliestam, 2009; Hoffmann *et al.*, 2010; Linnerud *et al.*, 2011; Mukheibir, 2013; NETL (National Energy Technology Laboratory), 2007; Ott and Richter, 2008; Williams, 2013), (Markoff and Cullen, 2008; Schaefli *et al.*, 2007),(Droogers, 2009). (Bloom *et al.*, 2008; Christensen and Busuioc, 2007; DOE, 2007; EPA, 2001; Haugen and Iversen, 2008; Honeyborne, 2009; Kurtz *et al.*, 2009; Kurtz *et al.*, 2011; Leckebusch *et al.*, 2008; Norton, 2006; Patt *et al.*, 2013; Pryor *et al.*, 2006; Pryor and Barthelmie, 2010; Pryor and Barthelmie, 2013; Pryor and Barthelmie, 2011; Pryor and Schoof, 2010; Sailor *et al.*, 2008; SPF, 2009; Walter *et al.*, 2006).

Notes: TH: thermal heating; PV: photovoltaic; CSP: concentrating solar power.

Table 10-2: Main impacts of climate change and extreme weather events 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, 1996; Cruz and Krausmann, 2013; Hines *et al.*, 2009; Krausmann and Mushtaq, 2008; Reed, 2008; Winkler *et al.*, 2010),(Vlasova and Rakitina, 2010), (Ward, 2013), (McColl, 2012).

Table 10-3: Economy-wide implications of 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 *et al.*, 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.*, 2007a)	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.*, 2010a; Eboli *et al.*, 2010a)	CGE	Rising temperatures/ changing demand for energy; climate impacts in 4 other sectors modelled (Global, 2002 - 2100)	By 2100, change in GDP due to climate impacts on energy 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.	8	17
(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
(de Lucena *et al.*, 2010)	PE	Changing precipitation -> Change in hydro production; rising temp -> lower NG thermal efficiency; rising temperature -> change in demand for energy (Brazil, 2010 - 2035)	New generating capacity needed to produce additional 153 – 162 TWh per year. Capital investment of $48 to $51 billion, which is equivalent to 10 years of capital expenditures in Brazil's long-term energy plan. $6.9 to $7.2 billion in additional operating expenses in years with worst-case hydro production	1	11
(Bye *et al.*, 2008)	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)	Econometric	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
(UNDP, 2011)	PE	Damage Case 1 (DC1): Hotter in Both Winter and Summer – Decreased demand for heating and increased demand for cooling; Damage Case 2 (DC2): Colder in Both Winter and Summer – Increased demand for heating and decreased demand for cooling,; Damage Case 3 (DC3): Colder in the Winter and Hotter in the Summer – Increased demand for heating and increased demand for cooling.(Macedonia, 2009 – 2030)	Change in electricity demand in residential and commercial sectors: DC1: 3.5% DC2: 0,3% DC3: 8% Change in electricity system cost: DC1: 0,8% DC2: 0.06% DC3: 1.74%	9	5
(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

Note: The regions indicated in the 'Regions' column vary in size and are model-specific.

Table 10-4: Observed normalized insured losses from weather hazards (trends significant at the 10% level are indicated as a trend).

Region / peril accounted for in normalized insured property losses	**Observation period**	**Trend in insured losses - otherwise specified (aggregation mode)**	**References**
World / all weather-related	1990-2008	No trend (annual aggregates)	[1]
Australia / aggregate of bushfire, flood, hailstorm, thunderstorm, tropical cyclone	1967-2006	No trend (annual aggregates)	[7]
West Germany / all weather-related	1980-2008	Positive trend (annual aggregates)	[1]
West Germany / floods	1980-2008	No trend (annual aggregates)	
West Germany / convective events	1980-2008	No trend (annual aggregates)	
West Germany / winter storms	1980-2008	Positive trend (annual aggregates)	
Southwest Germany / hailstorm	1986-2004	Positive trends in annual frequency of days exceeding thresholds of daily damage claim counts. Increase in annual count of hail damage claims.	[8]
Spain / floods	1971-2008	No trend (annual aggregates)	[2]
USA / winter storms (ice storms, blizzards and snow storms)	1949-2003	Positive trend (pentade totals) Positive trend (average loss per state, pentade totals)	[3]
USA / all flood (“flood only” and floods specifically caused by convective storms, tropical cyclones, snow-melt)	1972-2006	Positive trend (annual aggregates)	[4]
USA / tropical cyclones	1949-2004	Increase (7-year totals) No statistical trend assessment.	[5]
USA / hailstorm	1951-2006	Focus on top-ten major hail storm losses of the period 1951-2006. Increase in frequency and loss in the 1992-2006 period as compared to 1951-1991. No statistical trend assessment.	[6]
USA east of 109° W / convective events (hail, heavy precipitation and flash flood, straight-line wind, tornado)	1970-2009 March to September	Standard deviation (variability) by a factor 1.65 greater for 1990-2009 than for 1970-1989. Mean annual loss by a factor 2.67 greater for 1990-2009 than for 1970-1989. Data: normalized insured loss exceeding US$ 150 million per event, annual aggregates.	[9]
USA / all weather-related	1973-2008	Positive trend (annual aggregates)	[1]
USA / floods	1973-2008	Positive trend (annual aggregates)	
USA / convective events	1973-2008	Positive trend (annual aggregates)	
USA / winter storms	1973-2008	Positive trend (annual aggregates)	
USA / tropical cyclones	1973-2008	Positive trend (annual aggregates)	
USA / heat episodes	1973-2008	Positive trend (annual aggregates)	
USA / cold spells	1973-2008	No trend (annual aggregates)	

References: [1] (Barthel and Neumayer, 2012); [2] (Barredo *et al.*, 2012); [3] (Changnon, 2007); [4] (Changnon, 2008); [5] (Changnon, 2009a); [6] (Changnon, 2009b); [7] (Crompton and McAneney, 2008); [8] (Kunz *et al.*, 2009); [9] (Sander *et al.*, 2013).

Table 10-5: Climate change projections of insured losses and/or insurance prices.

Hazard/ insurance line	**Region**	**Projected changes in future time slices relative to current climate (Spatial distribution and vulnerability of insured values assumed to be unchanged over time).**
Winter storm/ Homeowners' insurance	Europe	Projected increases in mean annual loss ratio lie in a range from one to two-digit percentages in time slices before and around 2050 for regions such as France, Belgium/Netherlands, UK/Ireland, Germany, and Poland, with larger increases at the end of the century. Southern European regions expect decreases, such as Portugal/Spain (A1B, A2) [4] [5] [8] [13] [14] [15] [19]. Currently rare and high annual loss ratios are projected to occur more often: today's 20-year, 10-year, and 5-year return periods appear strongly reduced by the end of the century for individual countries. For entire Europe they will be halved (A2) [16]. Accordingly, return periods will have higher loss levels associated [19] [10], e.g., the 25-year loss in Germany is expected to rise by 5% to 41% in 2041–2070 (A1B) [10] [8].
River flood, maritime flood, flash flood from rainfall, melting snow/ Property and business interruption insurances	Europe, North America	Germany: projected increases in mean annual insured flood loss according to a seven-member dynamical downscaling ensemble mean (B1, A1B, A2) are 84% (2011-2040), 91% (2041-2070), and 114% (2071-2100) [7]. United Kingdom: projected increases in mean annual insured flood loss are 8% (for a +2°C rise in global mean temperature) and 14% (for a +4°C rise), with the one-in-hundred-year loss higher by 18% and 30%, respectively [4]. Norway, Canada: losses from heavy precipitation in property and business interruption insurances in four city areas in Canada are projected to rise by 13% (2016-2035), 20% (2046-2065), and 30% (2081-2100) in a five member ensemble mean (IS92a, A2/B2, A2). In three counties across southern Norway precipitation and snowmelt insurance losses are expected to be higher by 10% to 21% (A2) and 17% to 32% (B2) at the end of the century [9;3]. The Netherlands: expected annual property loss with an assumed flood insurance system is projected to lie by 125% higher in 2040 relative to 2015 (corresponding to 24 cm sea level rise) and by 1,784% higher in 2100 (85cm sea level rise) [1].
Tropical cyclones/ Foremost property insurance lines	North America, Asia	U.S.A.: three of four GCMs driving a specific tropical cyclone and loss model entail increasing insured hurricane losses over time (A1B) [6]. Two GCM outputs at coarser resolution for the ende of the century produce contrarious results of prolonged (ECHAM5/MPIOM A2) versus shortened (MRI/JMA A1B) return periods of current loss levels [17]. Analogously, a wide range of model projections is reflected in price levels of Florida's hurricane wind insurance that are projected to change by -20% to +5% (2020s) and -28% to +10% (2040s) (under the assumptions of strained reinsurance capacity and current adaptation) [12;18]. These approaches demonstrate uncertainty in the sign of change. China: projected increases of insured typhoon losses are 20% (for a +2°C rise in global mean temperature) and 32% (for a +4°C scenario), with the one in hundred-year loss higher by 7% and 9%, respectively [4].
Hailstorm/ Homeowners' insurance/ Agricultural insurances	Europe	The Netherlands: losses from outdoor farming insurance and greenhouse horticulture insurance are projected to increase by 25% to 29% and 116% to 134%, respectively, for a +1°C rise in global mean temperature. For a +2°C scenario, projected increases will be higher at 49% to 58% and 219% to 269%, respectively (statistical model) [2]. Germany: projected increases in mean annual loss ratios from homeowners' insurance due to hail are 15% (2011 – 2040) and 47% (2041 – 2070) (A1B, statistical model) [8].
Storms, pests, diseases/ Paddy rice insurance	Asia	Japan: paddy rice insurance payouts are projected to decrease by 13% at the end of the century, on the basis of changes in standard yield and yield variability [11].

References: [1] (Aerts and Botzen, 2011); [2] (Botzen *et al.*, 2010b); [3] (Cheng *et al.*, 2012); [4] (Dailey *et al.*, 2009); [5] (Donat *et al.*, 2011); [6] (Emanuel, 2011); [7] (German Insurance Association (Gesamtverband der Deutschen Versicherungswirtschaft), 2011); [8] (Gerstengarbe *et al.*, 2013); [9] (Haug *et al.*, 2011); [10] (Held *et al.*, 2013); [11] (Iizumi *et al.*, 2008); [12] (Kunreuther *et al.*, 2012); [13] (Leckebusch *et al.*, 2007); [14] (Pinto *et al.*, 2007); [15] (Pinto *et al.*, 2009); [16] (Pinto *et al.*, 2012); [17] (Raible *et al.*, 2012); [18] (Ranger and Niehoerster, 2012); [19] (Schwierz *et al.*, 2010).

Table 10-6: Fundamental supply-side challenges and sensitivities.

Challenges that might increase in the climate change context	**Example / Explanation**
Failure to reflect temporal changes in hazard condition in risk management	After 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%. Consequences 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;22]. 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;11;14;15]. In this respect, premium incentives to reduce residual flood risk are missing. Policyholders 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 [11;14;15]. All these features, among others, account for the fact that NFIP has continuously been running a cumulative operating deficit, reaching more than US$ 20bn in 2006, after the big hurricanes [6;7;14;15].
Non-quantifiable uncertainties increasing risk	There is ambiguity as to what degree climate change may modify regional weather hazards – model projections are not unequivocal [2;3], and there is uncertainty about prospects of post-disaster regulatory/jurisdictional pressures, e.g. to extend claims payments beyond the original coverage [9]. Such uncertainties materialize in risk-based capital loadings [12].
Liability insurance impacted by new climate risk	Chances of success for claims based on CO_2 emissions in the USA seem small, due to legal obstacles [4;5;8;18], even though allocation schemes to overcome these hurdles are being discussed [17;20]. Defense costs could be covered by liability insurance [21]. CO_2 emissions were declared pollution (US Supreme Court/EPA). Existing and future regulation on limits for CO_2 emissions could continue to displace liability claims for CO_2 emissions and at the same time create new liability risks in case of non-compliance. These risks have not yet been adequately taken into account, somewhat similar to the early stages of environmental liability claims in the U.S.A. in the twentieth century [10;16]. The Supreme Court of Virginia ruled in 2012 that coverage under liability insurance for claims based on CO_2 emissions and defense costs depends on the specific occurrence-definition underlying the contract (e.g., if the cover pertains to accident, warming due to CO_2 emissions and resulting damage does not match this definition) [19].
Share of insurance in national risk financing	In the years following weather-related disasters countries with high insurance penetration show almost no impact on sovereign deficit and increasing economic output (GDP), whereas low-penetration countries experience substantially rising government deficit and missing positive change in output [13;21]. The absence of developed insurance systems, as is the case in many middle- and low-income countries, translates into greater macroeconomic vulnerability than with developed insurance systems.

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] (Kunreuther *et al.*, 2009); [13] (Melecky and Raddatz, 2011); [14] (Michel-Kerjan, 2010); [15] (Michel-Kerjan and Kunreuther, 2011); [16] (Mills, 2009); [17] (Patton, 2011); [18] (Stewart and Willard, 2010); [19] (Supreme Court of Virginia, U.S.A., 2012); [20] (Taylor and Tollin, 2009); [21] (von Peter *et al.*, 2012); [22] (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	Flood hazard insurance zoning systems, e.g. HORA (Austria), SIGRA (Italy), and ZÜRS (Germany), hamper development in high-risk zones by allocating adequately high premiums [26]. 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 [42]. However, perceptions that motivate flood insurance uptake range from risk awareness [9] to pure peer group expectation [32] - the latter might blur the role of the risk-premiums-nexus in some societal contexts.
Conditions of insurance policies incentivizing vulnerability reduction	Premium discounts for compliance with local building codes or other prevention options [27;45]; share of the insured in claims payment by deductibles or upper coverage limits, and exclusion of systematically affected property [1;7;8;10;11;15;21]; long-term natural-hazard insurance tied to the property and linked to mortgages and loans granted for prevention measures [27;28;36]. The latter is contested by modelled high risk capital requirements and ambiguity loadings, rendering multiyear policies relatively expensive and less flexible for the insurance market [34].
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 [38].
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 in 2008 [16;18;20]. Investors in insurance linked securities are attracted by the lack of correlation to typical financial market risks (e.g., currency risks), and the well defined loss-per-index structure. The higher transparency relative to other asset-backed securities, such as mortgage-backed securities, contributed to the better performance of catastrophe bonds following the financial crisis of 2007/2008 [16;18]. As bonds typically cover large losses, the basis risk, i.e. suffering damage without parametric triggering, is reduced [44]; further reduction may be feasible by optimizing index measurements [16]. Weather derivatives are further instruments used to transfer risks to the capital markets [17;27;37]. Also multiple-trigger "hybrid" products are 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 [5;18].
Index-based weather crop insurance products	Agricultural insurances predominantly cover crop, but also livestock, forestry, aquaculture, and greenhouses. Main products are indemnity-based crop insurance (covers for single perils and multiple peril events), and index-based crop insurance [41]. The latter is available in 40% of middle-income countries, with enlarged systems beyond pilot implementation in India and Mexico, and growth in China [23;33;40;46]. Risk-based price signals may better foster adaptation if schemes are coupled with access to advanced technology, e.g. drought-resistant seed [4;15;23;33]. Various index definitions (cumulative rainfall, area-yield, etc.) and applications exist or have been proposed [4;29;30;31]. Adjusting to uncertain regional changes in temporal hazard condition is a basic challenge with climate change [14;24;29].
Improvements in index-based weather insurance	Basis risk, i.e. weak correlation between index and damage, can be reduced if the index scheme is applied to an area-yield trigger in a region with homogeneous production potential (e.g., based on a sample) and/or to the uppermost disaster risk layer only [14;15;22]. It can be better absorbed if index insurance works at aggregate level, e.g. to cover crop-credit portfolios, cooperatives or informal networks [43], and if satellite-based remote-sensing technology can be used to establish plot identification, yield estimation and loss assessment [22]. Satellite-based forage estimation is already used for livestock index insurance in East Africa [13]. Pooling local schemes across climate regions under one cooperative parent organization, thus realizing central management, economics of scale and risk diversification, can reduce capital requirements and advance performance [6;12;35]. The disaster risk layer and high start-up costs (weather-data collection, risk modelling, education) necessitate subsidies from the state or donors [15;33].
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 [3]. This theory proved inadequate if applied to relatively vulnerable small-sized middle to low-income countries [19],

	thereby rehabilitating sovereign insurance. For the Caribbean scheme CCRIF, that pools states, the reduction in premium cost per country is expected to be 45–50% [29]. Similar pooling schemes are being developed (e.g., African Risk Capacity, Pacific Catastrophe Risk Insurance Pilot) [2;39]. Pooling natural catastrophe risks across an array of megacities has also been proposed [25].

References: [1] (Aakre *et al.*, 2010); [2] (Wilcox *et al.*, 2010); [3] (Arrow and Lind, 1970) [4] (Barnett *et al.*, 2008) [5] (Barrieu and Loubergé, 2009) [6] (Biener and Eling, 2012); [7] (Botzen and van den Bergh, 2008) [8] (Botzen and van den Bergh, 2009); [9] (Botzen and van den Bergh, 2012); [10] (Botzen *et al.*, 2009) [11] (Botzen *et al.*, 2010a) [12] (Candel, 2007); [13] (Chantarat *et al.*, 2013); [14] (Clarke and Grenham, 2012); [15] (Collier *et al.*, 2009); [16] (Cummins, 2012); [17] (Cummins and Mahul, 2009); [18] (Cummins and Weiss, 2009); [19] (Ghesquiere and Mahul, 2007); [20] (Guy Carpenter, 2011); [21] (Hecht, 2008); [22] (Herbold, 2013b); [23] (Hess and Hazell, 2009); [24] (Hochrainer *et al.*, 2010); [25] (Hochrainer and Mechler, 2011); [26] (Kron, 2009); [27] (Kunreuther *et al.*, 2009); [28] (Kunreuther and Michel-Kerjan, 2009); [29] (Leblois and Quirion, 2011); [30] (Leiva and Skees, 2008); [31] (Linnerooth-Bayer and Mechler, 2009); [32] (Lo, 2013); [33] (Mahul and Stutley, 2010); [34] (Maynard and Ranger, 2012); [35] (Meze-Hausken *et al.*, 2009); [36] (Michel-Kerjan and Kunreuther, 2011); [37] (Michel-Kerjan and Morlaye, 2008); [38] (Muir-Wood and Grossi, 2008); [39] (The World Bank, 2013); [40] (Prabhakar *et al.*, 2013); [41] (Swiss Re, 2013a); [42] (Thieken *et al.*, 2006); [43] (Trærup, 2012); [44] (Van Nostrand and Nevius, 2011); [45] (Ward *et al.*, 2008); [46] (Zhu, 2011).

Table 10-8: Governance, public-private partnerships, and insurance market regulation.

Structural element	**Example/Explanation**
Public-private arrangements 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) [13]; see also [1;3;4;10;11;12;14].
Care for people who cannot afford insurance	Either by funds outside the insurance system, e.g. insurance vouchers, or by premium subsidies (particularly for the catastrophic risk portion) [1;6;14;17].
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 [2;8;9].
Concepts for adaptation-oriented climate change risk management frameworks linked to UNFCCC	Risk prevention and risk reduction often are the starting points that can absorb many of the smaller weather risks, and various forms of insurance, including international coordination, are meant to cover all of the remaining risks [7;15;16]. A global framework, where the wealthy agree to pool risks with the most vulnerable, equals social insurance that is different from a risk-based share in insurance funds [5].

References: [1] (Aakre *et al.*, 2010); [2] (Barnett *et al.*, 2008); [3] (Botzen and van den Bergh, 2008); [4] (Bruggeman *et al.*, 2010); [5] (Duus-Otterström and Jagers, 2011); [6] (Kunreuther *et al.*, 2009); [7] (Linnerooth-Bayer *et al.*, 2009); [8] (Linnerooth-Bayer *et al.*, 2011); [9] (Mahul and Stutley, 2010); [10] (Monti, 2012); [11] (Paudel, 2012); [12] (Schwarze and Wagner, 2007); [13] (Schwarze *et al.*, 2011); [14] (Van den Berg and Faure, 2006); [15] (Warner and Spiegel, 2009); [16] (Warner *et al.*, 2012); [17] ().

Table 10-9: Selected statistical characteristics of the social cost of carbon: average (Avg) and standard deviation (SD), both in dollar per tonne of carbon, and number of estimates (N; number of studies in brackets).

	Post-AR4			Pre-AR4			All studies		
	Avg	SD	N	Avg	SD	N	Avg	SD	N
0%	270	233	97	745	774	89	585	655	142
1%	181	260	88	231	300	49	209	284	137
3%	33	29	35	45	39	42	40	36	186
All	241	233	462 (35)	565	822	323 (49)	428	665	785 (84)

Sources: See Appendix 10.B.

Table 10-10: Summary of findings.

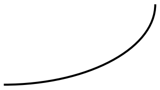
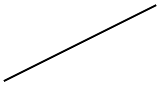
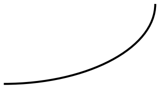
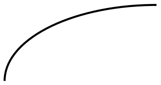
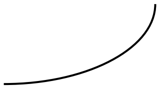
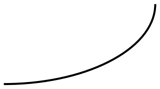
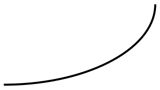
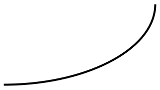
Sector	**CC Drivers**	**Sensitivity to CC**	**Sign**	**Other Drivers**	**Relative Impact of CC to Other Drivers**
Winter tourism	Temperature Snow		Negative	Population Lifestyle Income Aging	Much less
Summer tourism	Temperature Rainfall Cloudiness		Negative for suppliers in low altitudes and latitudes Positive for suppliers in high altitudes and latitudes Neutral for tourists	Population Income Lifestyle Aging	Much less
Cooling demand	Temperature Humidity Hot Spells		Positive for suppliers Negative for consumers	Population Income Energy Prices Technology Change	Less
Heating demand	Temperature Humidity Cold spells		Negative for suppliers Positive for consumers	Population Income Energy Prices Technology Change	Less
Health services	Temperature Precipitation		Positive for suppliers Negative for consumers	Aging Income Diet/Lifestyle	Less
Water infrastructure and services	Temperature Precipitation Storm Intensity Seasonal Variability		Negative for water users Positive for suppliers Spatially heterogeneous	Population Income Urbanization Regulation	Less in developing countries Equal in developed countries
Transportation	Temperature Precipitation Storm Intensity Seasonal Variability Freeze/Thaw Cycles		Negative for all users Positive for transport construction industry	Population Income Urbanization Regulation Mode Shifting Consumer and Commuter Behavior	Much less in developing countries Less in developed countries
Insurance	Floods Wind Storms Hail Drought Temperature		Negative for consumers Neutral for suppliers	Population Income Regulation Product Innovation	Less or equal in developing countries Equal or more in developed countries

Table 10.B.1: Estimates of the welfare loss due to climate change (as equivalent income loss in percent); estimates of the uncertainty are given in bracket as standard deviations or 95% confidence intervals.

Study	**Warming**	**Impact**	**Method**	**Coverage**
	(˚C)	**(%GDP)**		
(Nordhaus 1994b)	3.0	-1.3	Enumeration	Agriculture, energy demand, sea level rise
(Nordhaus 1994a)	3.0	-4.8 (-30.0 to 0.0)	Expert elicitation	Total welfare
(Fankhauser 1995)	2.5	-1.4	Enumeration	Sea level rise, biodiversity, agriculture, forestry, fisheries, electricity demand, water resources, amenity, human health, air pollution, natural disasters
(Tol 1995)	2.5	-1.9	Enumeration	Agriculture, biodiversity, sea level rise, human health, energy demand, water resources, natural disasters, amenity
(Nordhaus and Yang 1996)[a]	2.5	-1.7	Enumeration	Agriculture, energy demand, sea level rise
(Plamberk and Hope 1996)[a]	2.5	-2.5 (-0.5 to –11.4)	Enumeration	Sea level rise, biodiversity, agriculture, forestry, fisheries, electricity demand, water resources, amenity, human health, air pollution, natural disasters
(Mendelsohn et al. 2000)[a]	2.5	0.0	Enumeration	Agriculture, forestry, sea level rise, energy demand, water resources
(Mendelsohn et al. 2000)[a]	2.5	0.1	Statistical	Agriculture, forestry, energy demand
(Nordhaus and Boyer 2000)	2.5	-1.5	Enumeration	Agriculture, sea level rise, other market impacts, human health, amenity, biodiversity, catastrophic impacts
(Tol 2002)	1.0	2.3 (1.0)	Enumeration	Agriculture, forestry, biodiversity, sea level rise, human health, energy demand, water resources
(Maddison 2003)[a]	2.5	-0.1	Statistical	Household consumption
(Rehdanz and Maddison 2005)[a]	1.0	-0.4	Statistical	Self-reported happiness
(Hope 2006a)[a]	2.5	-0.9 (-0.2 to 2.7)	Enumeration	Sea level rise, biodiversity, agriculture, forestry, fisheries, energy demand, water resources, amenity, human health, air pollution, natural disasters
(Nordhaus 2006)	3.0	-0.9 (0.1) -1.1 (0.1)	Statistical	Economic output
(Nordhaus 2008)	3.0	-2.5	Enumeration	Agriculture, sea level rise, other market impacts, human health, amenity, biodiversity, catastrophic impacts
(Maddison and Rehdanz 2011)[a]	3.2	-11.5	Statistical	Self-reported happiness
(Bosello et al. 2012)	1.9	-0.5	CGE	Energy demand; tourism; sea level rise; river floods; agriculture; forestry; human health
(Roson and van der Mensbrugghe 2012)	2.3 4.9	-1.8 -4.6	CGE	Agriculture, sea level rise, water resources, tourism, energy demand, human health, labor productivity

[a] Results aggregated by (Tol 2013).

The database on the marginal damage costs of carbon dioxide emissions and its growth rate can be found at: http://www.sussex.ac.uk/Users/rt220/marginaldamagecost.xlsx

The following papers are included in the database on the marginal damage costs of carbon dioxide emissions: (Ackerman and Munitz 2012;Ackerman and Stanton 2012;Anthoff et al. 2009b;Anthoff et al. 2009a;Anthoff et al. 2009c;Anthoff et al. 2011a;Anthoff et al. 2011b;Anthoff and Tol 2010;Anthoff and Tol 2011;Anthoff and Tol 2013;Ayres and Walter 1991;Azar 1994;Azar and Sterner 1996;Cai et al. 2012;Ceronsky et al. 2006;Ceronsky et al. 2011;Clarkson and Deyes 2002;Cline 1992;Cline 1997;Cline 2004;Downing et al. 1996;Downing et al. 2005;EPA and NHTSA 2009;Eyre et al. 1999;Fankhauser 1994;Guo et al. 2006;Haraden 1992;Haraden 1993;Hohmeyer 1996;Hohmeyer 2004;Hohmeyer and Gaertner 1992;Hope 2005a;Hope 2005b;Hope 2006a;Hope 2006b;Hope 2008a;Hope 2008b;Hope 2011;Hope 2013;Hope and Hope 2013;Hope and Maul 1996;Interagency Working Group on the Social Cost of Carbon 2013;Kemfert and Schill 2010;Link and Tol 2004;Maddison 1995;Manne 2024;Marten 2011;Mendelsohn 2004;Narita et al. 2009;Narita et al. 2010;Newell and Pizer 2003;Nordhaus 2010;Nordhaus 1982;Nordhaus 1991;Nordhaus 1993;Nordhaus 1994b;Nordhaus 2008;Nordhaus and Boyer 2000;Nordhaus and Popp 1997;Nordhaus and Yang 1996;Parry 1993;Pearce 2003;Peck and Teisberg 1993;Penner et al. 1992;Perrissin Fabert et al. 2012;Plambeck and Hope 1996;Reilly and Richards 1993;Roughgarden and Schneider 1999;Schauer 1995;Sohngen 2010;Stern et al. 2006;Stern and Taylor 2007;Tol 1999;Tol 2005;Tol 2010;Tol 2012;Uzawa 2003;Wahba and Hope 2006;Waldhoff et al. 2011)

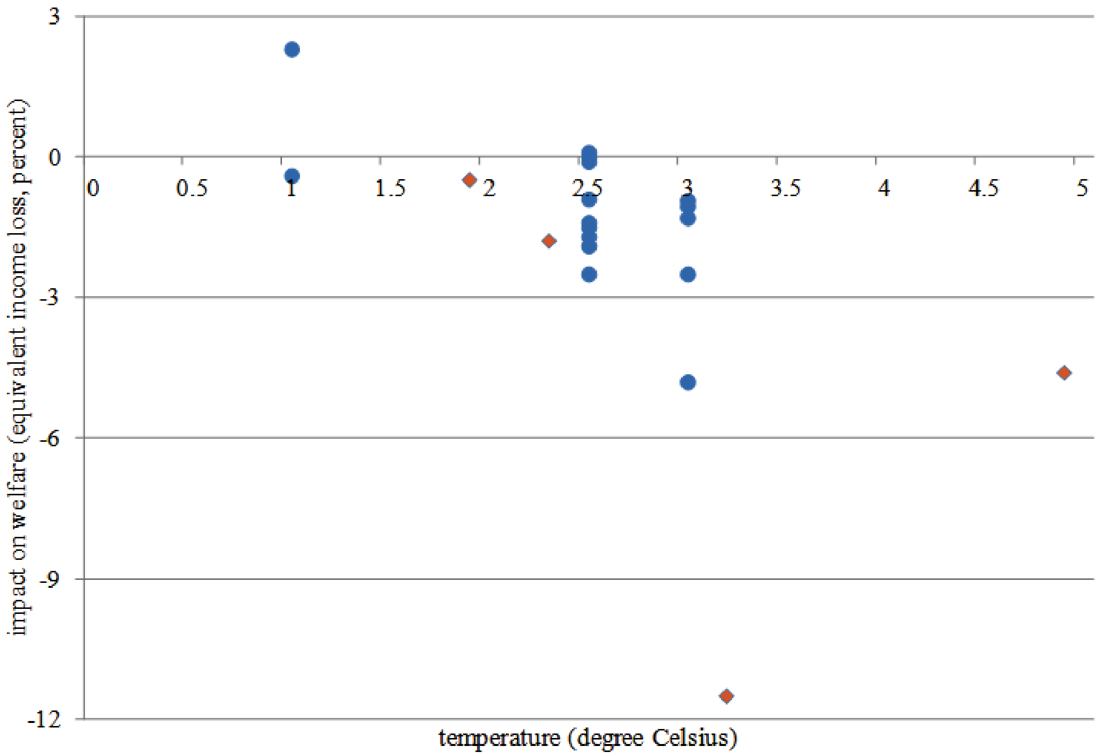


Figure 10-1: Estimates of the total impact of climate change plotted against the assumed climate change (proxied by the increase in the global mean surface air temperature); studies published since IPCC AR5 are highlighted as diamonds; see Table 10.B.1.

[Illustration to be redrawn to conform to IPCC publication specifications.]

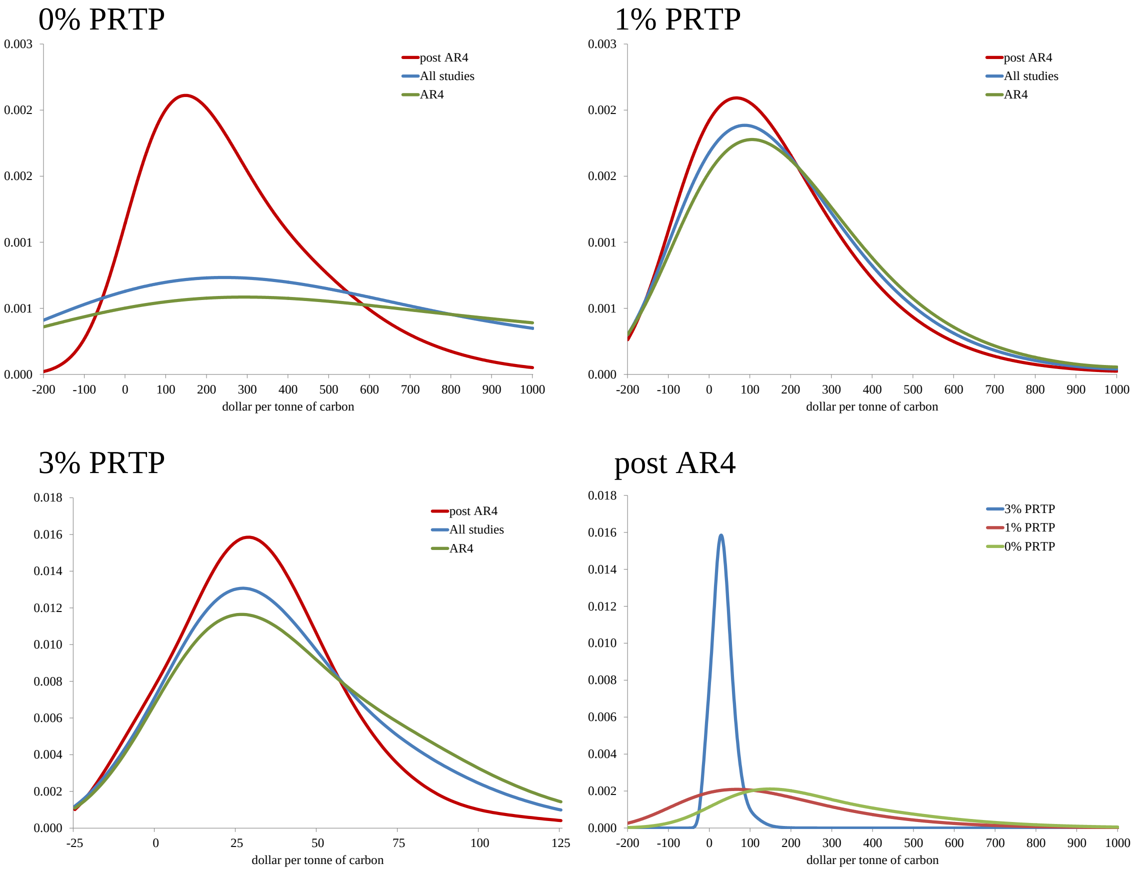


Figure 10-2: Kernel densities of the social cost of carbon for all studies and studies before or after AR4 for three alternative pure rates of time preference (PRTP).
[Illustration to be redrawn to conform to IPCC publication specifications.]

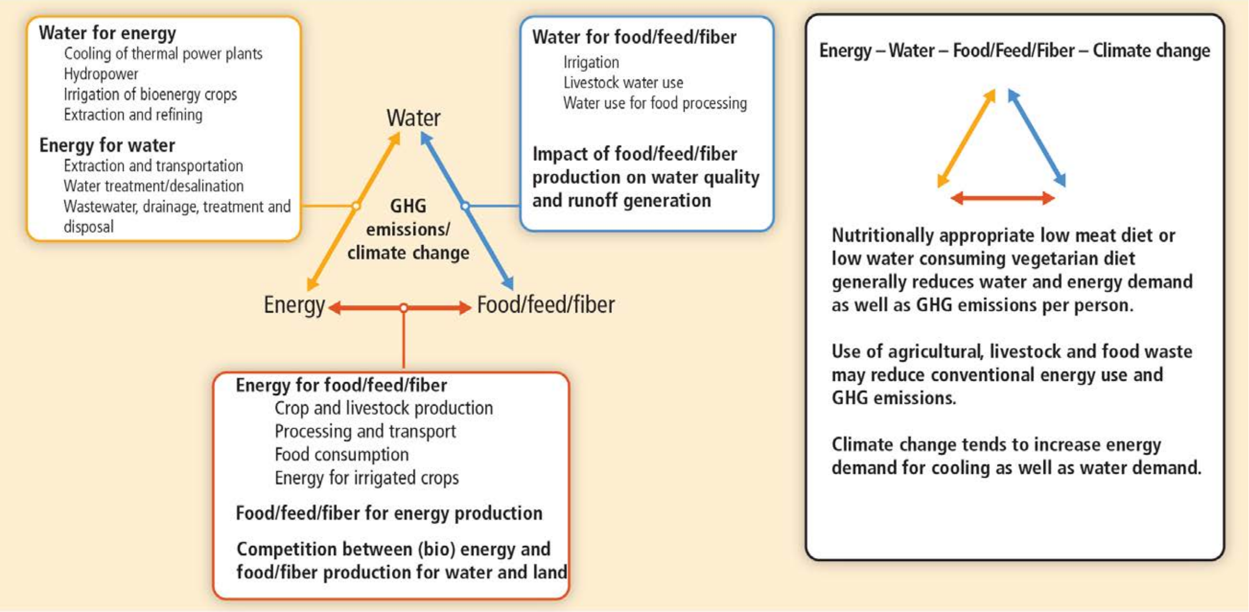


Figure WE-1: The water-energy-food nexus as related to climate change. The interlinkages of supply/demand, quality and quantity of water, energy and food/feed/fiber with changing climatic conditions have implications for both adaptation and mitigation strategies.