10. Key Economic Sectors and Services

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Appendix 10B. Industrial Classification and Literature Search

Executive Summary

Assessment of the literature on the impacts, vulnerability and adaptation of economic activities to climate change has emerged as an active research area. Initial work has developed in a few key economic sectors and through economy-wide 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.

Climate change will reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors; the balance of the two depends on the geographic, socioeconomic and technological conditions. Increasing income will allow people to regulate indoor temperatures to comfort level that leads to fast growing energy demand for air conditioning even in the absence of climate change in warm regions with low income levels at present. Energy demand will be influenced by changes in demographics (upwards by increasing population and decreasing average household size), lifestyles (upwards by larger floor area of dwellings), the design and heat insulation properties of the housing stock, the energy efficiency of heating/cooling devices and the abundance and energy efficiency of other electric household appliances. The relative importance of these drivers varies across regions and will change over time. (10.2)

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

Climate change may influence the integrity and reliability of pipelines and electricity grids. Pipelines and electric transmission lines have been operated for over a century in diverse climatic conditions on land from hot deserts to permafrost areas and increasingly at sea. Climate change may require the adoption of technological solutions for the construction and operation of pipelines and power transmission and distribution lines from other geographical and climatic conditions, adjustments in existing pipelines and improvements in the design and deployment of new ones in response to the changing climate and weather conditions. (10.2)

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

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

Because of climate change, tourists are likely to spend their holidays at higher altitudes and latitudes. Climate change would affect tourism resorts, particularlyski resorts, beach resorts, and nature resorts. The economic implications of climate-change-induced changes in tourism demand and supply may be substantial, with gains for countries closer to the poles and losses for countries closer to the equator. The demand for outdoor recreation is affected by weather and climate, but there are only a few anecdotal estimates of the impact of climate change. (10.6)

Climate change strongly influences insurance and related financial industries. More frequent and/or intensive weather disasters would increase losses and loss volatility in various regions through and challenge insurance systems to offer affordable coverage while generating more risk-based capital. The greatest challenge is in low- and middle-income countries. Solutions suggested include, first, assessing risk in a way that allows for temporal changes in hazard conditions, and second, transmitting the risk information to policyholders and stakeholders through premiums calibrated to existing risk, thereby encouraging them to reduce vulnerability. Reduction of vulnerability can be further incentivized through various insurance conditions. Large-scale public risk prevention programmes and government insurance of the non-diversifiable portion of risk are other forms of adaptation.,Commercial reinsurance and risk-linked securitization markets also have a role in ensuring financially healthy insurance systems. (10.7)

Climate change could affect the health sector through increases in the frequency, intensity, and extent of extreme weather events adversely affecting infrastructure and increase the demands for services, placing additional burdens on public health and health care personnel and supplies; these have economic consequences. (10.8)

The literature on the impact of climate change on many sectors of the economy is extremely sparse. Few studies have evaluated the possible impacts of climate change on mining, manufacturing or services (apart from health, insurance and tourism). (10.5, 10.8)

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

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

Based on a comprehensive assessment across economic sectors, few key sectors have been subject to detailed research. Further research, collection and access to more detailed economic data and the advancement of analytic methods and tools will be required to further assess the potential impacts of climate on key economic systems and sectors. (10.10)

10.1. Introduction and Context

This chapter discusses the implications of climate change on key economic sectors and services. An inclusive approach was taken, discussing all sectors of the economy. Appendix 10A shows the list of sectors according to the International Classification of Industrial Classification.

However, some sectors are little vulnerable to climate change and few words are devoted to these. There is little literature on other sectors. Section 10.10 discusses whether there may be vulnerable sectors that have yet to be studied. 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.

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

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

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

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

10.2. Energy

Studies conducted since AR4 and assessed here confirm the main insights about the impacts of climate change on energy well-known since the SAR (Acosta Moreno 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. Yet changes in climate and weather conditions are only one of the numerous driving forces of energy demand. Their relative importance among the drivers varies across regions and will change over time. In addition to the proliferation of demand studies, an increasing number of publications explore the vulnerability, impacts and the adaptation options in various energy sectors.

10.2.1. Energy Demand

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

The global picture is rather diverse. Isaac and van Vuuren (2009) use the reference climate change scenario from the TIMER/IMAGE model and show that energy demand for air conditioning increases rapidly in the 21st century. The increase is from close to 300 TWh in 2000, to about 4,000 TWh in 2050 and more than 10,000 TWh in 2100, mostly driven by increasing income in developing countries. Energy demand for heating increases too, but much less rapidly, since in most regions with the highest need for heating incomes are already high enough for people to heat their homes to the desired comfort level, except in some poor regions/households.

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

[INSERT FIGURE 10-1 HERE
Figure 10-1: Demand.]

Studies clustered in the upper right block in Figure 10-1 deal with countries and regions in which mean annual temperatures are already high but high incomes allow extensive deployment and operation of air conditioning (e.g., countries in the Persian Gulf). Further increases in temperature will be offset by heavier use of air-conditioning and will be the main driver of increasing the demand for electricity while increasing incomes will play a marginal role.

Countries and regions explored by studies in the upper left and upper central cells are also situated in already warm regions but the bulk of the population cannot afford to purchase and operate space-cooling equipment at the current income levels (India, countries in Southeast Asia). Although temperatures are projected to increase in these regions as well, the main driver of household energy demand (in the form of electricity) will be income growth, leading to expanding installation of air-conditioning.

The temperate climate conditions in countries and regions analysed by studies in the right middle zone involve colder and warmer seasons in a year but high incomes allow the population to heat/cool indoor temperatures to the desired comfort level (e.g., central to northern and Pacific states in the USA, Western Europe). Therefore changes in seasonal and total per capita energy and electricity demand and in the fuel mix will be largely driven by temperature changes: decreasing demand for heating (and thus for non-electric energy) during the winter and increasing demand for cooling (almost entirely operated by electricity) in the summer.

Warmer temperatures and increasing incomes will both be significant drivers of changes in energy demand in countries examined by studies in the central middle segment in Figure 10-1 (e.g., Central and Eastern Europe, Central Asia). In these regions space heating in winter is usually adequate to reach comfort level (although there are poor people even in OECD countries for whom this is not the case) but space cooling has been emerging only recently as increasing incomes allow more people to install air-conditioning equipment. As climate warms, reduction in energy demand for heating will be largely influenced by temperature while increase in energy demand for air-conditioning will be mostly driven by income (to achieve comfort levels under current climate) and partly by temperature increase (in response to higher cooling needs).

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

10.2.2. Energy Supply

Changes in various climate attributes (temperature, precipitation, windiness, cloudiness, etc.) will affect different energy sources and technologies differently. Gradual climate change (CC) will progressively affect normal operation over time. Possible changes in the frequency and intensity of extreme weather events (EWEs) represent a different kind of hazard for energy installations and infrastructure. This section considers both.

10.2.2.1. Thermal Power

Thermal power plants provide about 80% of global electricity and their share is projected to remain high even under ambitious but realistic climate mitigation scenarios (IEA 2010a, 2010b). Thermal power plants are operated under diverse climatic conditions from the cold artic to the hot tropical regions and are well adapted to the prevailing conditions. However, they might face new challenges and will need to respond by hard (design or structural methods) or soft (operating procedures) measures as a result of climate change (Sieber née Schulz, 2011). Impacts of CC and EWEs on thermal power plants and the adaptation options are summarized in Table 10-1.

[INSERT TABLE 10-1 HERE
Table 10-1: Impacts of CC and EWEs on thermal power generation.]

The most intrusive impact of CC on thermal power generation in many countries is the decreasing efficiency of thermal conversion as a result of rising temperature. This follows from Carnot's rule and cannot be offset per se. Yet there is much room to improve the efficiency of currently operating subcritical steam power plants (IEA, 2010b). As new materials allow higher operating temperatures in coal-fired power plants (Gibbons, 2011), supercritical and ultra-supercritical steam-cycle plants will reach even higher efficiency that can more than compensate the efficiency losses due to higher temperatures.

Another problem facing thermal power generation is the decreasing volume and increasing temperature of water for cooling, leading to reduced power generation, operation at reduced capacity and even temporary shutdown of power plants (Ott and Richter, 2008; Hoffmann et al., 2010; Sieber née Schulz, 2011). Adaptation possibilities range from relatively simple and low-cost options like exploiting non-traditional water sources and re-using process water to more drastic and expensive measures like installing dry cooling towers, heat pipe exchangers and regenerative cooling (Ott and Richter, 2008; de Bruin et al., 2009). While it is easier to plan for changing climatic conditions and select the conforming cost-efficient cooling technology for new builds, response options are more limited for existing power plants, especially for those towards the end of their economic lifetime.

10.2.2.2. Nuclear Energy

The impacts of CC and EWEs on the nuclear energy sector, together with the adaptation options are summarized in Table 10-2.

[INSERT TABLE 10-2 HERE
Table 10-2: Impacts of CC and EWEs on nuclear energy.]

CC impacts on thermal efficiency and cooling water availability affect nuclear power plants similarly to their thermal counterparts (Williams and Toth, 2011). Whereas there is no escape from Carnot's rule affecting efficiency, a range of alternative cooling options are available or increasingly considered to deal with water deficiency, ranging from re-using wastewater and recovering evaporated water (Feeley III et al., 2008) to installing dry cooling (EPA, 2001).

The implications of EWEs for nuclear plants can be severe due to the nature of the technology. Reliable interconnection (onsite power and instrumentation connections) of intact key components (reactor vessel, cooling equipment, control instruments, back-up generators) are indispensible for the safe operation and/or shutdown of a nuclear reactor. 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, 2011).

10.2.2.3. Hydropower

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

Assessing the impacts of climate change on hydropower generation is the most complex endeavour in the energy sector. A series of non-linear and region-specific changes in mean annual and seasonal precipitation and temperatures, the resulting evapotranspiration losses, shifts in the share of precipitation falling as snow and the timing of its release from high elevation make resource estimates difficult (see Chapters 3 and 4) while regional changes in water demand due to changes in population, economic activities (especially irrigation demand for agriculture) present competition for water resources that are hard to project (see Section 10.3). Further complications stem from the possibly increasing need to combine hydropower generation with changing flood control and ecological (minimum dependable flow) objectives induced by changing climate regime. This section focuses on possible impacts of CC on hydroelectricity and the adaptation options in the sector in response to the changes in the amount, seasonal and inter-annual variations of available water after changes in the resource base and other demands are accounted for. Table 10-3 provides an overview.

[INSERT TABLE 10-3 HERE
Table 10-3: Impacts of CC and EWEs on hydropower generation.]

The overall conclusion from the literature is that the impacts of CC and EWEs on hydropower generation will be diverse across large global regions (increases in most, decreases in some), across watersheds within regions and even across river basins within watersheds. The hydropower industry will need to enhance its long-term planning tools to cope with slow but persistent shifts in water availability and its short-term management models to deal with the impacts of EWEs. A series of hard and soft measures are available to protect the related infrastructure (dams, channels, turbines, etc.) and optimize incomes by timing generation when electricity prices are high.

10.2.2.4. Solar Energy

In various climate change mitigation scenarios, solar energy is expected to increase its currently negligible share in the global energy balance to a significant level (IEA 2008, 2009, 2010a, 2010b). The three main types of technologies for harnessing energy from insulation include thermal heating (TH) (by flat plate, evacuated tube (aka vacuum) and unglazed collectors), photovoltaic (PV) cells (crystalline silicon (Si) and thin film technologies) and concentrating solar power (CSP) (power tower and power trough producing heat to drive a steam turbine for generating electricity). The increasing body of literature exploring the vulnerability and adaptation options of solar technologies to CC and EWEs are reviewed by Patt et al. (2011). The impacts of CC and EWEs on solar technologies are summarized in Table 10-4.

[INSERT TABLE 10-4 HERE
Table 10-4: Impacts of CC and EWEs on solar energy.]

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

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

The above and the other CC and EWE hazards listed in Table 10-4 per se do not pose any particular constraints for the future deployment of solar technologies. ST is mature compared to PV and CSP, but technological development continues in all three solar technologies towards new designs, models and materials. One of the objectives of these development efforts is to make new models less vulnerable to current climate and EWEs. Technological development also results in a diverse portfolio of models to choose from according to the climatic and weather characteristics of the deployment site. These development efforts can be integrated in addressing the key challenge for solar technologies today: reducing the costs.

10.2.2.5. Wind

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

Pryor and Barthelmie (2011a) provide a comprehensive overview of the impacts of CC and EWEs on wind energy, based on which the relevant climatic attributes and EWEs possibly modified by CC, their impacts on wind power and the related adaptation options are summarized in Table 10-5.

[INSERT TABLE 10-5 HERE
Table 10-5: Impacts of CC and EWEs on wind power.]

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. Reviewing related studies (e.g., Bloom et al., 2008; Pryor and Schoof, 2010; Pryor et al., 2006; Sailor et al., 2008; Walter et al., 2006), Pryor and Barthelmie, 2010) find that in the next few decades wind resources (measured in terms of multi-annual wind power densities) are likely to remain within the ±50% of the values under current climate. The wide range of the estimates results from the circulation and flow regimes in different GCMs and regional climate models (RCMs) (Bengtsson et al., 2006; Pryor and Schoof, 2010) and it seems to narrow in more recent studies. 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, 2011a, 2011b). Yet little is known about changes in the inter-annual, seasonal or diurnal variability of wind resources.

Wind turbines already operate in diverse climatic and weather conditions. Engineering solutions have been developed to install the turbine design and material combination most suitable for the site conditions. As shown in Table 10-5, siting, design and engineering solutions are available to cope with various impacts of gradual changes in relevant climate attributes over the coming decades. The requirement 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, 2011a). In summary, the wind energy sector does not face insurmountable challenges resulting from climate change.

10.2.2.6. Bioenergy

The two main contributions of bioenergy to climate change mitigation and the green energy – sustainable development strategies include liquid motor fuels for transport and power generation by combustion. The impacts of climate change on growing plants for use as biofuels is assessed as part of climate impacts on land use and agriculture (Chapter 7). The transportation of related material (from fields to processing plants to the distribution network for liquids or to the power plants for combustion) is exposed to the same impacts as the transport sector in general (see 10.2.3 and 10.4). The impacts of climate change on the combustion of biofuels for power generation is largely the same as fossil-fuelled thermal power plants (see 10.2.2.1) and the impacts on their conversion into liquid fuels are comparable to those on refineries.

10.2.3. Transport and Transmission of Energy

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

10.2.3.1. Pipelines

Pipelines play a central role in the energy sector by transporting oil and gas from the wells to processing and distributing centres to distances from a few hundred to thousands of kilometres. With the spread of the carbon dioxide capture and storage (CCS) technology, another important function will be to deliver CO_2 from the capture site (typically thermal power plants) to the disposal site onshore or offshore. Pipelines have been operated for over a century in diverse climatic conditions on land from hot deserts to permafrost areas and increasingly at sea. This implies that technological solutions are available for the construction and operation of pipelines under diverse geographical and climatic conditions. Yet climate change may require adjustments in existing pipelines and improvements in the design and deployment of new ones in response to the changing climate and weather conditions. Table 10-6 provides an overview of the impacts of CC and EWEs, together with the options to reduce vulnerability.

[INSERT TABLE 10-6 HERE
Table 10-6: Impacts of CC and EWEs on pipelines.]

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

10.2.3.2. Electricity Grid

Due to its very function to transmit electricity from power plants to consumers, the bulk of the grid components (overhead lines, substations, transformers) are located outdoors and exposed to the vagaries of weather. The power industry has developed numerous technical solutions and related standards to protect those assets and to secure a reliable electricity supply under prevailing climate and weather conditions worldwide. Drawing on Ward (2011), impacts of CC and EWEs on the power grid are summarized in Table 10-7.

[INSERT TABLE 10-7 HERE
Table 10-7: Impacts of CC and EWEs on the electricity grid.]

Higher average temperatures decrease transmission efficiency by about 0.4%/°C but this effect is relatively small compared to the physical and monetary damages that can be caused by EWEs (Ward, 2011). 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). While the frequency and power of high wind conditions may increase in the future, vegetation management along existing power lines and rerouting new transmission lines along roads or across open fields would reduce wind related risks.

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

10.2.4. Market Impacts

Until recently, almost all economic research related to climate change has focused on mitigation rather than the economic implications of climate change itself. In the last few years, some analysts have begun to adapt models that had been used for economic analysis of mitigation to use for analysis of scenarios in which warming continues with or without adaptation policies.

As with mitigation policy, the full economic consequences of climate change are best examined by using computable general equilibrium (CGE) models or hybrid models with a CGE or full macroeconomic representation. Recent climate impact studies using a CGE model with energy sector detail include Jorgenson et al. (2004), Bosello et al. (2007), Aaheim et al. (2009), Boyd and Ibarraran (2009), Bosello et al. (2009), and Jochem and Schade (2009).

Jorgenson et al. (2004), using the Inter-temporal General Equilibrium Model (IGEM) for the United States, consider three climate scenarios (1.7, 3.1 and 5.3 °C increase by 2100) combined with pessimistic and optimistic assumptions regarding the ability of sectors to adapt. The authors find that for optimistic adaptation assumptions, the productivity of the energy sector in an average year is 4% to 6.7% higher with climate change compared to a reference case without climate change (over the period 2000 – 2100). For pessimistic assumptions, energy productivity is 0.5% to 2.2% lower with climate change. The response to climate change in the energy sector is based on changes to energy demand driven by warmer weather rather than changes in supply brought on by warmer weather, climate variability or extreme weather.

Bosello et al. (2007) employ a global 8-region one-period CGE model to evaluate climate change impacts on the global economy in 2050. The 2050 reference case is calibrated by adjusting 2001 GTAP data so that the model produces results consistent with 2050 rather than running an annual model that gradually evolves out to 2050. Bosello et al. find that crude oil production declines in all regions, ranging from 0.43% to 1.2% compared to the reference case without climate change. Natural gas production goes down in all but one region (Rest of World), ranging from 0.61% to 17.82%; Rest of World increases by 0.04%. On the other hand, coal production increases in all regions, from 0.133% to 3.37%. Electricity production varies. Most regions are expected to see electricity consumption go up by 0.58% to 1.89% in response to greater cooling demand. Electricity production in cooler regions is expected to decrease, ranging from -0.63% to -2.94% due to less cooling demand. Japan see a negligible change (-0.06%). Energy sector results are driven by expected changes in energy demand stemming from climate change rather than changes in supply.

Aaheim et al. (2009) examine the impact on Europe of a 2, 3 and 4 °C increase in global mean temperature using GRACE_adapt, an integrated macroeconomic general equilibrium model with 8 primary regions and 11 sectors calibrated to 2006 data (results are not forward looking and based on the current structure of the economy). The purpose of the study is to compare the GDP impact of the three temperature scenarios with and without adaptation, all relative to a reference case without climate change. Like other studies, the authors factor in the demand response to changing temperature (less need for heating and more need for cooling). Aaheim et al. also consider the direct impact of climate change on electricity generation. They assume that hydro, bio and wind resources change in response to changing rainfall patterns, temperatures, wind speeds, etc. in most regions, but other types of generation do not. The paper does not report sector-level results, but does report the magnitude of the changes in assumptions that were built into the GRACE_adapt model. Consumption of oil and gas is expected to decline in the range of 1 to 10% in all regions. Consumption of electricity is expected to decline in all regions except Southern Europe and the Iberian Peninsula (due to increased cooling demand). The authors assume that total electricity generation will increase by 11% to 20% or more in the coldest regions (Nordic Countries, Baltic States, and British Islands) where hydro, bio and wind power resources improve with warming. By contrast, Aaheim et al. assume that Southern Europe and the Iberian Peninsula will experience declines in generation from hydro (11% - 20% or more), bio (1% to 20%) and wind (1% to 10%). Total electricity generation is expected to decrease by 1% to 10% in the remaining warmer regions. The authors do not elaborate on how some regions will cope with reductions in generation output along with increased demand for electricity to provide cooling; presumably, this situation will lead to higher costs. Aaheim et al. find that climate change lowers GDP in cooler regions by around 0.25% (2 °C scenario) to 1% (4 °C scenario). GDP in warmer regions drops by around 0.5% (2 °C) to 2 – 3% (4 °C). The authors also find that adaptation policies can mitigate 80% to 85% of the overall economic impact of climate change in Europe, even with a 4 °C global mean temperature increase.

Boyd and Ibarraran (2009) study the implications of climate change on the Mexican economy using a CGE model that was "modified to account for imperfect competition (in the energy sectors) which presently exists in the Mexican economy." Climate change impacts are modelled as severe drought rather than mean global temperature change, and adaptation measures are also modelled in a separate scenario. All scenarios are compared to a reference case without climate change, and the model runs on an annual basis from 2004 to 2026, evolving over time. The authors find that without adaptation, electricity generation, refining, coal, and natural gas production decline 2.1%, 10.1%, 7.8% and 2.0% respectively in 2026 as a result of climate change. Crude oil production increases 1.7%. When adaptation is undertaken, all energy sectors increase production, ranging from 0.2% to 1.4%. Overall, GDP declines by 3.0% without adaptation and increases by 0.3% with adaptation.

Bosello et al. (2009) analyse the impact of climate change and adaptation policies worldwide using a hybrid 12-region hybrid inter-temporal optimization model that combines AD-WITCH, an Integrated Assessment Model (IAM), with ICES, a CGE model. Climate change impacts in the energy sector are modelled as space heating and cooling expenditures. The authors find that the net impact of energy expenditures as a result of climate change for all regions translates to a positive contribution to GDP of approximately 0% to 0.75% depending on the region (1.2°C scenario in 2050) or around 0% to 1.2% (3.1°C in 2050).

Jochem and Schade (2009) use an innovative hybrid model system (HMS) for Europe that combines three different macroeconomic models that cover different timeframes, along with several technology-based sector models. Jochem and Schade assume that the impact on the energy sector of climate change consists of changes to cooling and heating demand. If global mean temperature increases 4°C by 2050, fuel costs drop by an amount equal to 0.08% of GDP, while electricity costs increase by an amount equal to 0.02% of GDP. 63% of the fuel savings occur in Western Europe, and 84% of the added electricity costs are faced by Southern Europe.

Other related studies have been conducted using partial equilibrium and econometric models that attempt to analyse the impact of climate change on energy demand, though not with respect to the full macroeconomic implications as with the previously discussed studies. These demand-oriented studies generally conclude that direct fuel consumption by end-use residential and commercial sectors tends to decline as temperatures increase, and electricity consumption tends to increase in order to provide more space cooling (Kirkinen, 2005; Mansur, Mendelsohn et al., 2005; Mansur, Mendelsohn et al., 2008; Gunnar and Torben, 2010; Mideksa and Kallbekken, 2010; Rübbelke and Vögele, 2010).

Modellers focus on the impacts of climate change as a trigger for changes in energy demand and assess the economy-wide implications of this shift (substitutions in the consumer basket, shifts in the industrial output and investments on the supply side). Most modellers assume that fuel demand declines and electricity demand increases, but there are too few studies (and those focus on different regions and timeframes) to allow for larger conclusions about the economic implications. Few models (only Aaheim et al. and Boyd and Ibarraran) look at impacts on the resource base (water, windiness, insulation) or technological processes (efficiency of thermal generation) or cross-sectoral impacts (competition for water), not to mention the adaptation options (larger dams in hydro/water sector, closed cycle or dry cooling in thermal, etc.) partly because they do not have sufficient detail in their representation of energy sector technologies and partly because the impacts are less well understood. The studies are limited in scope even on the demand side; they mostly cover residential (and perhaps commercial) heating/cooling demand, but ignore agriculture energy demand (energy for crop drying, for pumping irrigation water, etc.).

10.2.5. Summary

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

10.3. Water

This section summarizes of some of the key works that have been carried out with regards to the economic aspects of climate change and adaptation in the field of water as it relates to economic activities. There has been much written and reported in previous IPCC assessments including a special report (Bates et al., 2008) on the biophysical impacts of the natural and managed water resource system and this is addressed in other chapters of this assessment. This section focuses on economic costs.

Efforts to quantify the economic impacts of future climate-related changes in water resources are hampered by a lack of data, the uncertainties in scenarios, and by the fact that the estimates are highly sensitive to both the cost estimation methods and the different assumptions used with regards to the allocation of changes in water availability across various types of water use (e.g., Chagnon, 2005; Schlenker et al., 2005; Young, 2005). In some regions hydrological changes may have impacts that are positive in some aspects and negative in others, for example increased annual runoff may produce benefits for a variety of both in-stream and out-of-stream water users by increasing renewable water resources, but may simultaneously increase flood risk. Overall, the IPCC states that it is very likely that the costs of climate change to the water sector will outweigh the benefits globally (Bates et al., 2008).

This section looks at the qualification of climate change impacts, costs and benefits, to individual economic sectors that utilize water resources as an input to production and/or mechanism for waste disposal and costs to adapt to these impacts. This section also reports on the state of knowledge of costs to public and private infrastructure of climate change impacts and adaptation due to flooding.

10.3.1. Water-Related Damages

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

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

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

Ward et al 2010 found the average annual costs of adaptation for riverine flood protection for World Bank eligible nations[1] to range from $3.5 to $6.0 billion per year over the period 2010–50. These are simply the additional costs of providing flood protection measures against monthly floods with a nominal return period (that is, 50 years and 10 years for urban and agricultural areas, respectively), but do not consider the damages that would be caused by flood events with longer return periods.

[INSERT FOOTNOTE 1 HERE: These were the low-income, lower-middle-income and upper-middle-income countries as defined in http://data.worldbank.org/about/country-classifications/country-and-lending-groups.]

10.3.2. Municipal and Industrial Water Supply

At the local, national, and river basin level, the geographical distribution of research is skewed towards developed countries. Examples include: the costs of adaptation measures to maintain water quality in the Assabet River near Boston (Kirshen et al., 2006); the costs of adaptation to maintain the availability of drinking water supply and the capacity of treating wastewater in Toronto (Dore and Burton, 2001); water management adaptation costs and benefits for the Berg River in South Africa through the establishment of an efficient water market and an increase in water storage by constructing a new dam (Callaway et al., 2006); the costs of defending the Netherlands against increased river and coastal flooding as a result of climate change (Deltacommissie, 2008); the costs of adaptation to reduce flood damage in the Rhine basin in Europe (EEA, 2007); and the costs of diverting water and building new water infrastructure at an accelerated pace in order to cope with a reduction in water yields and supply in Quito, Ecuador, as a result of glacier retreat (Vergara et al., 2007).

Muller (2007) estimated the costs of adapting urban water infrastructure in sub-Saharan Africa to climate change to be USD 2 - 5 billion per year. This study assumes that: (a) reliable yields from dams will reduce at the same rate as stream flow (e.g., a 30% reduction in stream flow will mean a 30% reduction in reliable yield, and the unit cost of water will go up by more than 40%); (b) where waste is disposed into streams, a reduction in stream flow by x% will mean that the pollutant load must be reduced by x%; and (c) power generation reduces linearly with stream flow. The costs of adapting existing urban water storage facilities are estimated at $50 - 150 million/year, and the costs of additional new developments are estimated at $15 - 50 million/year. For wastewater treatment, the adaptation costs of existing facilities are estimated at $100 - 200 million/year, and the costs of additional new facilities are estimated at $75 - 200 million/year.

Hurd et al (2004), based on partial equilibrium river basin models, estimate that for the USA climate change impacts on municipal and industrial welfare is less than a 1% decrease for both wet and dry scenarios.

Ward et al 2010 estimate the adaptation costs to provide enough raw water to meet future global industrial and municipal water demand, based on country-level demand projections to 2050. Increased demand is assumed to be met through a combination of increased reservoir yield and alternative backstop measures. The global adaptation costs of $12 bn p.a., with 83-90% in developing countries; the highest costs are in Sub Saharan Africa. Globally, adaptation costs are low compared to baseline costs (ca. $73 bn p.a.), which supports the notion of mainstreaming climate change adaptation into broader policy. The method provides a tool for estimating broad costs at the global and regional scale; such information is of key importance in international negotiations. The global cost estimates (developing and developed countries combined) of climate-change related adaptation in the water resources sector amount to 0.04–0.06 percent of world GDP. The baseline adaptation costs are significantly higher, but still low (0.33 percent).

10.3.3. Wastewater and Urban Stormwater

Climate change is expected to worsen many forms of water pollution, including the load of sediments, nutrients, dissolved organic carbon, pathogens, pesticides, and salt, as well as thermal pollution, as a result of higher water temperatures, increased precipitation intensity, and low flow periods (Kundzewicz et al., 2007). In addition, more frequent heavy rainfall events may overload the capacity of sewer systems and water and wastewater treatment plants more often. Increased occurrences of low flows will lead to decreased contaminant dilution capacities, and therefore higher pollutant concentrations.

Hughes, et al 2010, estimate the average annual costs of adaptation for urban sewers for World Bank eligible nations at $3.0 billion per year over the period 2010–50. Price, et 2010 estimate for Canada the cost of building and maintaining additional storm water storage capacity necessary to manage the additional runoff associated with the change in the 100-year, 24-hour storm at between $140 million to $2 billion present value from 2010 to 2100 with a 3% discount rate. In a similar analysis for 19 major USA cities, Price, et al 2011 estimates for each city the increase in annual cost from the changes in the 10-year, 24-hour storm for Los Angeles in 2100 is $135 million, Boston $7 million and Chicago $40 million.

10.3.4. Energy: Hydropower and Cooling Water

Hurd et al 2004, looking at intersectoral competition for water using a set of partial equilibrium river basin models, estimate that for the USA climate change impacts welfare impacts on thermal cooling water to be as great as losses $622 million per year or a 6.5 % welfare loss in the energy sector. Block, et al 2010 find that for Ethiopia adaption to climate change to maintain hydropower output from 2010 to 2050 would be an increase of 4% of capital cost under the most sever dry scenario and a reduction of 3% under the extreme wet scenario.

10.3.5. Inland Navigation

Millerd (2005) analyzes the economic impacts of lower water levels in the Great Lakes, with consequent reductions in vessel cargo capacities and increases in shipping costs. The lower water levels predicted as a result of a doubling of the atmospheric concentration of carbon dioxide could increase annual transportation costs by 29 percent, more moderate climate change could result in a 13 percent increase in annual shipping costs, based on current prices. The impacts vary between commodities and routes.

Middelkoop, et al 2001, examines climate change impacts on inland navigation on the Rhine. Increased frequency of flood periods will stop more often. Longer periods of low flow will also increase the average annual number of days during which inland navigation is hampered or stagnates. When the Rhine discharge drops below about 1000 to 1200 m3/s, ships on the major transport route Rotterdam-Germany-Basle cannot be fully loaded, and transporting cost rise. Current projects on channel improvements can only partly alleviate these problems. This provides a qualitative estimate to economic impact which could be substantial given the value of navigation on the Rhine System.

10.3.6. Irrigation

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

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

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

10.3.7. Nature Conservation

Future water demands for nature conservation will be different than today's (see Chapter 4). There is no published assessment of the economic implications.

10.3.8. Recreation and Tourism

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

10.3.9. Water Management and Allocation

Adaptation to changing conditions in water availability and demand has always been at the core of water management (Adger et al., 2007). Traditionally, water managers and users have relied on historical experience when planning water supplies and distribution (UNFCCC, 2007). Water supply management has mainly concentrated on meeting increasing water demand, and flood defense measures have assumed a stationarity of flood recurrence periods. However, under a changing climate these assumptions are no longer valid (Kundzewicz et al., 2007). Therefore, current water management practices need to be redesigned, and the procedures for designing water-related infrastructure need to be revised. Otherwise, systems may be wrongly conceived, and under- or overdesigned, with either inadequate performance or excessive costs as a result. However, necessary adaptation to climate change in the water sector goes beyond structural measures, but also includes forecasting/warning systems, insurance instruments and a large variety of means to improve water use efficiency and related behavioral change, economic and fiscal instruments, legislation, institutional change, etc. (Kundzewicz et al., 2008).

10.4. Transport

The issue of climate change in the transport sector is one that has received qualitative, but limited quantitative, focus by the research and government communities. As detailed below, several governments have actively explored the potential impacts of climate change on the transport sector. However, these studies are primarily informative in nature and focus on overall impacts such as impacts on transportation safety or disruptions of transportation service. A move toward quantitative, economic analysis is just beginning as researchers begin to bring the transport sector in line with efforts in the water and agriculture sectors. Examples of this initial work include economic studies by Larsen et al (2010), Chinowsky et al (2010), and Chinowsky et al (2011). Additional work that treats the transport sector as a complement to the work such as in disaster research (Hallegatte and Ghil 2008), is providing insights to the transport sector, but does not center on the sector itself. Additional work is in the early stages, but the transport sector remains as a focus for additional research.

The impact of climate change on transportation depends greatly on the climatic zone the infrastructure is in and how climate change will be manifest. There are three major zones that face the effects of climate change on the array of transportation areas.

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

10.4.1. Roads

10.4.1.1. Paved Roads

Studies on the effects of climate change on road networks are primarily focused on qualitative predictions concerning road impacts on both safety and road durability (TRB 2008; Galbraith et al 2005; AUSTROADS 2004). Typical of these findings are projections regarding the likelihood of reduced life spans for roads, increased erosion of unpaved roads, and potential effects of sea level rise on coastal roads. In these studies, paved roads are the primary focus due to the importance of these roads. Paved road degradation is directly related to climate change stressors including precipitation amounts, traffic, temperature, and flooding incidents, among other factors. In this section, these elements are presented in terms of paved roads and the vulnerability to climate change impacts.

10.4.1.1.1. Coastal roads

Coastal roads are at risk from a number of climatic change factors, including: sea level rise, storm surge, increased intensity and frequency of severe events, increased precipitation, increased temperature, and more frequent freeze thaw cycles for roads that lie in northern climates (Koetse, et al, 2009; URS 2010). Many of these are part of emergency evacuation networks from coastal metropolitan areas in cases of severe events such as hurricanes and extreme flooding (Potter, et al, 2008; Suarez, et al, 2005; TRB 2008). Many of the largest cities lie in coastal areas (New York, London, New Orleans, Tokyo, Kolkata, Shanghai, etc) and each have large road networks that are vulnerable to coastal effects (Kamal-Chaoui, et al, 2009). Of particular concern to coastal roads is the vulnerability to erosion on the seaward side due to increased wave erosion and higher tides. Many coastal road networks are built along slopes or hills, which are affected by precipitation events that undermine the integrity of the road base, leading to pavement failures or landslides. Hardening the seaward side of coastal roads is required to provide protection against increased hydrologic action and specifically to protect the roadbed from direct exposure to the elements (FHWA 2008). Finally, as the frequency of storm surges increases due to the increased severity of storms, the ability to utilize lower cost remedies for coastal road defenses decrease and more expensive options such as road relocation or elevation increase will be required to offset increased risks.

10.4.1.1.2. Pavements

There are numerous studies on the lifespan of road pavements in relation to natural elements including temperature, precipitation, and freeze-thaw cycles as well as traffic patterns and geographic factors (Koetse, et al, 2009). In terms of temperature increases, the concern for pavements is the softening of road surfaces due to higher maximum monthly temperature. This is a concern as these increases can lead to softening of the pavement as temperatures exceed design thresholds (Lavin 2003). This can cause rutting or bleeding of asphalt surfaces with the effect enhanced in higher traffic areas. Similar concerns exist with increased precipitation. Greater amounts of precipitation are shown to increase pavement degradation due to cracking and sub-base degradation (N.D. Lea International Ltd., 1995). Finally, an increase in the number of freeze-thaw cycles impacts both the base and pavement surface (FHWA 2006). The associated pavement damage will increase in areas where the number of freeze-thaw cycles is anticipated to increase.

10.4.1.1.3. Sub-base

Warming and the melting of permafrost in northern climates as well as increased precipitation and flooding threaten the integrity of road base and sub-bases. In northern climates, the melting of permafrost can shorten the trucking season, increase repair costs, and undermine the integrity of the road base in large areas. Changes in rainfall intensity and amount have the ability to threaten ground movement and slope instability (Larsen, et al, 2008). This affects the integrity of roads, rail, and pipeline beds. This may increase maintenance costs and cause safety issues. Where bridges exist, increased intensity and amount of precipitation can cause bridge scour, lessening the design life and resulting in safety concerns (TRB 2008; Larsen, et al, 2008).

10.4.1.1.4. Drainage

Drainage presents a specific problem for urban areas that experience precipitation events that are above their built environment capacity (Hunt 2010; Chicago Climate Action Plan). "Future increases in the intensity and frequency of heavy rainfall events would have implications for the design of roads, highways, bridges and culverts with respect to stormwater management, especially in urban areas where roads make up a large proportion of the land surface (Lemmen, et al, 2010)." In terms of paved roads, the challenge to these locations is the capacity of existing drainage networks, from culverts to storm sewers, to accommodate the projected increases in water flows. The failure of these systems to accommodate the increases will lead to both the undermining of road bases as well as overtopping of road surfaces (Kamal-Chaoui, et al, 2009). In terms of the former, the inability of drainage systems to move water away from the road surface will cause saturation of soils and result in both softening of the road base as well as erosion. Similarly, in areas prone to flooding, the inability of culverts to accommodate increased water levels will result in the overtopping of road surfaces. This hydrologic action will result in increased failure rates of pavements including cracking and shoulder erosion.

10.4.1.2. Unpaved Roads

Although paved roads are the primary transportation network in industrialized countries, unpaved roads continue to be ubiquitous throughout the rest of the world. In 2008 only about 25% of sub-Saharan Africa's primary roads were paved, compared to a global rate of 50% (Gwilliam et al 2008). Unpaved roads are vulnerable to a number of climate-based factors.

10.4.1.2.1. Winter roads

Winter roads are temporary roads found in cold climates where sufficient snow levels allow grading to be performed above environmentally sensitive areas that are exposed during warmer months. These roads require low temperatures to function properly and would be impacted by climatic warming (Mills et.al, 2007; Tighe et. al, 2002).

The usage of winter roads is likely to be restricted (night time use only) where temperatures are predicted to exceed -2ºC or be discontinued if temperatures exceed 0ºC due to unstable road bases. This will reduce economic viability of winter roads and lessen connectivity of rural areas in Northern climates (Mills and Andrey 2002).

10.4.1.2.2. Ice roads

Similar to winter roads, ice roads are found in northern climates where extended periods of freeze are standard during the winter months and are vulnerable to climatic warming (Mills et.al, 2007). However, ice roads differ from winter roads in that they are maintained over bodies of water. In these instances, ice roads are dependent on continuous freeze conditions to ensure that the ice is passable by heavy equipment and trucks. In many instances, these roads provide the only access to remote communities or mining camps. The temperature above which an ice road is likely to become unstable depends on several factors, including the thickness of the ice and the weight of the loads using the ice road (Treasury Board of Canada (undated)). The projected climate change indicators on increased temperature place in doubt the ability to maintain these roads for the current usage cycles, raising economic concerns.

10.4.1.2.3. Drainage and surface erosion

Unpaved roads, both dirt and gravel surface, are less vulnerable to temperature variations than paved roads, but have significantly higher vulnerability to changes in precipitation. Specifically, the rate of erosion on an unpaved road is linked with the level of traffic on the road, the slope of the road, and the precipitation striking the road surface among other lesser factors (Dube et al 2004; Sheridan and Noske 2005). As the amount of precipitation increases, the rate of erosion grows based on the slope and traffic levels. This degradation can be reduced, but not eliminated, through adaptations such as changing the surface of the road or increasing drainage.

10.4.1.2.4. Runoff

Since unpaved roads are less impervious than paved roads, the resulting rainfall from a storm is more likely to penetrate the surface of the road and gather sediment and soil within the unpaved roads causing erosion (Ziegler, 1997). This erosion has environmental impacts such as pollution to nearby streams and lakes as well as damages to vegetation and stream ecology (Turton, 2009; Gravel Road Maintenance Manual, 2010; Kahklen, 2001; Ziegler, 1997). Other factors which increase the erosion are: the steepness of road and cut-slopes (Arnáez, 2004; Ramos-Scharron, 2005), the amount of traffic intensity (Burroughs, 1989; Ziegler, 2001, Arnáez, 2004), rain splash (Ziegler, 2000) and where relative to a residential area the road is located (Shi, 2008). Adaptations include adding more vegetation or mulch, creating cut-slopes and ditches, and adding "proper" crowning to the unpaved surfaces (Turton, 2009; Arnáez, 2004)

10.4.2. Rail

Rail beds are susceptible to increases in precipitation, sea level rise, extreme events and incidence of freeze-thaw cycles. Similar to coastal roads, sea level rise endangers coastal rail lines by threatening the stability of the soil beneath the rail bed (Baker et al, 2010). Additionally, large coastal events, including hurricanes and storm surge, pose a threat to rail integrity through scour events.. Compounding these scour and visibility issues is the issue of drainage systems unable to accommodate increased precipitation levels. Washouts of overpasses or sections of tracks are common in areas where precipitation levels exceed design thresholds (DOT 2002; URS 2010). As precipitation increases, this may occur along greater lengths of track. Finally, in Northern climates, the melting of permafrost may lead to ground settlement, undermining stability (Potter, et al, 2008; Larsen et al 2008).

Increased temperatures pose a threat to rail integrity. For air temperatures over 43ºC, rail track deformities increase in likelihood (Baker, et al 2011; TRB 2008). However, there are suggestions that air temperature has a non-linear relationship to rail temperature. Of greater concern is the rail temperature: "If rail heats more than 33ºC above its neutral temperature then a thermal misalignment, track buckle, or sun kink may result and derailments are possible (Potter, et al, 2008)". Countermeasures to address this threat include adding air-cooling systems to keep rail temperatures closer to 'neutral' and preheating rails to increase the neutral temperature of the rail and decrease the impact of higher ambient air temperatures. These measures increase costs that will reflect in higher passenger and freight transport costs. In urban areas, increased temperatures pose a threat to underground transport systems that will see a burden on increased need for cooling systems (Hunt, et al 2010). In London, £178 million has been allocated to finding a workable solution for increasing the capacity of the Tube's underground cooling system (Arkell, et al, 2006).

Increased precipitation, flooding, storm surges, and extreme events can lead to the rendering of low-lying coastal or subterranean rail unusable until tracks are cleared (TRB 2008; Baker, et al 2010). This is of particular concern in coastal cities where rail is a major mode of transportation or where rail is used to transport goods form ports to other areas inland, such as New York, London, and New Orleans (Potter, et al, 2008; Kamal-Chaoui, et al, 2009; DOT 2002). These three cities have had extensive surveys and studies done for vulnerabilities and costs, but most major coastal urban areas are at some risk and merit greater investigation.

10.4.3. Pipeline

Increases in precipitation and temperature affect pipelines through scouring of base areas and unearthing of buried pipelines, compromised stability of bases built on permafrost,, and increases in necessary maintenance (TRB 2008; URS 2010). In cases of increased flood events, or temperature increases to create permafrost melting events, the pipeline can experience point failures in its support structure (Peterson, et al; Larsen, et al, 2008). The need for continuous stability along the pipeline creates the scenario where individual point failures can require extensive rerouting while the main pipeline is repaired. Temperature increase can result in thermal expansion of the pipelines, causing cracking at material connection points.

10.4.4. Shipping

10.4.4.1. Inland Navigation and Low Flows

Inland navigation impacts from climate change vary widely due to projected rise or fall in water levels (Middlekoop, et al, 2001). Increases in flooding events clog waterways, requiring additional time and resources to clear waterways or ports. Landslides from increased precipitation cause a need for additional dredging of harbors or narrow waterways (Peterson, et al; Potter, et al, 2008; UNCTAD 2009; Becker, et al 2011). Lower water levels negatively affect lock systems that are necessary for inland transportation in some regions (Koetse, et al, 2009). In areas where water level decreases, ships are restricted in terms of cargo weight and incur reductions to operating days (Jonkeren, et al, 2009; Turpjin 2010; DOT 2002). Where dredging is an option to mitigate lower water levels, environmental concerns including releasing toxins contained in the soils must be taken into account (Becker, et al 2011). Overall, the effects on inland navigation are projected to be negative, but are region-specific. In areas such as the Rhineland Basin, projected prolonged periods of low flow will increase the number of days during which inland navigation is hampered or stopped. In the Great Lakes/St. Lawrence region, "ice-free navigation and [the] longer shipping season is generally beneficial, but it is not likely to offset the losses associated with lower water levels (Lemmen, et al, 2010)." In Northern regions, increased days of ice-free navigation and a longer shipping season could positively impact shipping and reduce transportation costs (Koetse, et al, 2009; UNCTAD 2009).

10.4.4.2. Coastal/Ports and Sea-Level Rise

Coastal areas will be affected by climatic change events including increased temperatures, sea level rise, increased severe storm events, and increased precipitation (United Nations 2010; UNCTAD 2009; Potter, et al, 2008). Higher sea levels may increase the need for environmental mitigation to reduce contaminants that may enter the water system through leeching (Gallivan, et al, 2009). Rising sea levels may affect the navigability of some ports, specifically those with low-clearance bridge infrastructure (Gallivan, et al, 2009). It is important to distinguish that the relative effect of sea level rise, increased severe events and increasing temperature and precipitation predictions on coastal areas and ports seems to be negative overall, but differs widely by geographic location. The total assets of 136 of the world's largest port cities were examined and over $3 trillion in assets were deemed vulnerable from climatic change events. Coastal cities and ports cover only 2% of the world's geographic space, but house 13% of the world's urban population (United Nations 2010).

Concerns for port and marine areas in response to temperature include increased degradation of pavement and paved storage areas, increased energy required for refrigerated ground units, and degradation of metal equipment used in the port areas, such as cranes and warehousing units. For paved areas, the effects of temperature and precipitation are similar to those of paved roads: rutting, increased degradation, and asphalt bleeding. For existing infrastructure, it may prove necessary to upgrade or replace new equipment projected to be severely adversely affected by climate change (Potter, et al, 2008; UNCTAD 2009; United Nations 2010; Gallivan, et al, 2009).

10.4.4.3.Transport Costs: Storminess, Impacts, Effectual Speeds

Transport costs are projected to be directly affected by climate change, but regional variations determine whether the costs are expected to increase or decrease. Increased severe events and storminess in certain routes may affect safety considerations and raise cost of shipping through requiring additional safety measures or longer routes that are less prone to severe events (UNCTAD 2009; United Nations 2010). In ports where storminess and severe events disrupt supply chains by destroying port infrastructure, delaying access to ports through debris or soil deposits, or affects connecting road or rail infrastructure for transportation of goods, transport costs will increase and/or new routes will be sought, creating modal or geographic shifts in transportation (Becker, et al 2011). Increased storminess may also affect passage through lock systems, increasing weather-related delays and raising costs (UNCTAD 2009; Potter, et al, 2008). Increased storminess may increase maintenance costs for ships and ports and result in more frequent weather-related delays. In Northern climates, new shipping routes (Northwest Passage and Northern Sea Route) may reduce shipping costs by reducing the distance ships must travel and lengthening the number of days ships can travel through Arctic waters (United Nations 2010;TRB 2008).

10.4.5. Air

Airport pavement studies relating to climate change have mainly focused on the effects that increased/decreased precipitation, temperature, flooding, and extreme events will have on runways (DOT 2002; Fortier, et al). However, airports in general have large amounts of paved areas including parking structures, tarmacs, hangars and areas for loading and storage. Therefore the effect of temperature on airports is not restricted to runways, but rather imposes a risk on the entire facility (Pejovic, et al, 2009). These effects are very similar to paved roads including: increased rutting, softening and buckling under extreme temperatures, cracking, increased maintenance from greater freeze thaw days, and decreased freight loads under hot conditions (Potter, et al, 2008). Where airports have infrastructure built on permafrost that is projected to soften, this could compromise the base structures of runways and paved areas. In coastal airports, inundation of runways and other areas is of concern, specifically from projected sea level rise and risk of flooding and storm surges (Lemmen, et al, 2010; Potter, et al, 2008; Kamal-Chaoui, et al, 2009; DOT 2002). Flooding, storm surges, and increased extreme events all have effects on pavement and may degrade existing infrastructure faster than projected under current climate conditions. In a study of climate effects on infrastructure in Alaska, 24% of new costs are projected to come from airport maintenance and improvements resulting from climate change, specifically permafrost considerations. One positive aspect is that warmer temperatures may benefit airports in northern climates, including saved maintenance from less snow and ice removal and less degradation of pavement from plowing and chemical compounds (Lemmen, et al, 2010; Potter, et al, 2008; DOT 2002).

An increase in air temperature affects air density; hotter air is less dense. In summer months, especially at airports located at high altitudes or with extreme temperatures, this will result in limitations for freight capacity, safety, and weather-related delays (TRB 2008; Pejovic, et al, 2009). Hotter air requires less cargo or longer runways. However, several studies argue that technological innovations will negate the challenges posed by extreme temperatures (Chapman 2007). Increased storminess at airports, particularly those located in coastal regions, may increase the number of weather-related delays and cancellations (Pejovic, et al, 2009; Lemmen, et al, 2010).

10.5. Other Primary and Secondary Economic Activities

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

10.5.1. Primary Economic Activities

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

10.5.1.1. Crop and Animal Production

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

10.5.1.2. Forestry and Logging

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

10.5.1.3. Fisheries and Aquaculture

Chapter 4 assesses the impact of climate change on freshwater ecosystems, and Chapter 6 on marine ecosystems. These assessments include the effects on commercially valuable fish stocks, but exclude the effects on markets. Climate change impact the commercial fishing process through fish stock, capital, labour and enterprise, technological changes, prices and management practices (Link and Tol, 2009; Yazdi and Fashandi, 2010). (Allison *et al*., 2009), using an indicator based approach, analyzed the vulnerability of capture fishery of 132 economies. They find that though the precise impacts and direction of climate-driven change for particular fish stocks and fisheries are uncertain, they are likely to lead to either increased economic hardship or missed opportunities for development in countries that depend upon fisheries but lack the capacity to adapt. (Floc'h *et al*., 2008), for the Bay of Biscay fisheries, analyze the market position and its evolution in nine key fish and cephalopod species and find that a major part of the gross turnover remains potentially unaffected by long-term changes related to climate. On the other hand, (Garza-Gil *et al*., 2011) find a decline in Iberian-Atlantic sardine biomass and profitability due to climate change. The economic impact of climate change on fisheries is dominated by the impact of management regime and market (Eide and Heen, 2002; Eide, 2008; McGoodwin, 2007; McIlgorm, 2010; Merino *et al*., 2010).

10.5.1.4. Mining and Quarrying

Climate change would affect exploration, extraction, production, and shipping processes in the mining and quarrying industry (Pearce *et al*., 2011). An increase in climate-related hazards (such as forest fires, flooding, windstorm and likes) affects the viability of mining operations and potentially increases operating, transportation, and decommissioning costs. Most infrastructure was built based on presumption of a stable climate so that there is little preparation for adaptation (Ford *et al*., 2010; Ford *et al*., 2011; Pearce *et al*., 2011).

10.5.2. Secondary Economic Activities

10.5.2.1. Manufacturing

Climate change would impact manufacturing through three channels. First, climate change affects primary economic activities (see 10.5.1), and this means that prices and qualities of inputs are different. Second, the production process is affected. The impact of climate change on energy demand is well understood (see 10.2). Using a biophysical model of the human body, (Kjellstrom *et al*., 2009a) show that labour productivity may fall, particularly of manual labour in humid climates. (Hsiang, 2010) corroborate this with a statistical analysis of weather data and labour productivity in the Carribbean for 1970-2006. Third, climate change affects the demand for products. This is pronounced in manufactures that supply primary sectors (Kingwell and Farré, 2009) and construction material (see below). Unfortunately, there is no literature that quantifies these effects (see Appendix 10B).

10.5.2.2. Construction and Housing

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

10.6. Recreation and Tourism

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

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

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

10.6.1. Recreation and Tourism Demand

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

10.6.1.1. Recreation

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

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

Some studies confuse weather and climate, or suffer from selection bias. For instance, (Graff Zivin and Neidell, 2010) find that people recreate indoors when the weather is inclement. (Scott *et al.*, 2007) estimate the relationship between visitors to Waterton Lakes National Park and weather variables for eight years of monthly observations; and use this to project an increase in visitor numbers due to climate change. A survey among current visitors indicates that a deterioration of the quality of nature would reduce visitor numbers. (Taylor and Ortiz, 2009) estimate the impact of weather on domestic tourism in the UK, finding that tourists often respond to past weather. The hot summer of 2003 had a positive impact on revenues of the tourist sector. As another example, (Denstadli *et al.*,) find that tourists in the Arctic do not object to the weather in the Arctic. (Gössling *et al.*, 2006) reaches the same conclusion for tourists on Zanzibar. Neither study assesses the representativeness of their sample of all tourists.

10.6.1.2. Tourism

Climate (Braun *et al.*, 1999; Gómez Martín, 2005; Wall and Badke, 1994) and weather (Agnew and Palutikof, 2006; Garbas, 2006; Rossello, 2011; Rosselló-Nadal *et al.*, 2010; Álvarez-Díaz and Rosselló-Nadal, 2010) are important factors in tourist destination choice. (Maddison, 2001) estimates a statistical model of the holiday destinations of British tourists. (Lise and Tol, 2002) replicate this for Dutch tourists and (Bigano *et al.*, 2006) for tourists from 45 countries. Tourists have a clear preference for the climate that is currently found in Southern France, Northern Italy and Northern Spain. People from hot climates are more particular about where they spend their holidays than people from cool climates.

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

(Bigano *et al.*, 2007; Hamilton *et al.*, 2005a; Hamilton *et al.*, 2005b) use the above econometric analyses to construct a simulation of domestic and international tourism. (Hamilton and Tol, 2007) downscale the national results of these studies to the regions of selected countries. The advantage of such a model is that it assesses the logical consequences of the econometric results, which is not trivial as all potential holiday destinations see a simultaneous change in their attractiveness. The disadvantage is stylized representation of the effect of climate on destination choice. Two main findings emerge. First, climate change would drive tourists to higher latitudes and altitudes. International tourist arrivals would fall, relative to the scenario without warming, in hotter countries, and rise in colder countries. Tourists from Northwestern Europe, the main origin 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 the rate of growth in the tourism sector, but tourism nowhere shrinks.

10.6.2. Recreation and Tourism Supply

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

The main criticism of most biometeorological studies is that the predicted gradients and changes in tourism attractiveness have rarely been tested to observations of tourist behaviour. (De Freitas *et al.*, 2008) validate their proposed meteorological index to survey data. (Moreno *et al.*, 2008) and (Ibarra, 2011) use video of beach occupancy to test meteorological indices for beach tourism. (Gómez-Martín, 2006) tests meteorological indices against visitor numbers and occupancy rates.

Other studies put tourists centre stage. (Eijgelaar *et al.*, 2010) argues that so-called “last chance tourism” is a strong pull for tourists to visit Antarctica to admire the glaciers while they still can. (Farbotko, 2010) uses a similar mechanism to explain the rise in popularity of Tuvalu as a destination choice.

Studies on the supply side often focus on ski tourism. (Abegg and Elsasser, 1996) is one of the earliest papers. Under their particular climate scenario, a warming of 2ºC would raise the altitude of snow-reliable resorts by 300 metres in the Swiss Alps; 22% fewer resorts would be snow-reliable. (Elsasser and Bürki, 2002) point out that artificial snow-making cannot fully offset the loss in natural snowfall. (Hamilton *et al.*, 2007) reaches a similar conclusion for New England, highlighting the importance of “backyard snow” to induce potential skiers to visit ski slopes. (Pickering *et al.*, 2010) find a preference of skiers in Australia of natural snow over artificial snow. From a series of interviews, (Hill *et al.*, 2010) find that tourist operators in the Swiss Alps seek to maintain the status quo through adaptation, rather than search for viable alternatives to ski tourism; and argue that better coordination is needed for adaptation to be successful. (Scott and McBoyle, 2007) highlight that there are many options to adapt to a loss of snow for skiing. (Hoffmann *et al.*, 2009) use a survey of ski lift operators in the Swiss Alps and find that adaptation measures are driven by the ability to adapt (rather than the need) and that adaptation is more prevalent on higher slopes (which are less vulnerable). (Scott *et al.*, 2006) study the impact of climate change on six ski areas in eastern North America. Even with snowmaking, climate change could be an existential threat to 3 of the 6 ski areas by 2050; and climate change would lead to a contraction in each area in each scenario. (Dawson *et al.*, 2009) use past analogues to study the impact of future climate change on ski tourism in the Northeastern USA. They find that small and very large resorts will be hit hardest. (Scott *et al.*, 2008a) find that snowmobiling would have disappeared from the Northeastern USA by the end of the 21st century. Artificial snowmaking would halt the decline of ski resorts, but water scarcity and the costs of snowmaking would be increasingly large problems. (Scott *et al.*, 2003) reach the same conclusion for southern Ontario, (Scott *et al.*, 2007) for Quebec, and (Steiger and Mayer, 2008) for Tyrol. (Bicknell and Mcmanus, 2006) study adaptation for ski resorts in Southeastern Australia. They note that resorts may continue to be economically viable in the absence of snow by focusing on alternative activities. (Pickering and Buckley, 2010) note that artificial snow-making may be infeasible and uneconomic at the scale required to offset the loss of natural snow in Australia, and argue for a reorientation towards summer tourism and residential property development. (Moen and Fredman, 2007) find that alpine ski resorts in Sweden would become economically unviable, and that alternative livelihoods need to be developed. (Tervo, 2008) finds that the shortening of the Finnish ski season would be too limited to affect the economic viability of tourist operators. (Serquet and Rebetez, 2011) find that the Swiss Alps attract more tourists during hot summers, and argue that climate change would structurally improve the mountains as a summer tourism destination. (Bourdeau, 2009) argue along the same lines for the French Alps, stressing the importance of non-tourism alternatives as a source of economic development. (Potocka and Zajadacz, 2009) argue that prudent management supplies tourism services suitable for all weather.

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

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

A few studies consider all aspects of the impact of climate change for particular countries or regions. (Ren Guoyu, 1996) shows that domestic tourism in China will shift northwards, that sea level rise would damage some tourist facilities, and that the overall impact of climate change on China's tourist sector would be negative. (Harrison *et al.*, 1999) conclude that climate change would make Scotland less attractive to tourists in winter but more attractive in summer. (Ceron and Dubois, 2005) assess the impact of climate change on tourism in France. They argue that the French Riviera may benefit because it is slightly cooler than the competing coastal resorts in Italy and Spain. The Atlantic Coast, although warming, would become less attractive because of increased rainfall. The increase in summer tourism in the mountains is unlikely to offset the decrease in winter tourism. (Jones *et al.*, 2006) study the impact of climate change on three festivals in Ottawa. They argue for heat wave preparedness for Canada Day, find that skating on natural ice may become impossible for Winterlude, and fret that the dates of the Tulip Festival may need to be shifted to reflect changing phenology. (Dawson and Scott, 2010) assess the impacts in the Great Lakes regions, finding reduced tourism potential in winter but increased opportunities in summer. (Turton *et al.*, 2010) study Australia. They conclude that tourist operators find the uncertainty about climate change too large for early investment in adaptation.

10.6.3. Market Impacts

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

10.7. Insurance

10.7.1. Main Results of IPCC AR4

Property insurance, expanding with economic growth both in developed and developing countries, was identified in the AR4 as potentially affected by more intensive and/or frequent weather-related disaster events caused by climate change. With rising risk, insurability can be preserved through risk-reducing measures, where governments have an important responsibility (AR 4, WG II, 7.4.2.2.4). In order to incentivize adaptation to climate change, insurers communicate region specific risk information through risk commensurate prices to their stakeholders. They can relieve governments from a substantial part of their disaster liability, but need by themselves stay financially healthy, e.g. through improved risk management (AR 4, WG II, 7.6.3.).

[Information from SREX will be included in FOD]

10.7.2. Societal Role of Insurance Faced with Weather Hazards

Insurance provides individuals and enterprises with a way to internalize catastrophe risk costs prior to catastrophic events, reduces the economic impact of climate-related and other disasters, thus stabilizing income and consumption-flow and decreasing societal vulnerability. Fundamentally, insurance is based on the law of large numbers: the larger the pool of uncorrelated and relatively small risks, the smaller the statistical variance in the distribution of losses. Hence, an insurer with a large pool can predict the average loss per policy more accurately and thus charge a lower and more stable premium than an insurer with a smaller pool. In addition to spreading risk over a diversified pool, insurance spreads risk over time, because premium payments are manageable in each single year, as against the financial burden if a catastrophic loss materializes. However, weather disasters such as disastrous floods, that may increase in frequency and/or intensity with climate change, violate the principle of assuming uncorrelated risks, because many are affected simultaneously. Consequently, large losses are much more likely and loss variance is much greater than without correlation, and the actual incurred loss may considerably exceed the statistically expected loss of the pool (Cummins and Mahul, 2009; Aakre et al., 2010; Geneva Association, 2009). The more regional frequencies or intensities of weather disasters rise, the higher the demand for risk capital that insurers need to indemnify catastrophic losses and ensure financial solvency. This is either in the form of equity capital or purchased in the reinsurance and capital markets. The capital costs account for a substantial portion of premiums and the affordability and viability of weather peril insurance are subjects of ongoing research given future climate change in many regions (Herweijer et al., 2009; Kunreuther et al., 2009; Charpentier, 2008; Geneva Association, 2009; Hecht, 2008; Mills, 2009).

From this perspective, increasing volatility and burden of losses in many regions are expected to fundamentally impact on the industry, constituting grounds for insurers to adapt their business to the changing risk and to support the mitigation of GHG emissions in various ways (Hecht, 2008; Herweijer et al., 2009; Wilkins, 2010; Phelan, 2011).

10.7.3. Observed and Projected Losses from Weather Hazards

Insured losses from weather-related disasters are robustly evidenced to have increased substantially in recent decades both globally and in regions. One study determined the slope of the linear trend in global insured weather-related losses, deflated to 2008 values, in the period 1980–2008 to be US$ 1.4bn per year ([Barthel and Neumayer, 2011]; Schwierz et al., 2009; Crompton and McAneney, 2008). Insured losses are likely to be measured more accurately than direct economic loss estimates because insurers in competitive markets have to precisely register and monitor claims and payouts (Changnon, 2009a). Most prominent driver of the increase is socio-economic change, such as higher concentrations of people and destructible wealth in progressively urbanised environments with rising insurance penetration (Bouwer et al., 2007; Kunreuther and Michel-Kerjan, 2009). In order to look for trends beyond socio-economically triggered changes, the latter are removed from the time series of nominal weather losses by normalisation, i.e. scaling up losses from the event for the area affected based on relative changes in destructible property, inflation, damage susceptibility and insurance penetration between the year of the event and the present (e.g., Crompton and McAneney, 2008).

The few studies on trends in normalised insured weather-related losses focus mainly on individual perils and regions in the developed world, in particular Australia, USA and Germany. In two of these countries (USA, Germany), several upward trends were detected, e.g. for thunderstorms, floods or winter storms in the USA (Table 10-8). Trends in normalised insured losses can be influenced ,e.g., by changing damage susceptibilities (Crompton and McAneney, 2008), or by factors within the insurance system, e.g. changes in claims-handling. Given these uncertainties, it is hard to conclusively estimate, to what degree trends in normalised insured weather losses indicate that an external driver, such as climate, is mainly responsible. Such an impact presupposes the trend in normalised insured losses to run parallel with a corresponding trend in an observed causative meteorological parameter. One study demonstrates that the number of days when a regional insurer in southwest Germany sustains losses displays a trend since analysis started in 1986, while the meteorological parameters associated with severe convective storms in that region also show positive trends (Kunz et al., 2009). Similarly, increasing US thunderstorm-related normalised insured losses correspond with meteorological observations of increasingly favourable conditions of severe thunderstorm development ([Sander et al., 2012], -> WG I); the observed rise in US normalised insured flood losses corresponds to increased heavy precipitation events in many parts of the USA (-> WG I). In all these cases, no conclusive attribution of losses to anthropogenic climate change has yet been made. The recent upswing in hurricane hazard and associated losses seems at least partly to be connected to a mode of natural climate variability (-> WG I, Schmidt et al., 2009a, 2009b).

[INSERT TABLE 10-8 HERE
Table 10-8: Observed normalized insured losses from weather hazards.]

Most studies concerning climate-change projections for insured weather losses relate to the impact of the extratropical-storm hazard on homeowners' insurance in the various European countries. Climate model ensemble studies display a roughly consistent pattern of change until the period 2020–2050 and the end of the 21st century, respectively: annual expected loss ratios, i.e. insured loss relative to total insured value per region, declines at Mediterranean latitudes and increases in central, west and northern Europe, in parallel with the fields of high-percentile local wind speeds in those regions. In all studies, loss ratios decrease again with higher latitudes in Scandinavia and more eastern longitudes in eastern Europe. Increases in very large individual storms and associated large loss variability are indicated by increasing standard deviations of projected annual loss ratio distributions (Pinto et al., 2007; Donat et al., 2011). As regards the direction of change in most parts of Europe, there is robust climate modeling evidence and high agreement between the studies (Table 10-9).

[INSERT TABLE 10-9 HERE
Table 10-9: Climate change projections of insured losses.

Mean annual insured flood property losses in the UK are projected to rise with climate change (Table 10-9); confidence in the sign of change is high given recent attribution of increasing probabilities for heavy precipitation and flooding in the UK driven by anthropogenic climate change (-> WG I [Pall et al., 2011, Min et al., 2011]). Typhoon-wind and rainfall may lead to increased annual losses to insured property in China (Table 10-9). There is medium confidence in the sign of change, given some recent projections of more higher-intensity cyclone tracks close to China in a global warming scenario (-> WG I [Murakami et al., 2011, Emanuel et al., 2007]). Agricultural hailstorm insurance losses in the Netherlands are projected, based on regional climate-change scenarios, to increase, with high confidence on the direction of change given empirically established correlations to (minimum) temperatures (Table 10-9). For paddy rice insurance in Japan, an overall decrease in standard crop yield and insurance payouts is projected, due to changes in temperature, heat episodes and growth period length (Table 10-9).

Currently, projected impact analyses do not explicitly account for future economic growth and inflation, which would likely result in higher levels of insurance uptake, insured values and, accordingly, insured losses (Bouwer, 2011). However, premiums would grow too. Unlike socio-economic effects, adjustments are not automatically made for external drivers such as changing frequencies or intensities of hazardous events. Hence, projection studies using relative entities such as loss ratios and a frozen spatial distribution of insured property can be justified as a relevant approximation (Pinto et al., 2007; Donat et al., 2011). Research on the projection of insured losses is developing and, for many perils, information on expected future losses has to be inferred from studies on direct economic losses, where available (-> Ch 18). Knowledge of the projection of future changes in damage susceptibility is still poor.

10.7.4. Supply-Side Challenges and Sensitivities

10.7.4.1. High-Income Countries

The provision of property insurance covering weather hazards 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, provided that the risk, i.e. the loss-distribution features, has been assessed. On the cost side, the expected level of losses, expenses for risk assessment, product development, marketing, operating, and claims processing are included. Moreover, the revenue must provide a fair return on shareholders' equity and, to a substantial proportion, allow for the purchase of external capital needed to cover large loss if a disaster materialises. Achieving equilibrium between these factors on the supply and demand side determines marketable insurability (Kunreuther et al., 2009; Charpentier, 2008).

The balance within an insurance system between affordability and costs to be covered is very sensitive to climate-driven increases in large weather-losses. These may corrode an insurer's ability to cover the losses (solvability) if it fails to reflect the temporal changes in hazard condition in its risk management, or is hampered in doing so. Additionally, misguided incentives can aggravate the situation (Table 10-10).

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

Both the quantifiable and the non-quantifiable additional uncertainty, that might be involved with climate change, translate into a need for more risk capital to compensate for higher risk (Kunreuther et al., 2009). In high-risk areas, this can transfer some strain on the affordability of insurance and hence viable local economies (Table 10-10).

While climate-change impacts are considered as primarily affecting property insurance, health and life insurance are also expected to be impacted in some regions by increases in infectious and respiratory diseases, heat stress, and climate-linked pollution and malnutrition (Hecht, 2008). Liability insurance, too, may be susceptible to climate-change losses. So far, no damages have been awarded for greenhouse gas emissions as such, but litigation where damages are sought is pending, especially in the USA (Table 10-10).

10.7.4.2. Middle- and Low-Income Countries

Today, middle- and low-income countries account for a much smaller share of worldwide non-life insurance (12% of premiums in 2007) than high-income, industrialised countries (88%). Whereas in high-income countries around 40% of direct economic losses are covered by insurance, only about 13% in middle-income countries and approximately 4% in low-income countries is covered (Geneva Association, 2009; Cummins and Mahul, 2009). For instance, in Pakistan that was severely hit in 2010 by a major flood disaster, insured losses amounted to only approximately 1% of direct economic losses (US$ 100m of US$ 9.5bn) (Munich Re, 2011). These small-scale catastrophe insurance systems in middle- and low-income countries feature several challenges that may adversely combine with climate change impacts.

The small share of insurance in middle- and low-income countries' risk financing is not deemed economically prudent, because traditional post-disaster financing such as external credit or donor assistance materialises only many months after a disaster, leaving a risk financing gap in the months immediately following the event. Hence, in the short and medium term, pre-disaster financing instruments such as insurance or trigger-based risk-transfer products seem an appropriate means of providing prompt liquidity for households, farmers, businesses and governments (Ghesquiere and Mahul, 2007; Linnerooth-Bayer et al., 2009). These may gain even more importance, given an increase in disaster incidence with climate change.

Any endeavor to upscale catastrophe insurance in these countries to reduce the post-disaster risk financing gap, is challenged by both domestic pressures such as low business volumes, coupled with relatively high transaction costs, and external pressures, including high price phases in the international reinsurance markets following large disasters. When those stresses combine, small-scale (agricultural) insurance companies in middle- and low-income countries may find it difficult to ensure sufficient risk capital (Cummins and Mahul, 2009; Mahul and Stutley, 2010), particularly when faced with climate change driven increases in loss volatility.

Microinsurance schemes serve individuals, households and small enterprises in low-income markets by mainly providing limited health, life and in some regions funeral-expenses coverage, while maintaining transaction costs at the lowest operable level. Correlated weather risks aligned with enhanced risk capital requirements are among the grounds to deter such low-cost schemes from any substantial commitment to offer property insurance. Yet, there are schemes offering weather coverage, typically with government and NGO assistance and cross-subsiding by collaborating local insurers (Linnerooth-Bayer and Mechler, 2009; Qureshi and Reinhard, 2011). These schemes may be particularly sensitive to a regional rise in disaster risk due to climate change.

Another challenge that may compound losses associated with climate change is a situation of adverse selection, where many purchasers of insurance have not disclosed their high-risk situation, e.g. a floodplain site, to the insurer so as to benefit from lower rates. Consequently, the revenue calculated by the insurer is inadequate to cover the real risk. In low-income countries, where extensive monitoring involves relatively high costs and address-based, geographical risk-assessment tools are not available, this information asymmetry can cause catastrophe insurance markets to fail – particularly if weather-related losses are increasing in intensity or frequency (Barnett et al., 2008; Collier et al., 2009; 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 capital to cover the losses. This challenge can be addressed using several options that reduce vulnerability and sustain insurability. As vulnerability-related drivers of risk are most common, options to reduce vulnerability are deemed sound even if currently expected climate change impacts will not materialise in some regions. The most fundamental response option is to convey the risk signal to individuals and enterprises by premiums reflecting the existing risk that in turn encourages policyholders to reduce their vulnerability by implementing cost-effective adaptive measures (Hecht, 2008; Kunreuther et al., 2009; for an example see Table 10-11). Further, vulnerability reduction can effectively be incentivized by insurance conditions such as premium discounts for loss-prevention measures (Table 10-11). Moral hazard, where the purchase of insurance motivates the insured to subsequently adopt more risk-prone behavior than anticipated by the insurer, can be reversed towards risk-conscious behavior by involving the policyholder to some extent in the payment of losses (deductibles, upper limits of insurance coverage). Collaborative work of insurers together with authorities on damage prevention and building standards has a long-standing tradition and is crucial for reducing vulnerability (e.g., Herweijer et al., 2009; Ward et al., 2008). As another option, risk reduction can also be associated with innovative products, e.g. green residential policies (Table 10-11).

[INSERT TABLE 10-11 HERE
Table 10-11: Products and systems responding to changes in weather risks.]

Most commercial risk-assessment models now incipiently factor in temporal changes in climate-related hazard conditions, mainly by making adjustments to include higher hurricane frequencies encountered since the mid-1990s, while still assuming unchanging conditions over time for other weather hazards. Viewing past decades' temporally changing hazard conditions under stationary assumptions, i.e. not considering any change in hazard conditions, can result in an underestimation of current expected loss, loss volatility and risk capital requirements (Table 10-11). Other confounding factors in recent extremely large losses, e.g. systemic economic impacts, have been increasingly addressed (Table 10-11). Geographically referenced risk-assessment tools, e.g. flood-recurrence zoning in various countries aligned with premium differentiation, counteract scarce specific risk information and adverse selection (Kunreuther et al., 2009; Hecht, 2008). Adverse weather alert systems have been established by insurers and offered to clients (e.g., WIND, 2011).

Rating agencies in the USA – crucial to an insurer's credit rating – and upcoming Solvency II insurance regulation in Europe contribute to enhanced disaster resilience, requiring insurers to prepare for sufficient liquidity to sustain severe climate-related catastrophe hits such as two 100-year hurricane losses in one year or a 200-year loss from an European winter storm, respectively (Table 10-11). Looking ahead, insurance associations such as the Association of British Insurers and the German Insurance Association have taken steps to project climate change driven losses to allow for adaptation of the industry (Table 10-11). However, compared to other sectors' typical foresight periods, e.g. infrastructure planning, the insurance sector is better adaptable due to its short-term contracts (Botzen et al., 2010a).

Reinsurers are key to the supply of climate-related disaster risk capital. To absorb regional disaster loss peaks from typhoons, hurricanes, or other disasters, they operate globally to diversify their risk across non-correlated geographical regions and hazards. In 2007, the branch of global reinsurance that pays out when losses exceed fixed thresholds, offered seven times the capacity available in the capital market driven insurance-linked securities, thus highlighting the reinsurers' role (Cummins and Mahul, 2009; Kunreuther and Michel-Kerjan, 2009). Shortages in the international reinsurance market, occurring after major disaster shocks and making risk capital more expensive for primary insurers, have been moderating over the last two decades. This favorable development was mainly helped by easier inflow of new capital from the capital markets following large disasters, such as Hurricane Katrina (Table 10-11).

Truly disastrous climate-related risks, e.g. in excess of US$ 100bn, may make additional capacity desirable. These disasters can be diversified across the large global financial securitisation market. Here, natural catastrophe risks are not correlated with traditional capital market risks and hence are attractive to institutional investors through instruments such as catastrophe bonds to cover insured disaster losses (Table 10-11).

10.7.5.2. Middle- and Low-Income Countries

Index-based weather insurance products are considered particularly suitable for the agricultural sector in low- and middle-income countries, also in the perspective of climate change impacts in some places (e.g., Collier et al., 2009). Payouts depend on a physical trigger, e.g. cumulative rainfall at a nearby weather station, so that fixed transaction costs such as on-site loss assessments are avoided. Detrimental information asymmetry, resulting from moral hazard, is removed. Risk-based premiums signaling changes in risk related to climate change to the policyholder encourage adaptive responses, particularly if combined with access to advanced technologies, e.g. drought-resistant seed (Table 10-11). Basis risk, where some farmers suffer losses but no payout was triggered by weather-station readings and vice versa, is a crucial disadvantage of index-based schemes. As a difficult concept, it may cause the insured to lose confidence in the scheme (Patt et al., 2010). Here, improvements can be achieved (Table 10-11).

Many smaller developing countries can no longer diversify large-scale climate-related disaster risk caused by widespread floods, droughts or hurricanes. Post-disaster risk-financing instruments such as external credit or donor assistance provide liquidity only months after the event. Hence, dramatic liquidity gaps, aggravated by overstretched tax bases and substantially correlated infrastructure risks, render sovereign insurance economically sound for coping with increased disaster-risk levels (Ghesquiere and Mahul, 2007). Current schemes include government disaster reserve funds (FONDEN, Mexico) and pools of small states' sovereign risks (CCRIF, Caribbean). In both cases, peak risk is transferred to reinsurance and the capital market (catastrophe bonds) (Table 10-11).

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

10.7.6.1. High-Income Countries

Economic insurance theory favors a social arrangement where individual risk is insured, but the non-diversifiable disaster component of risk (that in many regions will rise with climate change) is shared among the society (Kunreuther et al., 2009; Borch, 1962). Accordingly, many high-income states already display public private partnerships between the insurers and the public that involve governmental intervention on the non-diversifiable catastrophic risk portion (Table 10-12). As a baseline across all these systems, the pro-adaptive and impact reducing features of insurance are most efficient, if the risk-adjusted price signal can be spread throughout the market, and the pool of insureds can be maximized, e.g. through bundled hazard packages (Kuhnreuther et al., 2009; Bruggeman et al., 2010). People who can no longer afford insurance due to premium adjustment and high risk-location can be cared for under the principle of social welfare (Table 10-12). Change in diversity is seen as key for adapting the insurance systems of many developed markets to climate change challenges, based on their cultural and socio-historic roots (Schwarze et al., 2011). While insurance regulation is ensuring availability and affordability of insurance for customers and is guarding against insurer insolvency, it often only adopts short-term to medium-term views. Climate change will pose long-term changes in average loss, loss volatility and risk-based capital, hence regulators have a new role in requiring insurers' risk-adequate price signals, risk education of consumers and advancing risk-reduction activities from a long-term perspective of viable insurance markets (Mills, 2009; Hecht, 2008; Grace and Klein, 2009).

[INSERT TABLE 10-12 HERE
Table 10-12: Governance, public-private partnerships, and insurance market regulation.]

10.7.6.2. Middle- and Low-Income Countries

From an emerging country's perspective, a key element of risk financing is deemed transfer of private risks to a competitive insurance market. This can efficiently reduce the governments' fiscal burden and uncertainty due to weather disasters by encouraging adaptation through risk adequate premiums and diminishing the need for supplementary budget (Cummins and Mahul, 2009; Ghesquiere and Mahul, 2009). With the establishment of competitive domestic insurance markets, interest in public-private partnerships may evolve, e.g. between farmers, government and insurers, in order to expedite agricultural development and resilience, e.g. by means of subsidies for the catastrophic risk portion (Collier et al., 2009; Mahul and Stutley, 2010; [Herbold, 2011], see Table 10-12). Technically well designed laws and regulation can encourage purchase of insurance, allowing for all sorts of relevant insurance mechanisms (indemnity-based and index-based). Coinsurance pools can diversify climate risks across larger regions, reduce premiums and render access to external risk capital more easy (Candel 2007, [Herbold 2011]).

In low-income and many middle-income countries, that are most vulnerable to climate change, even incipient domestic insurance markets hardly exist. In those countries, weather catastrophe insurance and associated capital requirements cannot be provided by the private sector alone. As a consequence, adaptation oriented climate change risk management frameworks were proposed to be included in the post-2012 adaptation regime of the UNFCCC. Insurance is a central risk management element in these proposals, that plan for funding premium from UNFCCC adaptation finance processes according to the principles of "common but differentiated responsibilities and respective capabilities" (UNFCCC Art.3.1) and "polluter pays" (Table 10-12).

In all, the availability of innovative insurance concepts in middle- and low-income countries, at least at pilot stage, that can advance adaptation to climate change impacts, is robustly evidenced with high agreement in the literature, including concepts for improved provision of increased disaster risk capital. For countries all over the world, the literature presents either available or at least realizable insurance designs based on premiums calibrated to existing risk and shaped to incentivize risk-reduction, thereby benefiting from risk assessing and modeling capabilities that allow for temporal changes in hazard conditions. Further contributing to a healthy state of insurance systems, also regulatory requirements for relevant amount of risk capital, and efficient risk capital resources such as the reinsurance and securitization markets are seen crucial in the literature. These provisions are deemed sound risk management, even if uncertainty materialises to the extent that specific projections of climate change will not be realised in some regions.

10.8 Services Other than Tourism and Insurance

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

10.8.1 Sectors Other than Health

The literature on the impact of climate change on other sectors of the economy is extremely sparse. Few studies have evaluated the possible impacts of climate change, and particularly the economic impacts, on these sectors. Tamiotti (2009) conducted a qualitative assessment of climate and trade. (Travers and Payne, 1998) and (Subak *et al*., 2000) find that weather significantly affects retail. (Sabbioni *et al*., 2009) note that climate change may require a greater effort to protect cultural heritage. Other studies have evaluated the potential increase in local and regional conflict, with implications for additional military expenditures, but did not complete an economic assessment (Gleditsch, 2009, Jensen and Gleditsch 2009, Nel and Righarts, 2008, Tol and Wagner, 2010, Zang 2006). Historical analysis indicates some correlation of climate related changes with conflict, but correlations can be weak and may weaken with further economic development (Tol and Wagner, 2010).

10.8.2. Health

Climate change could affect the health sector through increases in the frequency, intensity, and extent of extreme weather events adversely affecting infrastructure and increase the demands for services, placing additional burdens on public health and health care personnel and supplies; these have economic consequences. Large numbers of people are affected in weather-related disasters; for example, more than 600,000 people required immediate assistance in hydrological events in 2002 through 2010 (EM-DAT 2011). Although the proportion seeking medical treatment is a small subset, the additional burden on health care facilities can be significant (Hess et al. 2009). Just increases in ambient temperature and precipitation increase visits to health care facilities. For example, one trauma center in the U.S. found a 5.25% increase in hourly admissions for each approximately 5°C increase in temperature; and a 60-78% increase in admission for each 2.5 cm increase in precipitation in the previous three hours (Rising et al. 2006).

Heatwaves and other extreme events can increase hospitalizations (cf. Mayner et al. 2010; Chapter 11) with attendant increased costs. Heatwaves also can increase hospital visits by individuals looking for an air-conditioned location (Carthey et al. 2009). Storm surges, floods, and wildfires can damage hospitals and clinics, injure or kill health professionals, and/or affect transport so that health professionals cannot reach those affected or the affected can't reach treatment centers. There is a wide range of possible impacts of extreme events on hospitals and clinics range, such as overheating and possible failure of electrical equipment and computers; shortages of electricity, water, food, sewage, and other critical resources required for patient treatment; and physical damage and destruction of buildings (Carthey et al. 2009). Hospital equipment is not designed to be flood-proof, thereby requiring cleaning or replacement of critical equipment following flooding events. Flooding and wildfire events can require evacuation of critical care patients, with the attendant risks for the patients. Adverse impacts on transportation (such as flooded roads) exacerbate the situation. Very large events that affect multiple health care facilities challenge the ability of the community and/or region to properly care for the affected and those with ongoing health issues requiring medication and/or treatment. Areas projected to experience increases in the frequency and intensity of extreme events should consider adding "surge capacity" to increase the ability of health care facilities to manage such events without interruption of service (Banks et al. 2007; Hess et al. 2009).

Climate change is projected to increase the burden of major worldwide causes of childhood mortality: malnutrition, diarrheal diseases, and malaria (Chapter 11). Any increase in health burdens or risks would increase the demands for public health services (e.g. surveillance and control programs) and the demands for health care and relevant supplies (e.g. oral rehydration for severe cases of diarrheal disease).

The costs of treating additional cases of climate sensitive health outcomes could be significant (Ebi 2008; Pandey 2010). An estimate of the worldwide costs in 2030 of additional cases of malnutrition, diarrheal disease, and malaria due to climate change, assuming no population or economic growth, emissions reductions resulting in stabilization at 750 ppm CO2 equivalent in 2210, and current costs of treatment in developing countries, estimated treatment costs without adaptation could be $4 to 12 billion worldwide (Ebi 2008). The costs for additional infrastructure and health care workers were not estimated, nor were the costs of additional public health services, such as surveillance and monitoring. The costs were estimated to be unevenly distributed, with most of the costs borne by developing countries, particularly in South East Asia and Africa, to address the projected additional cases of diarrheal disease and malaria (Markandya and Chiabai 2009). 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 to 5 billion, with the costs expected to decline over time with improvement in basic health services. Over the period 2010-2050, the average annual costs were estimated to be around $2 billion, with most of the costs related to treating diarrheal disease; the largest burden is expected to be in Sub-Saharan Africa. The differences in costs from Ebi (2008) are primarily due to a reduction in the baseline burden of disease and lower costs for malaria treatment.

These estimates are in addition to the costs of improving health protection for diarrheal diseases and malaria, for example in the context of the Millennium Development Goals.

The malaria estimates from the global estimates of the costs of adaptation are comparable with estimates of the additional health care costs in 2025 in Southern Africa due to a climate change-related increase in the incidence of malaria (Van Rensburg and Blignaut, cited in Markandya and Chiabai 2009). Assuming low population growth and 2000 prices in purchasing power parity, additional costs for the prevention and treatment of malaria in South Africa were estimated to be approximately US$3.8 million; this represented 3% of GDP per capita in 2025. Smaller populations resulted in lower cost estimates for Botswana (US$ 125 million) and Namibia (US$ 177 million); for Namibia, this represented about 4.5% of GDP per capita.

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

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

10.9. Impacts on Markets and Development

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

10.9.1. General Equilibrium Effects

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

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

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

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

(Bigano *et al.*, 2008b) study the joint impacts on tourism and coasts, finding that tourism dominates the welfare impacts. (Kemfert, 2002) and (Eboli *et al.*, 2010) estimate the joint effect on the world economy of a range of climate change impacts, but conflate general equilibrium and growth effects. (Aaheim *et al.*, 2010) analyze the economic effects of impacts of climate change on agriculture, forestry, fishery, energy demand, hydropower production, and tourism on the Iberian peninsula. They find positive impacts on output in some sectors (agriculture, electricity) negative impacts in other sectors (forestry, transport) and negligible ones in others (manufacturing, services). (Ciscar *et al.*, 2011) study the combined effect of agriculture, sea level rise, river floods and tourism on the European economy. They find a welfare loss of 0.2-1.0% of income by the end of the century for the European Union. 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. At the same time, fifth, markets offer options for adaptation, particularly possibilities for substitution. This changes the size, and sometimes the sign of the impact estimate.

10.9.2. Growth Effects

10.9.2.1. The Rate of Economic Growth

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

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

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

10.9.2.2. Poverty Traps

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

(Galor and Weil, 1996) speculate about the existence of a climate-health-poverty trap. (Bonds *et al.*, 2010) and (Strulik, 2008) posit theoretical models and offer limited empirical support, while (Tang *et al.*, 2009) offers more rigorous empirical evidence. This is further supported by yet-to-be-published analyses (Bretscher and Valente, 2010;

Gollin and Zimmermann, 2008; Gollin and Zimmermann, 2010; Ikefuji *et al.*, 2010). Climate-related diseases such as malaria and diarrhea impair children's cognitive and physical development. This leads to poverty in their later life so that there are limited means to protect their own children against these diseases. Furthermore, high infant mortality may induce parents to have many children so that their investment in education is spread thin. An increase in infant and child mortality and morbidity due to climate change would thus trap more people in poverty.

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

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

10.9.2.3. Conclusion

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

10.10. Research Needs and Priorities

Evaluating the economic aspects of the impacts, vulnerability and adaptation to climate change 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. Despite an increasing number of studies implemented in developing countries about the impacts of climate change on the energy sector in recent years, there is still a strong asymmetry in the knowledge landscape between developed and developing countries. In energy supply, the deployment of extraction, transport and processing infrastructure, power plants and other installations are expected to proceed rapidly in developing countries in the coming decades to satisfy fast growing demand for energy. Designing newly deployed facilities with a view to projected changes in climate attributes and extreme weather patterns would require targeted inquiries into the impacts of climate change on the energy related resource base, conversion and transport technologies.

The economics of transportation systems and their role in overall economic activity have yet to be well understood. For water related sectors, improved estimation of flood damages to economic sectors, research on 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.

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

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

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

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.

Finally, assessments utilizing other approaches such as risk mitigation estimates, and stress testing of existing models suggest further research of factors that influence the economic impact estimates such as intergenerational discounting, population dynamics, and economic development is needed (Farmer and Geanakopolis, Cooke, Portney and Weyant).

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Appendix 10A. Industrial Classification and Chapter Outline

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

- A - Agriculture, forestry and fishing (10.5)
    - 01 - Crop and animal production, hunting and related service activities
    - 02 - Forestry and logging
    - 03 - Fishing and aquaculture
- B - Mining and quarrying (10.5)
    - 05 - Mining of coal and lignite
    - 06 - Extraction of crude petroleum and natural gas
    - 07 - Mining of metal ores
    - 08 - Other mining and quarrying
    - 09 - Mining support service activities
- C – Manufacturing (10.5, except C19)
    - 10 - Manufacture of food products
    - 11 - Manufacture of beverages
    - 12 - Manufacture of tobacco products
    - 13 - Manufacture of textiles
    - 14 - Manufacture of wearing apparel
    - 15 - Manufacture of leather and related products
    - 16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
    - 17 - Manufacture of paper and paper products
    - 18 - Printing and reproduction of recorded media
    - 19 - Manufacture of coke and refined petroleum products (10.2)
    - 20 - Manufacture of chemicals and chemical products
    - 21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations
    - 22 - Manufacture of rubber and plastics products
    - 23 - Manufacture of other non-metallic mineral products
    - 24 - Manufacture of basic metals
    - 25 - Manufacture of fabricated metal products, except machinery and equipment
    - 26 - Manufacture of computer, electronic and optical products
    - 27 - Manufacture of electrical equipment
    - 28 - Manufacture of machinery and equipment n.e.c.
    - 29 - Manufacture of motor vehicles, trailers and semi-trailers
    - 30 - Manufacture of other transport equipment
    - 31 - Manufacture of furniture
    - 32 - Other manufacturing
    - 33 - Repair and installation of machinery and equipment
- D - Electricity, gas, steam and air conditioning supply (10.2)
    - 35 - Electricity, gas, steam and air conditioning supply
- E - Water supply; sewerage, waste management and remediation activities
    - 36 - Water collection, treatment and supply (10.3)
    - 37 – Sewerage (10.3)

    - 38 - Waste collection, treatment and disposal activities; materials recovery (10.8)
    - 39 - Remediation activities and other waste management services (10.8)
- F – Construction (10.5)
    - 41 - Construction of buildings
    - 42 - Civil engineering
    - 43 - Specialized construction activities
- G - Wholesale and retail trade; repair of motor vehicles and motorcycles (10.8)
    - 45 - Wholesale and retail trade and repair of motor vehicles and motorcycles
    - 46 - Wholesale trade, except of motor vehicles and motorcycles
    - 47 - Retail trade, except of motor vehicles and motorcycles
- H - Transportation and storage (10.4)
    - 49 - Land transport and transport via pipelines
    - 50 - Water transport
    - 51 - Air transport
    - 52 - Warehousing and support activities for transportation
    - 53 - Postal and courier activities
- I - Accommodation and food service activities (10.6)
    - 55 - Accommodation
    - 56 - Food and beverage service activities
- J - Information and communication (10.8)
    - 58 - Publishing activities
    - 59 - Motion picture, video and television programme production, sound recording and music publishing activities
    - 60 - Programming and broadcasting activities
    - 61 - Telecommunications
    - 62 - Computer programming, consultancy and related activities
    - 63 - Information service activities
- K - Financial and insurance activities (10.7)
    - 64 - Financial service activities, except insurance and pension funding
    - 65 - Insurance, reinsurance and pension funding, except compulsory social security
    - 66 - Activities auxiliary to financial service and insurance activities
- L - Real estate activities (10.8)
    - 68 - Real estate activities
- M - Professional, scientific and technical activities (10.8)
    - 69 - Legal and accounting activities
    - 70 - Activities of head offices; management consultancy activities
    - 71 - Architectural and engineering activities; technical testing and analysis
    - 72 - Scientific research and development
    - 73 - Advertising and market research
    - 74 - Other professional, scientific and technical activities
    - 75 - Veterinary activities
- N - Administrative and support service activities (10.8 except N79)
    - 77 - Rental and leasing activities
    - 78 - Employment activities
    - 79 - Travel agency, tour operator, reservation service and related activities (10.6)
    - 80 - Security and investigation activities
    - 81 - Services to buildings and landscape activities
    - 82 - Office administrative, office support and other business support activities
- O - Public administration and defence; compulsory social security (10.8)
    - 84 - Public administration and defence; compulsory social security
- P – Education (10.8)
    - 85 - Education
- Q - Human health and social work activities (10.8)
    - 86 - Human health activities

  - 87 - Residential care activities
  - 88 - Social work activities without accommodation
- R - Arts, entertainment and recreation (10.6)
  - 90 - Creative, arts and entertainment activities
  - 91 - Libraries, archives, museums and other cultural activities
  - 92 - Gambling and betting activities
  - 93 - Sports activities and amusement and recreation activities
- S - Other service activities (10.8)
  - 94 - Activities of membership organizations
  - 95 - Repair of computers and personal and household goods
  - 96 - Other personal service activities
- T - Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use (10.8)
  - 97 - Activities of households as employers of domestic personnel
  - 98 - Undifferentiated goods- and services-producing activities of private households for own use
- U - Activities of extraterritorial organizations and bodies (10.8)
  - 99 - Activities of extraterritorial organizations and bodies

Appendix 10B. Industrial Classification and Literature Search

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

- A - Agriculture, forestry and fishing
  - 01 - Crop and animal production, hunting and related service activities
  - 02 - Forestry and logging
  - 03 - Fishing and aquaculture
- B - Mining and quarrying
  - 05 - Mining of coal and lignite
  - 06 - Extraction of crude petroleum and natural gas
  - 07 - Mining of metal ores
  - 08 - Other mining and quarrying
    - Climate change impact & quarrying: No results*
  - 09 - Mining support service activities
- C – Manufacturing
  - 10 - Manufacture of food products
    - Climate change economic & food products: No results*
    - Climate change economic & food processing: No results*
  - 11 - Manufacture of beverages
    - Climate change impact & beverages: No results*
  - 12 - Manufacture of tobacco products
    - Climate change impact & tobacco: No results*
  - 13 - Manufacture of textiles
    - Climate change impact & textiles: No results*
  - 14 - Manufacture of wearing apparel
    - Climate change impact & apparel: No results*
  - 15 - Manufacture of leather and related products
    - Climate change impact & leather: No results*
  - 16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
    - Climate change impact & wood: No results*
  - 17 - Manufacture of paper and paper products
    - Climate change impact & pulp paper: No results*

- 18 - Printing and reproduction of recorded media
  - Climate change impact & printing: No results*
  - Climate change impact & recorded media: No results*
- 19 - Manufacture of coke and refined petroleum products
- 20 - Manufacture of chemicals and chemical products
  - Climate change impact & chemical production: No results*
- 21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations
  - Climate change impact & pharmaceutical: No results*
- 22 - Manufacture of rubber and plastics products
  - Climate change impact & rubber: No results*
  - Climate change impact & plastic: No results*
- 23 - Manufacture of other non-metallic mineral products
  - Climate change impact & cement: No results*
  - Climate change impact & glass: No results*
- 24 - Manufacture of basic metals
  - Climate change impact & steel: No results*
  - Climate change impact & iron: No results*
  - Climate change impact & alumina: No results*
  - Climate change impact & aluminum: No results*
- 25 - Manufacture of fabricated metal products, except machinery and equipment
  - Climate change impact & metal: No results*
- 26 - Manufacture of computer, electronic and optical products
  - Climate change impact & equipment: No results*
- 27 - Manufacture of electrical equipment
  - Climate change impact & equipment: No results*
- 28 - Manufacture of machinery and equipment n.e.c.
  - Climate change impact & equipment: No results*
  - Climate change impact & machinery: No results*
- 29 - Manufacture of motor vehicles, trailers and semi-trailers
  - Climate change impact & vehicle: No results*
- 30 - Manufacture of other transport equipment
  - Climate change impact & equipment: No results*
- 31 - Manufacture of furniture
  - Climate change impact & furniture: No results*
- 32 - Other manufacturing
- 33 - Repair and installation of machinery and equipment
  - Climate change impact & equipment: No results*
  - Climate change impact & machinery: No results*

- D - Electricity, gas, steam and air conditioning supply
  - 35 - Electricity, gas, steam and air conditioning supply
- E - Water supply; sewerage, waste management and remediation activities
  - 36 - Water collection, treatment and supply
  - 37 - Sewerage
  - 38 - Waste collection, treatment and disposal activities; materials recovery
  - 39 - Remediation activities and other waste management services
- F – Construction
  - 41 - Construction of buildings
  - 42 - Civil engineering
  - 43 - Specialized construction activities
- G - Wholesale and retail trade; repair of motor vehicles and motorcycles
  - 45 - Wholesale and retail trade and repair of motor vehicles and motorcycles
  - 46 - Wholesale trade, except of motor vehicles and motorcycles
  - 47 - Retail trade, except of motor vehicles and motorcycles
- H - Transportation and storage

   - 49 - Land transport and transport via pipelines
   - 50 - Water transport
   - 51 - Air transport
   - 52 - Warehousing and support activities for transportation
   - 53 - Postal and courier activities
- I - Accommodation and food service activities
   - 55 - Accommodation
   - 56 - Food and beverage service activities
- J - Information and communication
   - 58 - Publishing activities
   - 59 - Motion picture, video and television programme production, sound recording and music publishing activities
   - 60 - Programming and broadcasting activities
   - 61 - Telecommunications
   - 62 - Computer programming, consultancy and related activities
   - 63 - Information service activities
- K - Financial and insurance activities
   - 64 - Financial service activities, except insurance and pension funding
   - 65 - Insurance, reinsurance and pension funding, except compulsory social security
   - 66 - Activities auxiliary to financial service and insurance activities
- L - Real estate activities
   - 68 - Real estate activities
- M - Professional, scientific and technical activities
   - 69 - Legal and accounting activities
   - 70 - Activities of head offices; management consultancy activities
   - 71 - Architectural and engineering activities; technical testing and analysis
   - 72 - Scientific research and development
   - 73 - Advertising and market research
   - 74 - Other professional, scientific and technical activities
   - 75 - Veterinary activities
- N - Administrative and support service activities
   - 77 - Rental and leasing activities
   - 78 - Employment activities
   - 79 - Travel agency, tour operator, reservation service and related activities
   - 80 - Security and investigation activities
   - 81 - Services to buildings and landscape activities
   - 82 - Office administrative, office support and other business support activities
- O - Public administration and defence; compulsory social security
   - 84 - Public administration and defence; compulsory social security
- P – Education
   - 85 - Education
- Q - Human health and social work activities
   - 86 - Human health activities
   - 87 - Residential care activities
   - 88 - Social work activities without accommodation
- R - Arts, entertainment and recreation
   - 90 - Creative, arts and entertainment activities
   - 91 - Libraries, archives, museums and other cultural activities
   - 92 - Gambling and betting activities
   - 93 - Sports activities and amusement and recreation activities
- S - Other service activities
   - 94 - Activities of membership organizations
   - 95 - Repair of computers and personal and household goods
   - 96 - Other personal service activities

- T - Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
    - 97 - Activities of households as employers of domestic personnel
    - 98 - Undifferentiated goods- and services-producing activities of private households for own use
- U - Activities of extraterritorial organizations and bodies
    - 99 - Activities of extraterritorial organizations and bodies

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

Table 10-1: Impacts of CC and EWEs on thermal power generation.

Type	Change in climatic or related attribute	Impact	Adaptation options
	Climate change		
All	Increasing air temperature	Reduces efficiency of thermal conversion [1] by 0.1-0.2% in the USA [2]; 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 [3]	
All	Increasing air temperature increasing temperature and reduces the availability of water for cooling [4]	Less power generation [5,6, 11-13]; annual average load reduction by 0.1-5.6% depending on scenario [15]	Use of non-traditional water sources (e.g., water from oil and gas fields, coal mines and treatment, treated sewage) [19, 20]; Re-use of process water from flue gases (can cover 25-37% of the power plants cooling needs) [5, 20], coal drying, condensers (dryer coal has higher heating value, cooler water enters cooling tower [21]), flue-gas desulphurization; Using ice to cool air before entering the gas turbine increases efficiency and output, melted ice used in cooling tower [5]; Condenser at the outlet of cooling tower to reduce evaporation losses (by up to 20%) [5]. Alternative cooling technologies: dry cooling towers, regenerative cooling, heat pipe exchangers [4, 23]; 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 [24]
All	Sea-level rise	Inundation of coastal power plants and related infrastructure [2, 5, 6, 12, 16]	Dykes, sea-walls, relocation [19, 33]
	Extreme weather events		
All	Increasing frequency of extreme hot temperatures	Exacerbating impacts of warmer conditions: reduced thermal and cooling efficiency [1]; overheating buildings; self-ignition of coal stockpiles	Cooling of buildings
	Reduced frequency of extreme cold/frost	Less corrosion due to frost, less freezing of coal stockpiles	
	Drought: reduced water availability	Exacerbating impacts of warmer conditions, reduced operation and output, shutdown	Same as reduced water availability under gradual CC
	Increasing heavy precipitation and resulting floods	Damage to power plant, Coal stockpile drenching - higher coal moisture reduces boiler	Change reference climate for drainage design [25], Barriers and windbreaks [26], spraying to

		efficiency (by 1%/10% increase in moisture content [7]).	create crusting surface [27]; plants/grass cover [28], compaction [29]
	Increasing frequency and intensity of extreme wind conditions (storm, tornado) and combined events (blizzards) [1]	Damage to building, cooling towers [8], storage tanks [8,9]	Adjust construction standards [25]
	Lightning	Storage tank damage [9, 10]	Enhanced lightning protection
	Floods	Damage to buildings and equipment, shutdown [17, 18]	Hard measures: flood protection by dams, embankment, flood control reservoirs, ponds, channels [19, 30, 31]; drainage improvement, rerouting and isolation of water pipes [32]. Soft measures: zoning, restrictions in flood-prone areas, building codes, flood insurance [31]

Sources: [1] Sieber nee Schulz (2011) [2] Parkpoom et al. (2004) [3] ADAM-Project (2009) [4] Ott & Richter 2008 [5] DOE/NETL (2007) [6] EPRI (2009) [7] Hatt (2004) [8] Bailey & Levitan (2008) [9] Chang & Lin (2006) [10] Stock (2009) [11] Kirkinen et al. (2005) [12] Krysanova & Hattermann (2007) [13] Mills (2007) [15] Hoffmann et al. (2010) [16] Paskal (2009) [17] Young et al. (2004) [18] Krausmann & Mushtaq (2008) [19] UNFCCC (2006) [20] Feeley et al. (2008) [21] Lambertz & Ewers (2006) [23] de Bruin et al. (2009) [24] Maulbetsch and Zammit (2003) [25] Auld et al. (2007) [26] Cal et al. (1983) [27] Chakraborti (1995) [28] Hatt (2003) [29] Fierro et al. (1999) [30] Thomalla et al. (2006) [31] Kundzewicz & Kaczmarek (2000) [32] Vaurio (1998) [33] Leary (2004)

Table 10-2: Impacts of CC and EWEs on nuclear energy.

Change in climatic or related attribute	Impact	Adaptation options
Higher mean temperatures	Increased heat reduces the thermal efficiency of nuclear plants [1]	Site selection for cooler local climates where possible
Changes in rainfall patterns	Can reduce the availability of water from rivers and lakes, leading to potential reductions in output or even shutdowns with low water levels [2]	Alternative cooling options: reuse wastewater and recover evaporated water in recirculating systems [3]; dry cooling [4, 3]
Increased windiness near coasts and dry areas	Salt sprays from sea can lead to long-term corrosion and short-circuit exposed electrical equipment [5]; dust and sand carried by wind can lead to equipment malfunction [5]	Weather seal critical equipment [6]
Extreme Weather Events		
Lightning	Can short-circuit or create false signals in instrumentation [7, 5]; can short-circuit onsite grid-connection [5]; can short-circuit back-up diesel connection and controls [5]	Ensure that circuits are insulated and grounded; bury key circuits underground; shield diesel generators controls
High winds	Wind-generated missiles can damage buildings and back-up generators [6]; can knock out grid interconnection	Install tornado missile shields [6]

Extreme cold	Ice can clog water cooling systems, leading to reduced generation or automatic shutdown [5]; ice can inhibit plant access; freezing pipes can lead to internal flooding [5]	Route heated water from cooling system to inlet area [5]; develop emergency weather plans [6]; insulate critical piping [5]
Extreme heat	Extreme heat can limit water discharge if temperatures are too high for water quality regulations, which can in turn reduce generation output or force a shutdown [8, 9, 2, 10]; heat can also reduce the effectiveness of cooling [2]; heat can foster the rapid growth of biological material that can clog water cooling intake, leading to reduced generation or shutdown [11, 5]	Reduce generation to avoid raising stream temperatures from discharged water above regulation [2, 8, 9, 10]; switch from once-through cooling to recirculating to reduce temperature of discharged wate [3]; switch from wet cooling to dry cooling [3]; increase maintenance of screens to ensure that biological matter does not clog water intake system [6]
Precipitation	Excessive rain or snow can collapse unreinforced structures [7]; excessive snow can inhibit plant access by critical personnel and supply deliveries [6]	Ensure that all building housing critical systems are reinforced; develop emergency weather plans [6]; special procedures for removal of snow and ice [6]
Drought	Low water levels can force plants to reduce generation output or shutdown [8, 9, 2, 10]	Implement alternative cooling options: reuse wastewater, recover evaporated water in recirculating systems, switch to dry cooling systems [3]
Floods/sea level rise	Some coastal plants are increasingly vulnerable to storm surges as sea levels rise and storms become more intense [10] while other plants may be vulnerable to river floods, both of which can force an automatic shutdown but can also damage critical safety systems, grid interconnections, and threaten spent fuel storage [6]	Site selection for new plants [12, 11]; earthworks to minimize risk of flooding [13, 10] ; upgrade flood-resistant doors [6]; raise elevation of backup diesel generators [6]
Forest and wildfire	Can disrupt plant access by critical personnel, supply deliveries, and emergency responders [11, 12]	Develop emergency access and response plans in case of nearby wildfires

[1] Linnerud et al. (2011) [2] Förster and Lilliestam (2009) [3] Feely III et al. (2008) [4] EPA (2001) [5] Williams and Toth (2011) [6] US NRC (2002) [7] IAEA (2003a) [8] Parey and Albrecht (2005) [9] Müller et al. (2007) [10] Kopytko and Perkins (2011) [11] IAEA (2003b) [12] IAEA (2003c) [13] IAEA (2003d)

Table 10-3: Impacts of CC and EWEs on hydropower generation.

Type	Change in climatic or related attribute	Impact	Adaptation options
	Climate change		
	Increase/decrease in average water availability	Increased/reduced power output [1-10]	
	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 [1-10]	Soft: adjust water management Hard: build additional storage capacity, improve turbine runner capacity [1-10]
	EWEs		
	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 [4,12]	Soft: adjust water management Debris removal Hard: increase storage capacity[12]
	Extreme cold conditions	Ice blocking turbine inlets [12]	Adopt operational strategies to reduce flow and manage ice-cover formation [12]

Notes: < yet to be completed >
Sources: [1] Schaefli et al. (2007) [2] Markoff and Cullen (2008) [3] Droogers (2009) [4] Watts et al. (2011) [5] Vicuna et al. (2008) [6] Ranzi et al. (2009) [7] AEG and Cubed (2005) [8] Iimi (2007) [9] Soito and Freitas (2011) [10] Maurer et al. (2009) [12] Sparks and Roy (2011)

Table 10-4: Impacts of CC and EWEs on solar energy.

Type	Change in climatic or related attribute	Impact	Adaptation options
	Climate change		
	Increasing mean temperature	Improving performance of SH (especially in colder regions), reducing efficiency of PV and CSP with water cooling; PV efficiency drops by ~0.5%/1°C temperature increase [1] for crystalline Si [11,12] and thin-film modules [13] as well, but performance varies across types of modules [14-16], 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 SH can use diffuse insolation [6].	Apply rougher surface for PV panels that use diffuse light better [24]; optimize fixed mounting angle for using diffuse light [25], apply tracking system to adjust angle for diffuse light conditions

		CSP more vulnerable (cannot use diffuse light) [1]	[26] Install/increase storage capacity [30-32]
	EWEs		
	Hot spells	Material damage for PV [17], 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 [27]	Cooling PV panels passively by natural ail flows [18] or actively by forced air or liquid coolants [19]
	Extreme cold periods	Reduced output from TH Unglazed collectors: heat loss when ambient temperature lower than that of liquid inside the plate collector, leading to reduced efficiency and output. Ambient temperature 50°C below inlet fluid temperature decreases efficiency by >50% in flat plate collectors and up to 20% in evacuated tube collectors [3, 4]	TH: in cold regions anti-freeze chemicals can be applied, but the system needs heat exchanger and secondary cycle for clean water [2]
	Wind storms	Material damage through wind load for all	Strengthened mounting structure [33]
	Wind and sand storms	Reduced power output due to sand and dust deposition [20], made worse by higher humidity [22]	Cleaning, tracking system to rotate panels out of wind [21]; using elastomeric coatings instead of grass [23] CSP: thermal storage to continue operation during sand storms, turning the mirrors upside down (trough) or out of wind (tower), cleaning [28,29]
	Hail	Material damage to SH: evacuated tube collectors are more vulnerable than flat plate collectors [1] Fracturing as glass plate cover, damage to photoactive material [1]	Flat plate collectors: using reinforced glass to withstand hailstones of 35mm (all of 15) or even 45 mm (10 of 15) [5]; only 1 in 26 evacuated tube collectors withstood 45mm hailstones [5] Increase protection to current standards [7,8] or beyond them [9,10]
	Lightning	Damage to inverter in PV [1]	Apply lightning protection [1]

Sources: [1] Patt et al. [2011] [2] Norton and Edmonds (1991) [3] Kalogirou (20040 [4] Norton (2006) [5] SPF (2009) [6] Honeyborne (2009) [7] Kurtz et al. (2009a) [8] Wohlgemuth et al. (2006) [9] Osterwald and McMahon (2009) [10] Speer et al. (2010) [11] Vick and Clark (2005) [12] Radziemska (2003) [13] Mohring et al (2004) [14] Makrides et al. (2009) [15] Carr and Prior (2003) [16] Gottschalg et al. (2004) [17] Kurtz et al. (2009b) [18] Tanagnostopoulos and Themelis (2010) [19] Royne et al. (2005) [20] Goossens and Van Kerschaever (1999) [21] Harder and Gibson (2011) [22] Mohandes et al. (2009) [23] Thornton (1992) [24] Nelson (2003) [25] Armstrong and Hurley (2010) [26] Kelly and Gibson (2009) [27] DOE (2007) [28] Bradsher (2009) [29] Jacobson and Delucchi (2010) [30] Khosla (2008) [31] Richter et al. (2009 [32] Trieb et al. (2009) [33] Deutsche Gesellschaft für Sonnenenergie (2008)

Table 10-5: Impacts of CC and EWEs on wind power.

Type	Change in climatic or related attribute	Impact	Adaptation options
All	Windiness: total wind resource [1] (multi-year annual mean wind power densities); likely to remain within ±50% of current values in Europe and North America [2-6]; within ±25% of 1979-2000 historical values in contiguous USA [7]	Change in wind power potential [1]	Site selection
All	Inter-annual, seasonal, diurnal variability [1, 8-9]; changes unclear	Timing of power availability	Reserve capacity
All	Precipitation, thermal regime, near-surface humidity [10] (little information) affect icing frequency: decrease in northern Europe [12], within ±40% of historical values in North America [13], increasing in Great Lakes region [13]	Operation problems [11], reduced power output in Finland [47] weak correlation between icing and output in Norway [48]	Passive: blade design; active: blade heating [11, 14]
All	Lower air density due to higher air temperature [13]	Reduced power production	-
On	Dryer air causing more wind-blown dust [15]	Dust deposition on blades [16], reduced power output	Turbine design and coatings, increased blade maintenance [43, 17]
On	Higher temperatures causing permafrost melting	Access to affected region difficult (construction, maintenance, repair) [18]	Site selection
Off	Sea-level rise [13]	Turbine foundations inundated	Consider SLR in design
Off	Increasing sea salinity	Corrosion [19]	Material choice, corrosion protection
Off	Changes in wave activity and wind-wave coupling [34] (highly uncertain); increasing wave activity in Northeast Atlantic [38], Baltic [32] but decreasing in Mediterranean Sea [40]	Structural damages and failure	Design specifications [35]
	Changes in sea-ice: declining [12, 42, 44]	Turbine foundation loading [41]	Support structure [36], construction material [37]
	Extreme weather events		
All	Wind speed extremes [20-23]: gust, direction change, shear [13]; increasing in Germany [24], associated with deep convective conditions in North America [25], southern Europe and southern Africa [26]	Structural integrity from high structural loads [27]; fatigue, damage to turbine components [13]; reduced output [28]	Turbine design [29-32], lidar-based protection [33]
All	Extreme low and high temperatures	Physical properties (expansion) of materials and fluids [13]	Turbine selection, lubricant selection [13]
All	Changing lightning frequency (direction unclear)	Damage to blades, mechanical and electrical components [13]	Lightning protection [45, 46]

Notes: On=onshore; off=offshore

Sources: [1] Pryor and Barthelmie (2010) [2] Bloom et al. (2008) [3] Pryor and Schoof (2010) [4] Pryor et al. (2006) [5] Sailor et al. (2008) [6] Walter et al. (2006) [7] Pryor and Barthelmie (2011b) [8] Pryor and Barthelmie (2003) [9] Pryor and Ledolter (2010) [10] Farzaneh (2008) [11] Hochart et al. (2008) [12] Clausen et al. (2007) [13] Pryor and

Barthelmie (2011a) [14] Tammelin and Seifert (2001) [15] de Vries (2009) [16] Corten and Veldkamp (2001) [17] Dalili et al. (2009) [18] Cheng (2005) [19] DNV/Risø (2002) [20] Haugen and Iversen (2008) [21] Leckebusch et al. (2008) [22] Christensen et al. (2007) [23] Pryor et al. (2011) [24] Pinto et al. (2010) [25] Lombardo et al. (2009) [26] Kruger et al. (2010) [27] Hand and Balas (2007) [28] Walter et al. (2009) [29] Bossanyi (2003a) [30] Bossanyi (2003b) [31] Jelavic and Peric (2009) [32] Kanev and van Engelen (2010) [33] de Vries (2010) [34] Barthelmie et al. (1999) [35] Saigal et al. (2007) [36] Colwell and Basu (2009) [37] van der Temple (2009) [38] Wang et al. (2004) [39] Meier (2006) [40] Lionello et al. (2008) [41] Mróz et al. (2008) [42] Vihma and Haapala (2009) [43] Corten and Veldkamp (2011) [44] Assel et al. (2003) [45] Cotton et al. (2001) [46] Rakov and Rachidi (2009) [47] Laakso et al. (2003) [48] Homola et al. (2008)

Table 10-6: Impacts of CC and EWEs on pipelines.

Type	Change in climatic or related attribute	Impact	Adaptation options
	Climate change		
	Melting permafrost	Destabilizing pillars, obstructing access for maintenance and repair [9]	Adjust design code and planning criteria, install disaster mitigation plans,
	EWEs		
	Increasing high wind, storms, hurricanes	Damage to offshore and onshore pipelines and related equipment, spills; lift and blow heavy objects against pipelines, damage equipment [1,3,7,10]	Enhance design criteria, update disaster preparedness
	Increasing heavy rain		
	Increasing lightning frequency	Piercing the pipeline, causing fire or explosion [11	
	Extreme high temperatures		
	Extreme low temperatures, ice	Offshore subsea pipelines winterization, cold flow assurance, ice conditions [4-6]	
	Flooding caused by heavy rain, storm surge or sea-level rise	Damage to pipelines, spills [2,8]	Siting (exclude flood plains), water proofing.
	Erosion, landslide or avalanche caused by heavy rain or snow	Can expose and rupture underground pipelines, damage to valves, pumping stations, river crossings, leading to spills, ignition of spilt oil, fire and air pollution [1-2]	
	Forest or bush fire caused by drought		

Sources: [1] Cruz and Krausmann (2011) [2] Vlasova and Rakitina (2010) [3] EEA (2005) [4] DeGeer (2010) [5] Sildnes (2008) [6] Mork (2007) [7] Cruz and Krausmann (2008) [8] Pascal (2010) [9] ACIA (2004) [10] Cruz et al. (2001) [11] Krausmann et al. (2011) [12] Renni et al. (2010a) [13] Renni et al. (2010b)

Table 10-7: Impacts of CC and EWEs on the electricity grid.

Type	Change in climatic or related attribute	Impact	Adaptation options
	Climate change		
	Increasing average temperature	Increased transmission line losses [1]	Include increasing temperature in the design calculation for maximum temperature/rating [1]
	EWEs		
All	Increasing high wind, storms, hurricanes	Direct mechanical damage to overhead lines, towers, poles, substations [1], 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 [2-5]	Adjust wind loading standards [1, 6], reroute lines alongside roads or across open fields [7], vegetation management [8-10], improved storm and hurricane forecasting [3, 11-13]
	Increasing heavy rain	Flashover faults across high voltage insulators [14]; short circuit in high voltage circuit breakers [1]	Improved design of insulators, siting and enhanced maintenance [1]
	Increasing lightning frequency	Flashover fault [5, 8, 10]	Add earth wire(s) above live conductors and to substations, fit spark gaps and surge arresters [6, 8, 15, 16]
	Extreme high temperatures	Lines and transformers may overheat and trip off; flashover to trees underneath expanding cable [6, 8]	Increase system capacity [8], increase tension in the line to reduce sag, add external coolers to transformers [6]
	Extreme low temperatures	Flashover caused by ice building up on insulators, switchgear or transformers	Improve insulator design [17-19]
	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 [6], reroute lines alongside roads or across open fields [7], improve forecasting of ice storms impacts on overhead lines [20] and on transmission circuits [21-24]
	Flooding caused by heavy rain, storm surge or sea-level rise	Damage to equipment at ground level (substations, transformers)	Improved insulator design, siting ground installations outside hazard zones [1]
	Landslide or avalanche based by heavy rain or snow	Damage to overhead line, underground cable, substation	Siting ground installations outside hazard zones [1]
	Forest or bush fire caused by drought	Damage to overhead line [5, 25, 26], flashover caused by smoke or combustion particles	Routing of transmission line, vegetation control [1]

Sources: [1] Ward (2011) [2] Davidson et al. (2003) [3] Winkler et al. (2010) [4] Reed (2008) [5]Hines et al (2010) [6] Baylis and Hardy (2007) [7] Martikainen et al. (2007) [8] Brown (2002) [9] IFC (2004) [10] EPRI (2006b) [11] Han et al. (2009) [12] Liu et al. (2008) [13] Bush (2008) [14] EPRI (2007) [15] EPRI (2006a) [16] EPRI (2004) [17] Gutman et al. (2002) [18] Berlijn et al. (2007a) [19] Berlijn et al. (2007b) [20] Musilek et al. (2009) [21] Broström and Söder (2005) [22] Broström and Söder (2007) [23] Broström et al. (2007) [24] Choinard & Erfani (2006) [25] Mitchell (2009) [26] Sunrise Powerlink Project (2008)

Table 10-8: Observed normalized insured losses from weather hazards.

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

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

Table 10-9: Climate change projections of insured losses.

Hazard / insurance line	Region	2021-2050 (2050s) relative to current climate	End of 21st century relative to current climate	References
Extratropical storm, Homeowners' insurance	Portugal/Spain France Switzerland UK/Ireland Germany North Rhine-Westphalia Belgium/Netherlands Sweden/Norway Poland Europe in general	-4% to -2% A1B [1] +2% to +9% A1B [1] - +6% to +13% A1B [1] +5% to +18% A1B [1] - +4% to +7% A1B [1] - +2% to +12% A1B [1] -	-10% to -5% A1B, A2 [1;3] +6% to +47% A1B, A2 [1;3;5] +19% A2 [5] +17% to +43% A1B, A2 [1;2;3;5;6] +15% to +114% A1B, A2 [1;2;3;5] +8% to +19% A1B, A2 [4] +8% to +80% A1B, A2 [1;5] +7% to +95% A1B, A2 [3;5] -23% to +12% A1B, A2 [1;5] +44% A2 [5]	[1] Donat et al., 2011; [2] Leckebusch et al., 2007; [3] Pinto et al., 2007; [4] Pinto et al., 2009; [5] Schwierz et al., 2009; [6] ABI, 2009.
Hail storm, Agricultural insurances	Netherlands	+1°C (+2°C) global mean temperature by 2050s: Outdoor farming insurance: +25% to +29% (+49% to +58%) Greenhouse horticulture insurance: +116% to +134% (+219% to +269%)		Botzen et al., 2010
Flood, Property insurance	United Kingdom	+2° global mean temperature (approx. 2040s according to A1B or A2) Mean annual loss +8% 100-year loss +18% 200-year loss +14%	+4° global mean temperature (approx. 2070s according to A1FI) Mean annual loss +14% 100-year loss +30% 200-year loss +32%	ABI, 2009
Typhoon, Property insurance	China	+2° global mean temperature (approx. 2040s according to A1B or A2) Mean annual loss +20% 100-year loss +7% 200-year loss +14%	+4° global mean temperature (approx. 2070s according to A1FI) Mean annual loss +32% 100-year loss +9% 200-year loss +17%	ABI, 2009
Storms, pests, diseases driven by climate, Paddy rice insurance	Japan		Decrease in rice yield in central and western Japan, increase in northern Japan. Paddy rice insurance payouts will decrease by 13%, caused by changed standard yield.	Iizumi et al., 2008

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

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

Challenges that increase in the climate change context	Example / Explanation
Failure to reflect temporal changes in hazard condition in risk management	Following the devastating 2004 and 2005 hurricane seasons, the losses of Florida's homeowners' insurance accumulated since 1985 exceeded the cumulative direct premiums earned by 31%. Consequence of the upswing and peak in hurricane activity: One insurer liquidated, two seized by regulation due to insolvency; reduced coverage availability in high-risk areas [9] .
Misguided incentives additionally increasing risk	US National Flood Insurance Program (NFIP) could not prevent development of settlements in flood plains and suffers from non-risk-adequate premiums [1;6;7]. Plausible exlanation [13]: NFIP incentive scheme may reward affluent flood-plain residents who, influenced by increasing flood experience, pressure local governments to undertake flood-mitigation activities. Result: improved NFIP ratings and premium discounts, attracting prospective homeowners and businesses into high-risk flood plains by reduced insurance rates [13].
Non-quantifiable uncertainties increasing risk	Ambiguity as to what degree climate change may modify regional weather hazards – model projections are not unequivocal [2;3]. Uncertainty about prospects of post-disaster regulatory/jurisdictional pressures, e.g. to extend claims payments beyond the original coverage [9].
Liability insurance impacted by new climate risk	Chances for success of litigation in the U.S. where damages from greenhouse gas emissions are sought seem small, due to legal obstacles [4;5;8;12]. But defence costs can be high and may be covered by liability insurance. As CO2 emissions were declared pollution (US Supreme Court/EPA), regulation on limits for CO2 emissions is ongoing and non-compliance could impose liability for CO2 emissions in the near future, which will be covered by liability insurance. This pending risk has not yet been adequately taken into account, as was the case with escalating environmental liability claims in the late twentieth century [10;11].

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] Mills, 2009; [12] Steward and Willard, 2010; [13] Zahran et al., 2009

Table 10-11: Products and systems responding to changes in weather risks.

Response option	Example/Explanation
Risk-adjusted premiums convey the risk to the insureds, encouraging them to adaptive measures	According to an investigation, prior to Germany's disastrous River Elbe flood in 2002, 48.5% of insured households had obtained information on flood mitigation or were involved in emergency networks and 28.5% implemented one of several mitigation measures compared with 33.9% and 20.5%, respectively, of uninsured households [35].
Conditions of insurance policies incentivizing vulnerability reduction	Premium discounts for compliance with local building codes or other prevention options [36]; long-term natural-hazard insurance tied to the property and linked to mortgages and loans granted for prevention measures [24;25]; share of the insured in claims payment payments by deductibles or upper coverage limits; exclusion of systematically affected property [1;6;7;8;9;12;18;35].
Coverage for buildings following so-called green standards	Green residential policies covering new green buildings or upgrades to green building standards, following losses or by way of normal renovation. Nevertheless, those standards' damage reducing feature remains uncertain [18;32].
Consideration of temporal changes in hazard condition (non-stationary behavior)	[11] presents an illustrative example on the recurrence period of US tornado losses in excess of US$ 3bn, that dropped from almost 90 years in 1980 to almost 60 years in 2000 (including effects from climate and increase in wealth); see also [21;34;37].
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 [33].
Enhanced disaster resilience prescribed to insurers' risk management in Europe and USA	USA: regulatory capital requirements for disaster risk are absent [16]; rating agencies require insurers to reflect enhanced hurricane incidence since mid-1990s in catastrophe models and guarantee liquidity for more than one severe catastrophe per year, e.g. two 100-year hurricane losses [24]. Under upcoming Solvency II regulations in Europe, insurers have to guarantee liquidity for 200-year losses [31].
Insurance associations projecting climate change driven market-wide losses	[2;3;14] [PLACEHOLDER - there will be two publications from the GDV by 2012 inferring recommendations on adaptive strategies for insurers from projected future losses]
Diversifying large disaster risk across securitization markets	Following the hurricane disasters of 2004 and 2005, securitisation instruments, e.g. catastrophe bonds, industry loss warranties and sidecars acquired greater prominence and have been recovering again from the market break of the financial crisis [17]. Catastrophe bonds, covering part of the exposure to disaster losses, are designed so that in the absence of a large catastrophe the investor receives an above-market return. If a parametric trigger point is exceeded, e.g. an index based on observed gust wind speeds, the (re)insurer's obligation to pay the interest and/or principal is waived. The (re)insurer can use the funds to cover the corresponding losses. Weather derivatives are further instruments used to transfer risks to the capital markets [13;26;31].
Index-based weather crop insurance products	Index-based crop insurance is available in 40% of middle-income countries, with enlarged systems beyond pilot impelmentation only in India and Mexico [29;22]. There are schemes coupled with access to advanced technology [5;12;22;29]. Various schemes exist – often in pilot form – or have been proposed for cumulative rainfall, cumulative temperature, vegetation index, livestock mortality per region, or cumulative reservoir inflow for irrigation purposes [5;26;28]. Pooling local schemes across climate regions can reduce risk capital requirements [10;30]. The disaster risk layer and high start-up costs (weather-data collection, risk modelling, education) necessitate subsidies from the state or donors [12;20].
Improvements to basis risk coupled to index-based weather insurance	Basis risk can be strongly reduced if the index scheme is applied to an area-yield trigger in a region with homogeneous production potential and/or to the uppermost disaster risk layer only. Further on, it can be absorbed if the index insurance works at

	aggregate level, e.g. to cover crop-credit portfolios or cooperatives, and if once satellite-based remote-sensing technology can be used to establish plot identification, vegetation status, yield estimation and loss assessment [19]
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 [4]. This theory proved inadequate if applied to relatively vulnerable small-sized middle to low-income countries [15], thereby rehabilitating sovereign insurance. For the Caribbean scheme CCRIF, that pools states, the reduction in premium cost per country is estimated to be 45–50% [28]. Pooling natural catastrophe risks across an array of megacities has also been proposed, but not yet implemented [23].

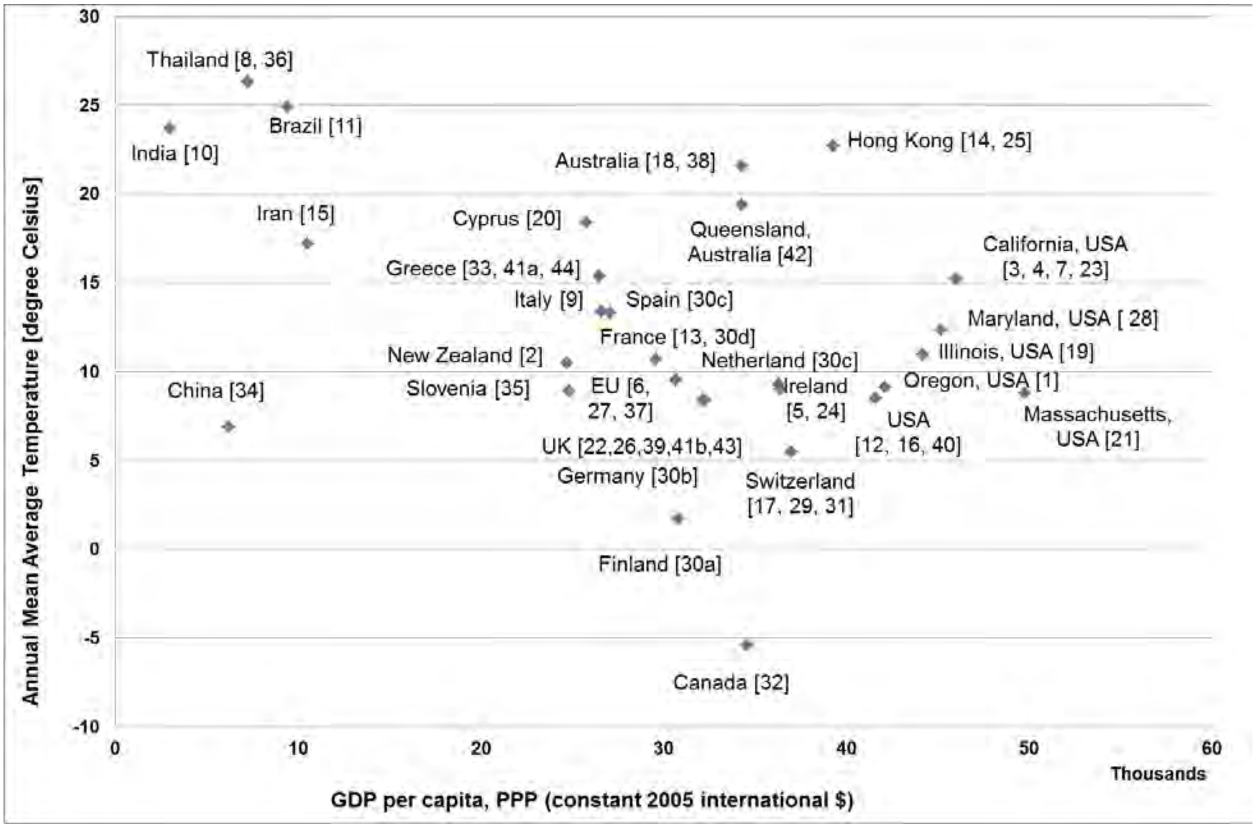
References: [1] Aakre et al., 2010; [2] ABI, 2005; [3] ABI, 2009; [4] Arrow and Lind, 1970; [5] Barnett et al., 2008; [6] Botzen and van den Bergh, 2008; [7] Botzen and van den Bergh, 2009; [8] Botzen et al., 2009; [9] Botzen et al., 2010a; [10] Candel, 2007; [11] Charpentier, 2008; [12] Collier et al., 2009; [13] Cummins and Mahul, 2009; [14] [GDV, 2012]; [15] Ghesquiere and Mahul, 2007; [16] Grace and Klein, 2009; [17] Guy Carpenter, 2011; [18] Hecht, 2008; [19] Herbold, 2010; [20] [Herbold, 2011]; [21] Herweijer et al., 2009; [22] Hess and Hazell, 2009; [23] Hochrainer and Mechler, 2011; [24] Kunreuther et al., 2009; [25] Kunreuther and Michel-Kerjan, 2009; [26] Leiva and Skees, 2008; [27] Linnerooth-Bayer et al., 2009; [28] Linnerooth-Bayer and Mechler, 2009; [29] Mahul and Stutley, 2010; [30] Meze-Hausken et al., 2009; [31] Michel-Kerjan and Morlaye, 2008; [32] Mills, 2009; [33] Muir-Wood and Grossi, 2008; [34] [Sander et al., 2012]; [35] Thieken et al., 2006; [36] Ward et al., 2008; [37] Watson and Johnson, 2008.

Table 10-12: Governance, public-private partnerships, and insurance market regulation.

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

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

Figure 10-1: Demand.



Sources: [1] Hamlet et al. (2010) [2] Chen and Lie (2010) [3] Franco and Sanstad (2008) [4] Vine (2008) [5] Semmler et al. (2009) [6] Aaheim et al. (2009) [7] Lebassi et al. (2010) [8] Parkpoom and Harrison (2008) [9] Beccali et al. (2007) [10] Akpinar-Ferrand and Singh (2010) [11] De Lucena et al. (2010) [12] Mansur et al. (2008) [13] Dubus (2010) [14] Wong et al. (2010) [15] Delfani et al. (2010) [16] Scott and Huang (2007) [17] Christenson et al. (2006) [18] Wang et al. (2010) [19] Hayhoe et al. (2010) [20] Zachariadis (2010) [21] Amato et al. (2005) [22] Jenkins et al. (2008) [23] Miller et al. (2008) [24] Liu and Twumasi (2008) [25] Lam et al. (2010) [26] Wu and Pett (2006) [27] Eskeland et al. (2008) [28] Ruth and Lin (2006) [29] Frank (2005) [30] Pilli-Sihvola et al. (2010) [31] Aebischer et al. (2007) [32] Zmeureanu and Renaud (2008) [33] Mirasgedis et al. (2007) [34] Asadoorian et al. (2008) [35] Dolinar et al. (2010) [36] Wangpattarapong et al. (2008) [37] Eskeland and Mideksa (2009) [38] Thatcher (2007) [39] Chow and Levermore (2010) [40] Dergiades and Tsoulfidis (2008) [41] Psiloglou et al. (2009) [42] Ziser et al. (2010) [43] Collins et al. (2010) [44] Mirasgedis et al. (2006)