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Key Economic Sectors and Services

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Executive Summary

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

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

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

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

Climate change may influence the integrity and reliability of pipelines and electricity grids (*medium evidence*, *medium agreement*). Pipelines and electric transmission lines have been designed and operated for more than a century in diverse and often extreme climatic conditions on land from hot deserts to permafrost areas and increasingly at sea. Owing to the private nature and high economic value to the energy sector, they have been designed to higher tolerance levels than most transportation infrastructure. Climate change may require changes in design standards for the construction and operation of pipelines and power transmission and distribution lines. Adopting existing technology from other geographical and climatic conditions may reduce the cost of adapting new infrastructure as well as the cost of retrofitting existing pipelines and grids to the changing climate, sea level, and weather conditions, which is likely to become more intense over time. {10.2}

Climate change will have impacts, positive and negative and varying in scale and intensity, on water supply infrastructure and water demand (*robust evidence*, *high agreement*), but the economic implications are not well understood. Economic impacts include flooding, scarcity, and cross-sectoral competition. Flooding can have major economic costs, both in term of impacts (capital destruction, disruption) and adaptation (construction, defensive investment). Water scarcity and competition for water—driven by institutional, economic, or social factors—may mean that water is not available in sufficient quantity or quality for some uses or locations. {10.3}

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

Climate change will affect tourism resorts, particularly ski resorts, beach resorts, and nature resorts (*robust evidence*, *high agreement*) and tourists may spend their holidays at higher altitudes and latitudes (*medium evidence*, *high agreement*). The economic implications of climate change-induced changes in tourism demand and supply entail gains for countries closer to the poles and higher up the mountains and losses for other countries. The demand for outdoor recreation is affected by weather and climate, and impacts will vary geographically and seasonally. {10.6}

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

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

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

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

Global economic impacts from climate change are difficult to estimate. Economic impact estimates completed over the past 20 years vary in their coverage of subsets of economic sectors and depend on a large number of assumptions, many of which are disputable, and many estimates do not account for catastrophic changes, tipping points, and many other factors. With these recognized limitations, the incomplete estimates of global annual economic losses for additional temperature increases of ~2°C are between 0.2 and 2.0% of income (±1 standard deviation around the mean) (*medium evidence*, *medium agreement*). Losses are *more likely than not* to be greater, rather than smaller, than this range (*limited evidence*, *high agreement*). Additionally, there are large differences between and within countries. Losses accelerate with greater warming (*limited evidence*, *high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above. Estimates of the incremental economic impact of emitting carbon dioxide lie between a few dollars and several hundreds of dollars per tonne of carbon (*robust evidence*, *medium agreement*). Estimates vary strongly with the assumed damage function and discount rate. {10.9}

Not all key economic sectors and services have been subject to detailed research. Few studies have evaluated the possible impacts of climate change on mining, manufacturing, or services (apart from health, insurance, and tourism). Further research, collection, and access to more detailed economic data and the advancement of analytic methods and tools will be required to assess further the potential impacts of climate on key economic systems and sectors. {10.5, 10.8, 10.10}

10.1. Introduction and Context

This chapter discusses the implications of climate change on key economic sectors and services, for example, economic activity. Other chapters discuss impacts from a physical, chemical, biological, or social perspective. Economic impacts cannot be isolated; therefore, there are a large number of cross-references to sections in other chapters of 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? What is the effect on the overall economy, and on welfare?

An inclusive approach was taken, discussing all sectors of the economy. Section SM10.1 found in this chapter's on-line supplementary material shows the list of sectors according to the International Standard Industrial Classification. This assessment reflects the breadth and depth of the state of knowledge across these sectors; many of which have not been evaluated in the literature. We extensively discuss five sectors: energy (Section 10.2), water (Section 10.3), transport (Section 10.4), tourism (Section 10.6), and insurance (Section 10.7). Other primary and secondary sectors are discussed in Section 10.5, and Section 10.8 is devoted to other service sectors. Food and agriculture is addressed in Chapter 7. Sections 10.2 through 10.8 discuss individual sectors in isolation. Markets are connected, however. Section 10.9 therefore assesses the implications of changes in any one sector on the rest of the economy. It also discusses the effect of the impacts of climate change on economic growth and development. Chapter 19 assesses the impact of climate change on economic welfare—that is, the sum of changes in consumer and producer surplus, including for goods and services not traded within the formal economy. This is not attempted here. The focus is on economic activity. Section 10.10 discusses whether there may be vulnerable sectors that have yet to be studied.

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

10.2. Energy

Studies conducted since AR4 and assessed here confirm the main insights about the impacts of climate change on energy demand as reported in the Second Assessment Report (SAR; Acosta et al., 1995) and reinforced by the Third Assessment Report (TAR; Scott et al., 2001) and AR4 (Wilbanks et al., 2007): ceteris paribus, in a warming world, energy demand for heating will decline and energy demand for cooling will increase; the balance of the two depends on the geographic, socioeconomic, and technological conditions. The relative importance of temperature changes among the drivers of energy demand varies across regions and will change over time. Earlier IPCC assessments did not write much about energy supply, but an increasing number of studies now explore its vulnerability, impacts, and adaptation options (Karl et al., 2009; Troccoli, 2010; Ebinger and Vergara, 2011). The energy sector will be transformed by climate policy (WGIII AR5 Chapter 7) but impacts of climate changes too will be important for secure and reliable energy supply.

10.2.1. Energy Demand

Most studies conducted since AR4 explore the impacts of climate change on residential energy demand, particularly electricity (Mideksa and Kallbekken, 2010). Some studies encompass the commercial sector as well but very few deal with industry and agriculture. In addition to a few global studies based on global energy or integrated assessment models, the new studies tend to focus on specific countries or regions (Zachariadis, 2010; Olonscheck et al., 2011), rely on improved methods (more advanced statistical techniques; de Cian et al., 2013) and data (both

Frequently Asked Questions

FAQ 10.1 | Why are key economic sectors vulnerable to climate change?

Many key economic sectors are affected by long-term changes in temperature, precipitation, sea level rise, and extreme events, all of which are impacts of climate change. For example, energy is used to keep buildings warm in winter and cool in summer. Changes in temperature would thus affect energy demand. Climate change also affects energy supply through the cooling of thermal plants, through wind, solar, and water resources for power, and through transport and transmission infrastructure. Water demand increases with temperature but falls with rising carbon dioxide (CO_2) concentrations as CO_2 fertilization improves the water use efficiency plant respiration. Water supply depends on precipitation patterns and temperature, and water infrastructure is vulnerable to extreme weather, while transport infrastructure is designed to withstand a particular range of weather conditions, and climate change would expose this infrastructure to weather outside historical design criteria. Recreation and tourism are weather-dependent. As holidays are typically planned in advance, tourism depends on the *expected* weather and will thus be affected by climate change. Health care systems are also impacted, as climate change affects a number of diseases and thus the demand for and supply of health care.

historical and regional climate projections), and many of them explicitly include non-climatic drivers of energy demand (e.g., sources). A few studies consider changes in demand together with changes in climate-dependent energy sources, such as hydropower (Hamlet et al., 2010).

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

At the global scale, energy demand for residential air conditioning in summer is projected to increase rapidly in the 21st century under the reference climate change scenario (medium population and economic growth globally, but faster economic growth in developing countries; no mitigation policies in addition to those in place in 2008) by the Targets IMAGE Energy Regional Model/Integrated Model to Assess the Global Environment (TIMER/IMAGE) model (Isaac and Van Vuuren, 2009). The increase is from nearly 300 TWh in 2000 to about 4000 TWh in 2050 and more than 10,000 TWh in 2100, about 75% of which is due to increasing income in emerging market countries and 25% is due to climate change. Energy demand for heating in winter increases too, but much less rapidly, since in most regions with the highest need for heating, incomes are already high enough for people to heat their homes to the desired comfort level (except in some poor households). In these regions, energy demand for heating will decrease.

These general patterns and especially the quantitative results of the projected shifts in energy and electricity demand can be modified by many other factors. In addition to changes in temperatures and incomes, the actual energy demand will be influenced by changes in demographics (upward by increasing population and decreasing average household size, mixed effects from urbanization), lifestyles (upward by larger floor area of dwellings), building codes and regulations for the design and insulation of the housing stock, the energy efficiency of heating/cooling devices, the abundance and energy efficiency of other electric household appliances, the price of energy, and so forth.

10.2.2. Energy Supply

Changes in climate attributes (temperature, precipitation, windiness, cloudiness, etc.) will affect different energy sources and technologies differently. Gradual climate change will progressively affect the operation of energy installations and infrastructure over time. Possible changes in the frequency and intensity of extreme weather events (EWEs) as a result of climate change represent a different kind of hazard for them. (EWEs are weather events that are rare at a particular place and time of the year; they are usually defined as rare or rarer than the 10th and 90th percentiles of a probability density function estimated from observations; see Glossary). Rummukainen (2013) and Mika (2013) summarize recent trends and prospects relevant for the energy sector. This section assesses the most important impacts and adaptation options in both categories. Table 10-1 provides an overview.

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

A general impact of climate change on thermal power generation (including combined heat and power) is the decreasing efficiency of thermal conversion as a result of rising temperature that cannot be offset per se. Yet there is much room to improve the efficiency of currently operating subcritical steam power plants (IEA, 2010b). As new materials allow higher operating temperatures in coal-fired power plants (Gibbons, 2012), supercritical and ultra-supercritical steam-cycle plants (operating at much higher pressure and temperature conditions than conventional power plants) will reach even higher efficiency that can more than compensate the efficiency losses due to higher temperatures. Yet in the absence of climate change, these efficiency gains from improved technology would reduce the costs of energy, so there is still a net economic loss due to climate change. Another problem facing thermal power generation in many regions is the decreasing volume and increasing temperature of water for cooling, leading to reduced power generation, operation at reduced capacity, and even temporary shutdown of power plants (Ott and Richter, 2008; Hoffmann et al., 2010; IEA, 2012; Sieber, 2013). Both problems will be exacerbated if carbon dioxide (CO_2) capture and handling equipment is added to fossil-fired power plants: energy efficiency declines by 8 to 14% (IPCC, 2005) and water requirement per MWh electricity generated can double (Macknick et al., 2011). Using partial equilibrium river basin models, (Hurd et al., 2004; Strzepek et al., 2013) estimate USA welfare loses due to thermal cooling water changes at US$622 million per year up to 2100, a 6.5% welfare loss in the energy sector. Van Vliet et al. (2012) find that the southeastern United States, Europe, eastern China, southern Africa, and southern Australia could potentially be affected by reduced water available for thermoelectric power and drinking water, inducing changes to dry or hybrid cooling (with concomitant loss in electric output), or plant shut downs, with associated impacts on local and regional economic activity.

Adaptation possibilities range from relatively simple and low-cost options such as exploiting non-traditional water sources and re-using process water to measures such as installing dry cooling towers, heat pipe exchangers, and regenerative cooling (Ott and Richter, 2008; De Bruin et al., 2009), all which increase costs. Water use regulation, heat

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

Technology	Changes in climatic or related attributes	Possible impacts	Adaptation options
Thermal and nuclear power plants	Increasing air temperature	Reduces efficiency of thermal conversion by 0.1–0.2% in the USA; by 0.1–0.5% in Europe, where the capacity loss is estimated in the range of 1–2% per 1°C temperature increase, accounting for decreasing cooling efficiency and reduced operation level/shutdown	Siting at locations with cooler local climates where possible
	Changing (lower) precipitation and increasing air temperature increases temperature and reduces the availability of water for cooling.	Less power generation; annual average load reduction by 0.1–5.6% depending on scenario	Use of non-traditional water sources (e.g., water from oil and gas fields, coal mines and treatment, treated sewage); re-use of process water from flue gases (can cover 25–37% of the power plant's cooling needs), coal drying, condensers (drier coal has higher heating value, cooler water enters cooling tower), flue-gas desulfurization; using ice to cool air before entering the gas turbine increases efficiency and output, melted ice used in cooling tower; condenser mounted at the outlet of cooling tower to reduce evaporation losses (by up to 20%). Alternative cooling technologies: dry cooling towers, regenerative cooling, heat pipe exchangers; costs of retrofitting cooling options depend on features of existing systems, distance to water, required additional equipment, estimated at US$250,000–500,000 per megawatt
	Increasing frequency of extreme hot temperatures	Exacerbating impacts of warmer conditions: reduced thermal and cooling efficiency; limited cooling water discharge; overheating buildings; self-ignition of coal stockpiles	Cooling of buildings (air conditioning) and of coal stockpiles (water spraying)
	Drought: reduced water availability	Exacerbating impacts of warmer conditions, reduced operation and output, shutdown	Same as reduced water availability under gradual climate change
Hydropower	Increase/decrease in average water availability	Increased/reduced power output	Schedule release to optimize income
	Changes in seasonal and inter-annual variation in inflows (water availability)	Shifts in seasonal and annual power output; floods and lost output in the case of higher peak flows	Soft: adjust water management Hard: build additional storage capacity, improve turbine runner capacity
	Extreme precipitation causing floods	Direct and indirect (by debris carried from flooded areas) damage to dams and turbines, lost output due to releasing water through bypass channels	Soft: adjust water management Debris removal Hard: increase storage capacity
Solar energy	Increasing mean temperature	Improving performance of TH (especially in colder regions), reducing efficiency of PV and CSP with water cooling; PV efficiency drops by ~0.5% per 1°C temperature increase for crystalline silicon and thin-film modules as well, but performance varies across types of modules, with thin film modules performing better; long-term exposure to heat causes faster aging.	
	Changing cloudiness	Increasing unfavorable (reduced output), decreasing beneficial (increased output) for all types, but evacuated tube collectors for TH can use diffuse insolation. CSP more vulnerable (cannot use diffuse light)	Apply rougher surface for PV panels that use diffuse light better; optimize fixed mounting angle for using diffuse light, apply tracking system to adjust angle for diffuse light conditions; install/increase storage capacity
	Hot spells	Material damage for PV, reduced output for PV and CSP; CSP efficiency decreases by 3–9% as ambient temperature increases from 30 to 50°C and drops by 6% (tower) to 18% (trough) during the hottest 1% of time	Cooling PV panels passively by natural air flows or actively by forced air or liquid coolants
	Hail	Material damage to TH: evacuated tube collectors are more vulnerable than flat plate collectors. Fracturing as glass plate cover, damage to photoactive material	Flat plate collectors: using reinforced glass to withstand hailstones of 35 mm (all of 15 tested) or even 45 mm (10 of 15 tested); only 1 in 26 evacuated tube collectors withstood 45-mm hailstones. Increase protection to current standards or beyond them
Wind power	Windiness: total wind resource (multi-year annual mean wind power densities); likely to remain within ±50% of current values in Europe and North America; within ±25% of 1979–2000 historical values in contiguous USA	Change in wind power potential	Site selection
	Wind speed extremes: gust, direction change, shear	Structural integrity from high structural loads; fatigue, damage to turbine components; reduced output	Turbine design, lidar-based protection

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

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

discharge restrictions, and occasional exemptions might be an institutional adaptation (Eisenack and Stecker, 2012). Though it is easier to plan for changing climatic conditions and select the site and the conforming cost-efficient cooling technology for new builds, response options are more limited for existing power plants, especially for those toward the end of their economic lifetime.

Climate change impacts on thermal efficiency and cooling water availability affect nuclear power plants as well but the safety regulations are stricter than for fossil-fired plants (Williams and Toth, 2013). A range of alternative cooling options are available to deal with water deficiency, ranging from re-using wastewater and recovering evaporated water (Feeley III et al., 2008) to installing dry cooling (EPA, 2001).

The implications of EWEs for nuclear plants can be severe if not properly addressed. Reliable interconnection (on-site power and instrumentation connections) of intact key components (reactor vessel, cooling equipment, control instruments, back-up generators) is indispensable for the safe operation and/or shutdown of a nuclear reactor. For most of the existing global nuclear fleet, a reliable connection to the grid for power to run cooling systems and control instruments in emergency situations is another crucial item (IAEA, 2011). Several EWEs can damage the components or disrupt their interconnections. Preventive and protective measures include technical and engineering solutions (circuit insulation, shielding, flood protection) and adjusting operation to extreme conditions (reduced capacity, shutdown) (Williams and Toth, 2013).

Hydropower is by far the largest of renewable energy sources in the current electricity mix. It is projected to remain important in the future, irrespective of the climate change mitigation targets in many countries (IEA, 2010a,b). The resource base of hydropower is the hydrologic cycle driven by prevailing climate and topology. The former makes the resource base and hence hydropower generation highly dependent on future changes in climate and related changes in extreme weather events (Ebinger and Vergara, 2011; Mukheibir, 2013).

Assessing the impacts of climate change on hydropower generation is highly complex. A series of nonlinear and region-specific changes in mean annual and seasonal precipitation and temperatures, the resulting evapotranspiration losses, shifts in the share of precipitation falling as snow and the timing of its release from high elevation, and the climate response of glaciers make resource estimates difficult (see Chapters 2 and 3) while regional changes in water demand due to changes in population and economic activities (especially irrigation demand for agriculture) present competition for water resources that are hard to project (see Section 10.3). Further complications stem from the possibly increasing need to combine hydropower generation with changing flood control and ecological (minimum dependable flow) objectives induced by changing climate regimes. For hydropower locations, adaption to climate change to maintain output has been reported; in Ethiopia, Block and Strzepek (2012) report that capital expenditures through 2050 may either decrease by approximately 3% under extreme wet scenarios or increase by up to 4% under a severe dry scenario. In the Zambezi river basin, hydropower may fall by 10% by 2030, and by 35% by 2050 under the driest scenario (Strzepek et al., 2012). Lower generation is likely in the upstream power stations of the Zambezi basin and increases are *likely* downstream (Fant et al., 2013).

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

Solar energy is expected to increase from its currently small share in the global energy balance across a wide range of mitigation scenarios (IEA, 2008, 2009, 2010a,b). The three main types of technologies for harnessing energy from insolation include thermal heating (TH; by flat plate, evacuated tube, and unglazed collectors), photovoltaic (PV) cells (crystalline silicon and thin film technologies), and concentrating solar power (CSP; power tower and power trough producing heat to drive a steam turbine for generating electricity). The increasing body of literature exploring the vulnerability and adaptation options of solar technologies to climate change and EWEs is reviewed by Patt et al. (2013).

All types of solar energy are sensitive to changes in climatic attributes that directly or indirectly influence the amount of insolation reaching them. If cloudiness increases under climate change (WGI AR5 Chapters 11, 12), the intensity of solar radiation and hence the output of heat or electricity would be reduced. Efficiency losses in cloudy conditions are less for technologies that can operate with diffuse light (evacuated tube collectors for TH, PV collectors with rough surface). Since diffuse light cannot be concentrated, CSP output would cease under cloudy conditions but the easy and relatively inexpensive possibility to store heat reduces this vulnerability if sufficient volume of heat storage is installed (Khosla, 2008; Richter et al., 2009).

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

Climate change and EWE hazards per se do not pose any particular constraints for the future deployment of solar technologies. Technological development continues in all three solar technologies toward new designs, models, and materials. An objective of these development efforts is to make the next generation of solar technologies less vulnerable to existing physical challenges, changing climatic conditions, and the impacts of EWEs. Technological development also results in a diverse portfolio of models to choose from according to the climatic and

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weather characteristics of the deployment site. These development efforts can be integrated in addressing the key challenge for solar technologies today: reducing the costs.

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

The key question concerning the impacts of a changing climate regime on wind power is related to the resource base: how climate change will rearrange the temporal (inter- and intra-annual variability) and spatial (geographical distribution) characteristics of the wind resource. In the next few decades, wind resources (measured in terms of multi-annual wind power densities) are estimated to remain within the ±50% of the mean values over the past 20 years in Europe and North America (Pryor and Barthelmie, 2010). The wide range of the estimates results from the circulation and flow regimes in different General Circulation Models (GCMs) and Regional Climate Models (RCMs) (Bengtsson et al., 2006; Pryor and Barthelmie, 2010). A set of four GCM-RCM combinations for the period 2041–2062 indicates that average annual mean energy density will be within ±25% of the 1979–2000 values in all 50-km grid cells over the contiguous USA (Pryor et al., 2011; Pryor and Barthelmie, 2013). Yet, little is known about changes in the interannual, seasonal, or diurnal variability of wind resources.

Wind turbines already operate in diverse climatic and weather conditions. As shown in Table 10-1, siting, design, and engineering solutions are available to cope with various impacts of gradual changes in relevant climate attributes over the coming decades. The requirements to withstand extreme loading conditions resulting from climate change are within the safety margins prescribed in the design standards, although load from combinations of extreme events may exceed the design thresholds (Pryor and Barthelmie, 2013). In summary, the wind energy sector does not face insurmountable challenges resulting from climate change.

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

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

10.2.3. Transport and Transmission of Energy

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

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

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

Table 10-2 | Main impacts of climate change and extreme weather events on pipelines and the electricity grid.

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

Sources: Bayliss (1996); Krausmann and Mushtaq (2008); Reed (2008); Hines et al. (2009); Winkler et al. (2010); Vlasova and Rakitina (2010); McColl (2012); Cruz and Krausmann (2013); Ward (2013).

Owing to the very function of the electricity grid to transmit power from generation units to consumers, the bulk of its components (overhead lines, substations, transformers) are located outdoors and exposed to EWE. The power industry has developed numerous technical solutions and related standards to protect assets and provide reliable electricity supply under existing climate and weather conditions worldwide. However, these assets and the reliability of supply may be vulnerable to changes in the frequency and intensity of EWEs under changing climate conditions (DOE, 2013). Higher average temperatures increase transmission efficiency and reduce current carrying capacity, but this effect is relatively small compared to the physical and monetary damages that can be caused by EWEs (Ward, 2013). Historically, high wind conditions, including storms, hurricanes, and tornados, have been the most frequent cause of grid disruptions (mainly due to damages to the distribution networks); and more than half of the damage was caused by trees (Reed, 2008). Other impacts include freezing precipitation, ice and winter storms, wildfires caused by higher temperatures, less precipitation, and increased tree death caused by pests. If the frequency and power of high wind conditions, as well as extreme precipitation events, will increase in the future, vegetation management along existing power lines, and rerouting new transmission lines along roads or across open fields or moving them underground might help reduce related risks. An important institutional option is to redefine technical standards to provide incentives for grid operators to implement appropriate adaptation measures. Such measures are less expensive to implement as part of the maintenance-renewal cycle than as independent retrofit measures.

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

10.2.4. Macroeconomic Impacts

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

Assessing across a broad array of studies that focus on different regions and regional divisions, examine different climate change impacts, include a different mix of sectors, model different time frames, make different assumptions about adaptation, and employ different types of models with different output metrics leads to the overall conclusion that the macroeconomic impact of climate change on energy demand is *likely* to be minimal in developed countries (Bosello et al., 2007a, 2009; Aaheim et al., 2009; Jochem et al., 2009; Eboli et al., 2010).

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

Table 10-3 | Economy-wide implications of impacts of climate change and extreme weather on the energy sector.

Study	Model type	Climate impacts modeled	Energy/economic impacts	Regions	Sectors studied
Bosello et al. (2009)	IAM	Rising temperatures/changing demand for energy; impacts from four other sectors/events (Global, 2001–2050)	Change in gross domestic product (GDP) in 2050 due to rising temperatures and changing energy demand: 0–0.75% (+1.2°C); –0.1% to 1.2% (+3.1°C)	14	4
Jorgenson et al. (2004)	CGE	Rising temperatures/changing demand for energy; climate impacts from three other sectors (USA, 2000–2100)	Optimistic adaptation: 4–6.7% higher energy productivity per year (2000–2100) Output from electricity: –6% in 2050; GDP is +0.7% (aggregate all sectors, average annual 2000–2100) Pessimistic adaptation: 0.5–2.2% lower energy productivity per year Output from electricity: +2% in 2050; GDP is –0.6% (aggregate impact all sectors)	1	35
Bosello et al. (2007a)	CGE	Rising temperatures/changing demand for energy (Global, 2050)	Change in GDP in 2050 (perfect competition): –0.297% to 0.027% Change in GDP in 2050 (imperfect competition): –0.303% to 0.027%	8	1
Aaheim et al. (2009)	CGE	Change in precipitation affects share of hydroelectric power; rising temperatures/changing demand for energy; impacts from four other sectors (Western Europe, 2071–2100)	Impact from all sectors in 2100: GDP in cooler regions: –1% to –0.25% GDP in warmer regions: –3% to –0.5% Adaptation can mitigate 80–85% of economic impact	8	11
Boyd and Ibarraran (2009)	CGE	Drought scenario affecting hydroelectric plus three other sectors (Mexico, 2005–2026)	• Generation output in 2026: –2.1% • Refining output: –10.1% • Coal output: –7.8% • NG output: –2% • Crude oil output: +1.7% • GDP: –3% With adaptation: • Generation output in 2026: 0.24% • Refining output: 1.36% • Coal output: 1.09% • NG output: 0.34% • Crude oil output: 0.22% • GDP: 0.33%	1	2
Jochem et al. (2009)	PE/CGE	Rising temperatures/changing demand for energy; change in technical potential of renewables; change in rainfall induces change in hydroelectric production; high temperatures induce water temperatures exceeding regulatory limits (Europe); high temperatures induce greater electric grid losses and lower thermal efficiency; generic extreme events induce reduced capital stock in CGE model (EU27+2, 2005–2050)	• GDP (Europe): –50 billion € p.a. in 2035 • GDP (Europe): –240 billion € p.a. in 2050 • GDP (EU regions): –0.1% to –0.4% in 2035 • GDP (EU regions): –0.6% to –1.3% in 2050 • Jobs (Europe): –380K in 2035 • Jobs (Europe): –1 million in 2050	25	1
Eboli et al. (2010a)	CGE	Rising temperatures/changing demand for energy; climate impacts in four other sectors modeled (Global, 2002–2100)	By 2100, change in GDP due to climate impacts on energy demand vary by country between about –0.15% and 0.7%. USA and Japan were negative and all other countries positive. Overall economic impact from all sectors is neutral to positive for developed countries and negative for developing ones.	8	17
Golombek et al. (2011)	PE	Rising temperatures/changing demand for energy; rising temperatures/reduced thermal efficiency; change in water inflow (Western Europe, 2030)	Net impact on the price of electricity is a 1% increase. Generation decreases by 4%.	13	4
de Lucena et al. (2010)	PE	Changing precipitation induces change in hydroelectric production; rising temperatures induce lower NG thermal efficiency; rising temperatures induce change in demand for energy (Brazil, 2010–2035)	New generating capacity needed to produce additional 153–162 TWh per year. Capital investment of US$48–51 billion, which is equivalent to 10 years of capital expenditures in Brazil's long-term energy plan. US$6.9–7.2 billion in additional annual operating expenses for each year in which worst-case hydroelectric production occurs	1	11
Bye et al. (2008)	PE	Water shortages (Nordic countries, hypothetical 2-year period)	Water shortage scenarios can lead to a 100% increase in electricity prices at peak demand over a 2-year period. Higher prices lead to marginal reductions in demand (about 1–2.25%).	4	1
Koch et al. (2012)	PE	High temperatures induce water temperatures exceeding regulatory limits (Berlin, 2010–2050)	Thermal plant outages amounting to 60 million € for plants in Berlin through 2050	1	1
Gabrielsen et al. (2005)	Econometric	Rising temperatures/changing demand for energy; change in water inflow; change in wind speeds (Nordic countries, 2000–2040)	Net change in electricity supply in 2040: 1.8% Change in electricity demand: 1.4% Change in electricity price: –1.0%	4	1

Table 10-3 (continued)

Study	Model type	Climate impacts modeled	Energy/economic impacts	Regions	Sectors studied
UNDP (2011)	PE	Damage Case 1 (DC1): hotter in both winter and summer—decreased demand for heating and increased demand for cooling; Damage Case 2 (DC2): colder in both winter and summer—increased demand for heating and decreased demand for cooling; Damage Case 3 (DC3): colder in the winter and hotter in the summer—increased demand for heating and increased demand for cooling (Macedonia, 2009–2030)	Change in electricity demand in residential and commercial sectors: • DC1: 3.5% • DC2: 0.3% • DC3: 8% Change in electricity system cost: • DC1: 0.8% • DC2: 0.06% • DC3: 1.74%	9	5
DOE (2009)	PE	Drought scenario (Western Electric Coordinating Council, USA, 2010–2020)	In 2020, 3.7% reduction in coal generation; 43.4% increase in NG generation; 29.3% reduction in hydroelectric generation. Production cost increase of US$3.5 billion. Average monthly electricity prices up 8.1% (Nov) to 24.1% (July)	1	1

Note: The regions indicated in the Regions column vary in size and are model-specific. CGE = Computable General Equilibrium; PE = Partial Equilibrium; IAM = Integrated Assessment Model.

Despite the considerable number of potential climate change and extreme weather phenomena—higher mean temperatures, changes in rainfall patterns, changes in wind patterns, changes in cloud cover and average insolation, lightning, high winds, hail, sand storms and dust, extreme cold, extreme heat, floods, drought, fire, and SLR—and their potential impacts on electricity generation and transmission systems, fuel infrastructure and transport systems, and energy demand (Williams, 2013), the range of impacts modeled in the literature (Table 10-3) is quite limited. Most studies consider changing energy demand (specifically, changes in electricity and fuel consumption for space heating/cooling) resulting from rising temperatures as the only or primary climate change impact. These studies draw on recent literature refining the relationship between climate change and energy demand: the demand for natural gas and oil in residential and commercial sectors tends to decline with climate change because of less need for space heating, and demand for electricity tends to increase because of greater need for space cooling (Gabrielsen et al., 2005; Kirkinen et al., 2005; Mansur et al., 2005; Eskeland and Mideksa, 2010; Mideksa and Kallbekken, 2010; Rübbelke and Vögele, 2010).

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

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

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

Partial equilibrium models, by their nature, do not have a full macroeconomic representation and therefore rarely report changes in GDP. Instead, these models focus on details in the energy sector, such as price and quantity effects for fuels and electricity (and the mix of generation). For example, Rübbelke and Vögele (2013) conclude that the short-term effects of climate-related problems affecting water cooling and hydropower production can have negative distributional effects. de Lucena et al. (2010) find that rising temperature and changing precipitation lead to the need for an additional 153 to 162 TWh per year by 2035 with a capital investment of US$48 to 51 billion.

Golombek et al. (2011) report a 1% increase in the price of electricity for Western Europe in 2030 stemming from rising temperatures that affect demand and thermal efficiency of supply, as well as water inflow. UNDP (2011) finds between a 0.06% and 1.74% increase in electricity system costs for Macedonia resulting from temperature changes. Gabrielsen et al. (2005) conclude that for Nordic countries in 2040, as a result of rising temperatures that affect demand, changes in water inflow, and changes in wind speeds, the wholesale price of electricity will decline by 10%. Koch et al. (2012) conclude that thermal plant outages in Berlin resulting from heat wave-driven water temperatures that exceed regulatory limits can amount to a cumulative cost of about US$80 million over the period 2010 through 2050 for 2850 MW of capacity. Assuming an 80% capacity factor, the premium for high water temperatures in Berlin is US$0.1 per MWh. The magnitude of change in electricity price is small in each of the previously mentioned studies that evaluate gradual temperature increases.

In contrast, studies that consider shorter-term heat waves and water shortages find considerably higher price impacts. Bye et al. (2008) consider a hypothetical water shortage scenario—25% lower inflow over 2 years—in Nordic countries and conclude that the price of electricity can double over a 2-year period and then return to normal as water flow returns. McDermott and Nilsen (2013) find more generally that electricity prices in Germany increase by 1% for every degree that water temperatures rise above 25°C and by 1% for every 1% that river levels fall. DOE (2009) also finds that a drought scenario can lead to average monthly electricity prices that are 8.1% (November) to 24.1% (July) higher. Pechan and Eisenack (2013) find that an equivalent of the 2006 German heat wave can result in an increase in electricity prices of 11% or even 24% (affected plants running at minimum output) and 50% (affected plants at zero output).

10.2.5. Summary

The balance of evidence emerging from the literature assessed in this section suggests that climate change per se will likely increase the demand for energy in most regions of the world. At the same time, increasing temperature will decrease the thermal efficiency of fossil, nuclear, biomass, and solar power generation technologies (Mideksa and Kallbekken, 2010). However, gradual temperature-induced impacts on energy supply will probably make a relatively small contribution to the cost of energy and electricity. Acute heat waves and droughts can have a much greater, albeit short-term, impact on electricity prices. In addition, many other potential climate impacts on energy supply are possible but have not been fully studied, leading to cost estimates to date, based only on temperature change, that underestimate the full cost of climate change on energy supply. Preexisting subsidies may distort signals for adaptation. Climate change impacts on energy supply will be part of an evolving picture dominated by technological development in the pursuit for safer, less expensive, and more reliable energy sources and technologies as well as mitigation and adaptation response pathways.

Given the limitations in the literature, sweeping conclusions about results may be premature on macroeconomic implications. However, some narrow conclusions are possible. The change in GDP due to temperature-induced changes in energy demand—even if combined with other climate impacts—range from –3% to 1.2%. Jochem et al. (2009) provide the most detailed and comprehensive study, and report only a 1.3% drop in GDP in 2050 in Europe due to at least seven climate impacts in the energy sector. The GDP impact in warmer regions tends to be greater than in cooler regions, which benefit from less need for space cooling. Energy-related economic impact is anticipated to be negative for developing countries and positive in developed countries. Adaptation within the energy sector can lower the cost of climate change, but these results may be driven largely by assumption because specific policies have not been modeled in these macroeconomic impact studies. Results from some of the partial equilibrium models suggests that CGE modeling studies, which largely focus on changes in energy demand, may be neglecting some potentially costly impacts from extreme weather events such as drought (see, e.g., Box CC-WE), which, if modeled, may lead to greater GDP losses than reported thus far in the literature.

Much research is still needed to understand the implications of climate change and extreme weather on the energy sector and to identify cost-effective adaptation options. The best understood area is the implications of climate on energy demand. A comprehensive evaluation of a full range of supply-side climate change impacts and adaptation options for all aspects of energy infrastructure is needed. This information will lead to an improved assessment of climate impacts due to the use of better, empirically based assumptions about the relationship of climate impacts and the economy, as well as about the effectiveness of adaptation options.

10.3. Water Services

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

10.3.1. Water Infrastructure and Economy-Wide Impacts

Between the 1950s and the 1990s, the annual economic losses from large extreme events, including floods and droughts, increased 10-fold, with developing countries being hardest hit (Kabat et al., 2003). Over the past few decades, flood damage constitutes about a third of the economic losses inflicted by natural hazards worldwide (Munich Re, 2005). The economic losses associated with floods worldwide have increased by a factor of five between the periods 1950–1980 and 1996–2005 (Kron and Berz, 2007). In 1990–1996 alone, there were six major floods throughout the world in which the number of fatalities exceeded 1000, and 22 floods with losses exceeding US$1 billion each (Kabat et al., 2003). Although these increases are primarily due to several non-climatic drivers, climatic factors are also partly responsible (Kundzewicz et al., 2007). Chapter 4 of the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) provides a comprehensive look at the impacts of extreme events on water supply (IPCC, 2012) and flooding at a wide range of spatial scales.

Most of the studies examining the economic impacts of climate change on the water sector have been carried out at the local, national, or river-basin scale; and the global distribution of such studies is skewed toward developed countries (Schreider et al., 2000; Chen et al., 2001; Middelkoop et al., 2001; Choi and Fisher, 2003; Hall et al., 2005; Hurd and Rouhi-Rad, 2013). In other studies, the economic impacts of climate variability on floods and droughts in developing countries were reported as substantial. These studies address climate variability; climate change may impact both mean and variability of the hydro-climatic system. The floods associated with the 1997–1998 El Niño and the drought associated with the 1998–2000 La Niña show a cost to Kenya of 11% and 16% of GDP, respectively (Mogaka et al., 2006). Floods and droughts are estimated to cost Kenya about 2.4% of GDP annually at mid-century, and water resources degradation a further 0.5% (Mogaka et al., 2006). For Ethiopia, economy-wide models incorporating hydrological variability show a drop in projected GDP growth by up to 38% compared to when hydrological variability is not included (World Bank, 2006). Syria is projected to experience reduction in economy-wide growth and incomes of urban households (Breisinger et al., 2013). However, it is not hydrological variability per se that causes the problem, but rather a lack of the necessary capacity, infrastructure, and institutions to mitigate the impacts (Grey and Sadoff, 2007). Similarly, future flood damages will depend not only on changes in the climate regime, but also on settlement patterns, land use decisions, flood forecasting quality, warning and response systems, and other adaptive measures (Pielke and Downton, 2000; Changnon, 2005; Ward et al., 2008). In many developing countries, water-related impacts are likely to be more pronounced with climate change (Chapter 3) and associated economic costs can be expected to be more substantial in the future, holding all other factors constant.

Climate change could increase the annual cost of flooding in the UK almost 15-fold by the 2080s under high emission scenarios. If climate change increased European flood losses by a similar magnitude, annual costs could increase by up to US$120 to 150 billion, for the same high emission scenarios (ABI, 2005). Feyen et al. (2012) project average annual damage in the EU to increase to US$18 to 28 billion by 2100 depending on the scenario, compared to US$8.5 billion today. Continental U.S. mean annual flood damages may increase by US$5 billion and US$12 billion in 2050 and 2100, respectively (Wobus et al., 2013). Ntelekos et al. (2010) estimate a range of US$7 to 19 billion, depending on the economic growth rate and the emissions scenarios. Dasgupta et al. (2010) report that by 2050 Bangladesh will face incremental cost to flood protection (against both sea and river floods) of US$2.6 billion initial costs and US$54 million annual recurring costs. Ward et al. (2008) found that the average annual costs to adapt to a 1-in-50-year river flood to range from US$3.5 to 6.0 billion per year for low- to upper-middle-income countries over the period 2010–2050 for the SRES A2 scenario.

10.3.2. Municipal and Industrial Water Supply

Municipal and industrial water supply economic systems are also impacted through changes in precipitation patterns and quantities. These impacts are evaluated as current costs of building in resiliency to the system to adapt to anticipated future changes. For example, the costs of adaptation to maintain supply and quality of water for municipal and industrial uses have been reported for the Assabet River near Boston (Kirshen et al., 2006), Toronto (Dore and Burton, 2001), and Quito (Vergara et al., 2007). Initial analysis indicates that adaptation measures may be beneficial for water infrastructure with an economic and engineering life of more than 25 years. Nassopoulos et al. (2012) suggest that neglecting to account for future climate change while designing water supply reservoirs can cost 0.2 to 2.8% of the net present value, based on analysis for Greece. For sub-Saharan Africa, adapting urban water infrastructure (storage facilities, wastewater, and additional supply infrastructure) to a 30% reduction in runoff could be US$2 to 5 billion per year (Muller, 2007). Climate change impacts on the Berg River in South Africa are estimated to account for 20% revenue loss for the water supply provider and 15.2% loss in social welfare (Callaway et al., 2012). For the Organisation for Economic Co-operation and Development (OECD), the cost of adaption in the water supply sector is 1 to 2% of base costs and would save US$6 to 12 billion per year (Hughes et al., 2010). U.S. impacts are estimated to be less than 1% of municipal and industrial welfare (Hurd et al., 2004; Strzepek et al., 2013). In Colorado, a 30% decrease in annual runoff will result in a 12% treatment cost increase and a 22% rise in residential costs (Towler et al., 2011).

Ward et al. (2010) estimate the costs of adaptation to climate change to ensure enough raw water to meet future industrial and municipal water demand for each country to 2050. Increased demand is assumed to be met through a combination of increased reservoir yield and alternative backstop measures. The global adaptation costs are estimated to be US$12 billion per year (0.04 to 0.06% of GDP), on top of US$73 billion per year to meet the needs of development, with 83 to 90% in developing countries. The highest costs are in sub-Saharan Africa, and may be as high as 16% of the global total. Adding adaptive measures to water infrastructure adds 10 to 20% to the total costs of developing countries meeting the water-related millennium goals (Ward et al., 2010).

10.3.3. Wastewater and Urban Stormwater

More frequent heavy rainfall events may overload the capacity of sewer systems and water and wastewater treatment plants more often, and increased occurrences of low flows will lead to higher pollutant concentrations. It is projected for USA in 2100 that national wastewater treatment costs will increase by US$0.6 to 8 billion per year (Henderson et al., 2013). The annual costs of urban stormwater system adaptation, averaged costs over 17 climate models simulating the SRES A2 emissions scenario, is US$3 billion per year in low- to upper-middle-income nations over the period 2010–2050 (Hughes et al., 2010). Adaptation costs estimates (for a 10-year, 24-hour storm in 2100) for various locations in the USA are relatively low; for example, US$135 million for Los Angeles, US$7 million for Boston, and US$40 million for Chicago (Neumann et al., 2013). Adapting bridges to altered urban floods could cost US$140 to 250 billion in the USA through the 21st century (Wright et al., 2012).

10.3.4. Inland Navigation

See Section 10.4.4.

10.3.5. Irrigation

Climate change impacts on the economics of irrigation reflect the anticipated change in temperature, precipitation, and agricultural demand and practices. Assessments of surface, ground, and gray water irrigation supplies are addressed in Chapter 3; implications for food production are covered in Chapter 7. By 2080, the global annual costs of additional irrigation water withdrawals for currently existing irrigated land are estimated at US$24 to 27 billion (Fischer et al., 2007). The global cost of improved irrigation efficiency to maintain yields is US$1.5 to 2.0 billion per year for the A2 scenario in developing countries in 2050 (Nelson et al., 2009).

Adaptation to maintain agricultural production in Ethiopia would be best achieved by better soil water management with the application of integrated irrigation and drainage systems, improved irrigation efficiency, and research related to on-farm practices; adaptation costs range from US$68 million per year for the dry scenario dominated by irrigation, to US$71 million per year under the wet scenario dominated by drainage (Strzepek et al., 2010).

10.3.6. Nature Conservation

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

10.3.7. Recreation and Tourism

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

10.3.8. Water Management and Allocation

Water scarcity and competition for water, driven by institutional, economic, or social factors, may mean that water assumed to be available for a sector is not and thus economic analyses at the sectoral level are crucial; inter-sectoral and economy-wide assessments are needed for comprehensive economic impacts of water services.

Changes in water availability, demand, and quality due to climate change would impact water management and allocation decisions. Traditionally, water managers and users have relied on historical experience when planning water supplies and distribution (Adger et al., 2007; UNFCCC, 2007). Under a changing climate, existing allocations may no longer be appropriate. Arndt et al. (2012) examine the implications of alternative development paths and water allocations to suggest climate-smart development strategies in Africa; under stress situations, allocations of water to energy-generation and irrigation may have economy-wide welfare implications. Water resource-related climate change impacts on the U.S. economy measured as cumulative undiscounted welfare changes over the 21st century range from plus US$3 trillion for wet scenarios to minus US$13 trillion under dry scenarios (in US$[2000]; Henderson et al., 2013).

10.3.9. Summary

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

10.4. Transport

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

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

As detailed in Sections 10.4.1, 10.4.2, 10.4.4, and 10.4.5, several studies have explored the potential impacts of climate change on the transport sector—focusing, for example, on safety or disruptions of service. Quantitative, economic analyses of the impact on physical infrastructure include Larsen et al. (2008), Chinowsky et al. (2010, 2011), and Hunt and Watkiss (2010) and on wider economic implications, Arndt et al. (2012).

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

10.4.1. Roads

Studies on the direct effects of climate change on road networks are focused primarily on qualitative predictions and surveys concerning impacts on road durability (National Research Council, 2008; Koetse and Rietveld, 2009; Eisenack et al., 2012; Ryley and Chapman, 2012); with some studies of the quantitative effects (Nemry and Demirel, 2012; Chinowsky et al., 2013). Noted impacts from changes in precipitation and temperature include changes in required road maintenance. These quantitative studies focus on specific impacts such as maintenance in an effort to quantify the long-term costs that need to be assumed by national and regional road agencies. Examples of the metrics used include kilometers of roads lost over time, redistribution requirements of transport funds, and benefits from adaptation on long-term maintenance.

Chapter 8 addresses the indirect effects of climate change on roads in the areas of congestion and safety. As an example, increases in heavy precipitation events will negatively affect driving safety through decreased driver visibility and changing surface conditions (Qiu and Nixon, 2008).

Paved road degradation is directly related to heat stress that can lead to softening of the pavement as temperatures exceed design thresholds (Lavin, 2003), and an increase in the number of freeze-thaw cycles impacts both the base and pavement surface (FHWA, 2006). The melting of permafrost in northern climates, as well as increased precipitation and flooding, threaten the integrity of road base and sub-bases (Qin et al., 2005). Drainage presents a specific problem for urban areas that experience rainfall above their built capacity and will influence new design standards and costs for urban transport (City of Chicago, 2008; Hunt and Watkiss, 2010; Lemmen and Warren, 2010). Increased fire danger from droughts could also pose a threat to roads.

Unpaved roads are vulnerable to a number of climate-based factors especially to increasingly intense precipitation, leading to wash out and disruption of service (Chinowsky and Arndt, 2012). Increased precipitation in agricultural areas may have negative economic impacts in addition to the direct impact on infrastructure. In cold climates, temporary winter roads are susceptible to warming and associated lower connectivity of rural areas and reduced economic activity in northern climates (Mills and Andrey, 2002). Warming could imply that ice roads can no longer be maintained.

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

10.4.2. Rail

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

10.4.3. Pipeline

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

10.4.4. Shipping

Impacts on inland navigation vary widely due to projected rise or fall in water levels. Overall, the effects on inland navigation are projected to be negative, and are region specific.

Increased frequency of flood periods will stop ship traffic on the Rhine more often; longer periods of low flow will also increase the average annual number of days during which inland navigation is hampered or stagnates due to limited load carrying capacity of the river; channel improvements can only partly alleviate these problems (Middelkoop et al., 2001). Economic impact could be substantial given the value of navigation on the Rhine (Krekt et al., 2011). See Chapter 23.

Virtually all scenarios of future climate change project reduced Great Lakes water levels and connecting channel flows, mainly because of increased evaporation resulting from higher temperatures. The potential economic impact may result in reductions in vessel cargo capacities and increases in shipping costs. The lower water levels predicted as a result of a doubling of atmospheric CO_2 could increase annual transportation costs by 29%, while more moderate climate change could result in a 13% increase in annual shipping costs. The impacts vary across commodities and routes (Millerd, 2010).

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

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

Increased storminess in certain routes may raise cost of shipping through additional safety measures or longer routes that are less storm

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prone (UNCTAD, 2009; UNECE and UNCTAD, 2010). Transport costs would increase or new routes sought if storms disrupt supply chains by destroying port infrastructure connecting road or rail (Becker et al., 2011). Increased storminess may also affect passage through lock systems (CCSP, 2008; UNCTAD, 2009). Increased storminess may increase maintenance costs for ships and ports and result in more frequent weather-related delays.

10.4.5. Air

Hotter air is less dense. In summer months, especially at airports located at high altitudes, this may result in limitations for freight capacity, safety issues, and weather-related delays, unless runways are lengthened (National Research Council, 2008; Pejovic et al., 2009). Chapman (2007) suggests that technological innovations will negate the challenges posed by extreme temperatures.

Increased storminess at airports, particularly those located in coastal regions, may increase the number of weather-related delays and cancellations (Pejovic et al., 2009; Lemmen and Warren, 2010) and increase maintenance and repair costs (Gusmao, 2010). Clear-air turbulence will increase in the Atlantic corridor, leading to longer and bumpier trips (Williams and Joshi, 2013). The impact of climate change on airport pavement is very similar to paved roads (DOT, 2002; Allard et al., 2007). The effect of temperature and increased precipitation intensity on airports imposes a risk to the entire facility if pavements are not adapted to these increases (Pejovic et al., 2009).

10.5. Other Primary and Secondary Economic Activities

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

10.5.1. Primary Economic Activities

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

10.5.1.1. Crop and Animal Production

Chapters 7 and 9 assess the impact of climate change on agriculture, including the effects on (international) markets for crops.

10.5.1.2. Forestry and Logging

Chapter 4 assesses the biophysical impact of climate change on forestry. Including adaptation in forest management, climate change will accelerate tree growth. This will reduce prices to the benefit of consumers everywhere. Low to mid latitude producers will benefit too as they switch to short-rotation forest plantations. Mid- to high-latitude producers will be hurt by lower prices while their productivity increases only modestly (Sohngen and Mendelsohn, 1997, 1998; Sohngen et al., 2001; Perez-Garcia et al., 2002; Lee and Lyon, 2004; Seppala et al., 2009). The value of the forest land in Europe would fall between 14 and 50% by 2100 (Hanewinkel et al., 2013). Different trees will be affected differently (Aaheim et al., 2011a,b). Higher biomass prices differentially impact different forest-based industries (Moiseyev et al., 2011).

10.5.1.3. Fisheries and Aquaculture

Chapter 4 assesses impacts of climate change on freshwater ecosystems, and Chapters 5, 6, and 30 on marine ecosystems. These assessments include the effects on commercially valuable fish stocks, but exclude the effects on markets. Adaptation and markets will substantially change the effect of climate change on fisheries (Link and Tol, 2009; Yazdi and Fashandi, 2010).

Allison et al. (2009), using an indicator-based approach, analyzed the vulnerability of capture fishery of 132 economies. Incongruously, they find that the sign and size of climate-driven change for particular fish stocks and fisheries are uncertain but are expected to lead to either increased economic hardship or missed opportunities for development in countries that depend on fisheries but lack the capacity to adapt. A major part of the gross turnover of nine key fish and cephalopod species in the Bay of Biscay remains potentially unaffected by climate change (Le Floc'h et al., 2008). In contrast, Iberian-Atlantic sardine biomass and profitability declines due to climate change (Garza-Gil et al., 2011). The economic impact of climate change on fisheries is dominated by the impact of management regime and market (Eide and Heen, 2002; McGoodwin, 2007; Eide, 2008; McIlgorm, 2010; Merino et al., 2010).

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

10.5.1.4. Mining and Quarrying

Climate change will affect exploration, extraction, production, and shipping in the mining and quarrying industry (Pearce et al., 2011). An increase in climate-related hazards (such as forest fires, flooding, windstorm) affects the viability of mining operations and potentially increases operating, transportation, and decommissioning costs.

Most infrastructure was built based on presumption of a stable climate, and is thus not adapted to climate change (Ford et al., 2010, 2011; Pearce et al., 2011). Damigos (2012) estimates the damages due to climate change under the SRES A1B scenario for the period 2021–2050 of the extent of US$0.8 billion for the Mediterranean Region. Note that other factors such as research and development might influence the viability of mining operations by lowering the cost of adaptation.

10.5.2. Secondary Economic Activities

10.5.2.1. Manufacturing

Climate change will impact manufacturing through three channels. First, climate change affects primary economic activities (see Section 10.5.1), and this means that prices and qualities of inputs are different. Second, the supply chain is affected, or the quality of the product. The impact of climate change on energy demand is well understood (see Section 10.2). Using a biophysical model of the human body, Kjellstrom et al. (2009) project labor productivity to fall, particularly of manual labor in humid climates. Labor productivity losses will be accentuated by increased incidences of malaria and vector-borne diseases. Note that the loss in labor productivity can be offset by the technological progress. Hübler et al. (2008) uphold the finding with a German case study, and Hsiang (2010) corroborates it with a statistical analysis of weather data and labor productivity in the Caribbean for 1970–2006. Some manufacturing activity is location specific, perhaps because it is tied to an input or product market, and will thus have to cope with the current and future climate; other manufacturing has discretion over its location (and hence its climate). Third, climate change affects the demand for products. This is pronounced for manufactures that supply primary sectors (Kingwell and Farré, 2009) and construction material (see Section 10.5.2.2). Unfortunately, there are only a few studies that quantify these effects (see Section SM10.1 of the on-line supplementary material).

10.5.2.2. Construction and Housing

Climate and climate change affect construction in three ways. First, weather conditions are one of the key factors in construction delays and thus costs. Climate change will change the length of the building season. In addition, precipitation affects the cost of construction through temporary flood protection (coffer) structures, slope stabilization management, and dewatering of foundations. There are adaptation measures that may reduce some of the costs. Apipattanavis et al. (2010) show a reduction in the expected value of road construction delays and associated costs. Second, buildings and building materials are designed and selected to withstand a particular range of weather conditions. As climate changes, design standards will change too. Exterior building components including windows, roofing, and siding are all specified according to narrow environmental constraints. Climate change will introduce conditions that are outside the prescribed operating environment for many materials, resulting in increased failures of window seals, increased leaks in roofing materials, and reduced lifespan of timber or glass-based cladding materials. Similarly, the interior building systems that allow for proper airflow in a facility face significant issues with climate change. For example, the increases in temperature and precipitation will lead to increased humidity as well as indoor temperatures. This requires increased airflow in facilities such as hospitals, schools, and office buildings—that is, upgrades to air conditioning and fan units, and perhaps further renovations that may be significant in scope and cost. Third, a change in the pattern of natural disasters will imply a change in the demand for rebuilding and repair. Unfortunately, these impacts have yet to be quantified (Hertin et al., 2003). Note that the direction and magnitude of the effect on construction and housing costs will possibly vary geographically. Cost impacts due to changing precipitation and storms patterns (magnitude, frequency, and/or variation) will vary as these changes are expected to vary by region as well. Air to air heat exchangers, heat recovery ventilators, and dehumidifiers and other technologies may be useful in adapting indoor air quality.

10.6. Recreation and Tourism

Recreation and tourism is one of the largest sectors of the world economy. In 2011, it accounted for 9% of global expenditure, and employed 260 million people (WTTC, 2011). Supply of tourism services is the dominant activity in many regional economies.

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

There is a large literature on the impact of climate change on tourism (Gössling et al., 2012; Scott et al., 2012a; Pang et al., 2013). Some studies focus on the changes in the behavior of tourists—that is, the demand for recreation and tourism services (see Section 10.6.1). Other studies look at the implications for tourist operators and destinations—that is, the supply of recreation and tourism services (see Section 10.6.2). A few studies consider the interactions between changes in supply and demand (see Section 10.6.3).

10.6.1. Recreation and Tourism Demand

Conventionally, recreation does not involve an overnight stay whereas tourism does. That implies that recreation, unlike tourism, is done close to home. Whereas tourists, to a degree, chose the climate of their holidays, recreationists do not (although climate is a consideration in the choice where to live). Tourists would adapt to climate change by changing the region, timing, and activities of their holidays; recreationists would adapt only timing and activities (Becken and Hay, 2007).

10.6.1.1. Recreation

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

There are case studies that indicate the impact of climate change on recreation. Buckley and Foushee (2012) find a trend toward earlier visits to U.S. national parks between 1979 and 2008. They argue this is due to climate change, but do not rigorously test this hypothesis nor control for other explanations. Whitehead et al. (2009) find a substantial decrease in the recreational value of sea shore fishing in North Carolina due to

SLR. Daugherty et al. (2011) conclude that climate change will make it more difficult to guarantee adequate water levels for boating and angling in artificial reservoirs. Pouta et al. (2009) project a reduction in cross-country skiing in Finland, particularly among women, the lower classes, and urban dwellers. Shih et al. (2009) find that weather affects the demand for ski lift trips. Hamilton et al. (2007) highlight the importance of "backyard snow" to induce potential skiers to visit ski slopes. One could expect people to adopt other ways of enjoying themselves but such alternatives were excluded from these studies.

There are positive effects too (Richardson and Loomis, 2005). Scott and Jones (2006, 2007) foresee an increase in golf in Canada due to climate change. Kulshreshtha (2011) sees positive impacts on recreation on the Canadian Prairies, and Coombes et al. (2009) predict an increase in beach tourism in East Anglia. Graff Zivin and Neidell (2010) find that people recreate indoors when the weather is inclement.

Scott et al. (2007) estimate the relationship between visitors to Waterton Lakes National Park and weather variables for 8 years of monthly observations, and use this to project an increase in visitor numbers due to climate change. A survey among current visitors indicates that a deterioration of the quality of nature would reduce visitor numbers. Jones et al. (2006) study the impact of climate change on three festivals in Ottawa. They argue for heat wave preparedness for Canada Day, find that skating on natural ice may become impossible for Winterlude, and that the dates of the Tulip Festival may need to be shifted to reflect changing phenology.

10.6.1.2. Tourism

Climate (Becken and Hay, 2007; WTO and UNEP, 2008) and weather (Álvarez-Díaz and Rosselló-Nadal, 2010; Rosselló-Nadal et al., 2010; Rossello, 2011; Førland et al., 2012; Day et al., 2013; Falk, 2013) are important factors in tourist destination choice, and the tourist sector is susceptible to extreme weather (Forster et al., 2012; Hamzah et al., 2012; Tsai et al., 2012). Eijgelaar et al. (2010), for instance, argue 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) and Prideaux and Mcnamara (2012) use a similar mechanism to explain the rise in popularity of Tuvalu as a destination choice. Huebner (2012) find no impact of future climate change on current travel choices. Taylor and Ortiz (2009) show that domestic tourists in the UK often respond to past weather; the hot summer of 2003 had a positive impact on revenues of the tourist sector. Denstadli et al. (2011) find that tourists in the Arctic do not object to the weather in the Arctic; Gössling et al. (2006) reaches the same conclusion for tourists on Zanzibar; and Moreno (2010) for tourists in the Mediterranean.

There are a number of biometeorological studies of the impact of climate change on tourism. Yu et al. (2009a) find that Alaska has become more attractive over the last 50 years and Florida less attractive to tourists. Yu et al. (2009b) conclude that the climate for sightseeing has improved in Alaska, while the climate for skiing has deteriorated. Matzarakis et al. (2010) construct a composite index of temperature, humidity, wind speed, and cloud cover, and use this to map tourism potential. Lin and Matzarakis (2008, 2011) apply the index to Taiwan POC and eastern China. Endler and Matzarakis (2010a,b, 2011) use an index to study the Black Forest in Germany in detail, highlighting the differences between summer and winter tourism, and between high and low altitudes (Endler et al., 2010). Zaninović and Matzarakis (2009) and Matzarakis and Endler (2010) use this method to study Freiburg and Hvar. Matzarakis et al. (2007) project this potential into the future, finding that the Mediterranean will probably become less attractive to tourists. Hein et al. (2009), Perch-Nielsen et al. (2009), Giannakopoulos et al. (2011), Amelung and Moreno (2012), and Amengual et al. (2012) reach the same conclusion, but also point out that Mediterranean tourism may shift from summer to the other seasons. Giannakopoulos et al. (2011) note that coastal areas in Greece may be affected more than inland areas because, although temperature would be lower, humidity would be higher. Moreno and Amelung (2009), on the other hand, conclude that climate change will not have a major impact (before 2050) on beach tourism in the Mediterranean because sunbathers like it hot (Moreno, 2010; Rutty and Scott, 2010). Amelung et al. (2007) use a weather index for a global study of the impact of climate change on tourism, finding shifts from equator to pole, summer to spring and autumn, and low to high altitudes. Perch-Nielsen (2010) combines a meteorological indicator of exposure with indicators of sensitivity and adaptive capacity, and uses this to rank the vulnerability of beach tourism in 51 countries. India stands out as the most vulnerable, and Cyprus as the least vulnerable.

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

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

Bigano et al. (2007) and Hamilton et al. (2005a,b) construct a simulation model of domestic and international tourism and climate change (but not SLR), considering the simultaneous change in the attractiveness of all potential holiday destinations (Dawson and Scott, 2013); Hamilton and Tol (2007) downscale these national results to the regions of selected countries. Two main findings emerge. First, climate change would drive tourists to higher latitudes and altitudes. International tourist arrivals would fall, relative to the scenario without warming, in hotter countries, and rise in colder countries. Tourists from northwestern Europe, the main origin worldwide of international travelers at present, would be more inclined to spend the holiday in their home country, so that the total number of international tourists falls. Second, the impact of climate change is dominated by the impact of population growth and, particularly, economic growth. In the worst affected countries, climate change slows down, but nowhere reverses, growth in the tourism sector.

10.6.2. Recreation and Tourism Supply

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

Other studies consider beach tourism. Scott et al. (2012b) highlight the vulnerability of coastal tourism facilities to SLR. Hamilton (2007) finds that tourists are averse to artificial coastlines, so that hard protection measures against SLR would reduce the attractiveness of an area. Raymond and Brown (2011) survey tourists on the Southern Fleurieu Peninsula. They conclude that tourists who are there for relaxation worry about climate change, particularly SLR, while tourists who are there to enjoy nature (inland) do not share that concern. Becken (2005) finds that tourist operators have adapted to weather events, and argues that this helps them to adapt to climate change. Belle and Bramwell (2005) find that tourist operators on Barbados are averse to public adaptation policies. Uyarra et al. (2005) find that tourists on Barbados would consider holidaying elsewhere if there is severe beach erosion. Buzinde et al. (2010a,b) find that there is a discrepancy between the marketing of destinations as pristine and the observations of tourists, at least for Mexican beach resorts subject to erosion. They conclude that tourists have a mixed response to environmental change, contrary to the officials' view that tourists respond negatively. Jopp et al. (2013) find that an increase in tourism in the shoulder season may offset losses in the peak season in Victoria.

Some studies focus on nature tourism. Cavan et al. (2006) find that climate change may have a negative effect on the visitor economy of the Scottish uplands as natural beauty deteriorates through increased wild fires. Saarinen and Tervo (2006) interviewed nature-based tourism operators in Finland, and found that about half of them do not believe that climate change is real, and that few have considered adaptation options. Nyaupane and Chhetri (2009) argue that climate change would increase weather hazards in the Himalayas and that this would endanger tourists. Uyarra et al. (2005) find that tourists on Bonaire would not return if coral were bleached. Hall (2006) finds that small tourist operators in New Zealand do not give high priority to climate change, unless they were personally affected by extreme weather in recent times. The interviewed operators generally think that adaptation is a sufficient response to climate change for the tourism sector. Klint et al. (2012) find that tourist operators in Vanuatu give low priority to adaptation to climate change and Jiang et al. (2012) find Fiji poorly prepared. Saarinen et al. (2012) find that tourist operators in Botswana think that climate change would not affect them. Wang et al. (2010) note that glacier tourism is particularly vulnerable to climate change, highlighting the Baishiu Glacier in China. Brander et al. (2012) estimate the economic impacts of ocean acidification on coral reefs under four IPCC marker scenarios using value transfer function approach and find that the annual economic impacts increase rapidly overtime, though it remains a small fraction of total income.

While the case studies reviewed above provide rich detail, it is hard to draw overarching conclusions. A few studies consider all aspects of the impact of climate change for particular countries or regions (Ren Guoyu, 1996; Harrison et al., 1999). In France, the Riviera may benefit because it is slightly cooler than the competing coastal resorts in Italy and Spain; the Atlantic Coast, although warming, would not become more attractive because of increased rainfall; it is not probable that the increase in summer tourism in the mountains would offset the decrease in winter tourism (Ceron and Dubois, 2005). In the Great Lakes regions, there is a reduced tourism potential in winter but increased opportunities in summer (Dawson and Scott, 2010). Tourist operators in Australia find the uncertainty about climate change too large for early investment in adaptation (Turton et al., 2010).

10.6.3. Market Impacts

There are only two papers that consider the economic impacts of rather stylized climate change-induced changes in tourism supply and demand. Both studies use a global computable general equilibrium model, assessing the effects on the tourism sector as well as all other markets. Berrittella et al. (2006) consider the consumption pattern of tourists and their destination choice. They find that the economic impact is qualitatively the same as the impact on tourist flows (discussed above): Colder countries benefit from an expanded tourism sector, and warmer countries lose. They also find a drop in global welfare, because of the redistribution of tourism supply from warmer (and poorer) to colder (and richer) countries.

Bigano et al. (2008) extend the analysis with the implications of sea level rise. The impact on tourism is limited because coastal facilities used by tourists typically are sufficiently valuable to be protected against SLR. The economic impacts on the tourism sector are reinforced by the economic impacts on the coastal zone; the welfare losses due to the impact of climate change on tourism are larger than the welfare losses due to SLR.

10.7. Insurance and Financial Services

10.7.1. Main Results of the Fourth Assessment Report and IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation on Insurance

More intense or frequent weather-related disaster would affect property insurance, of which coverage is expanding with economic growth (WGII AR4 Section 7.4.2.2.4). Insurability can be preserved through risk-reducing measures. Adaptation to climate change can be incentivized through risk-commensurate insurance premiums. Improved risk management would further financial resilience (WGII AR4 Sections 7.4.2.2.4, 7.6.3). Insurance is linked to disaster risk reduction and climate change adaptation, because it enables recovery, reduces vulnerability, and provides knowledge and incentives for reducing risk (IPCC, 2012).

10.7.2. Fundamentals of Insurance Covering Weather Hazards

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Insurance is organized either through private markets, publicly, or public-private partnerships. It internalizes catastrophe risk costs prior to catastrophic events, reducing the economic impact of weather-related and other disasters to individuals, enterprises, and governments—thus stabilizing income and consumption, and decreasing societal vulnerability (Melecky and Raddatz, 2011; see also Section 17.5.1). Insurance is based on the law of large numbers: the larger the portfolio of uncorrelated and relatively small risks, the more accurately the average loss per policy can be predicted and charged accordingly, allowing for a lower premium than with a smaller ensemble. Besides spreading risk over a diversified insured population, insurance spreads risk over time. However, weather-related disasters such as floods simultaneously affect many, and thus violate the principle of uncorrelated risks. Consequently, large losses are much more probable, the loss variance is greater, and the tail risk is higher (Kousky and Cooke, 2012).

If insurance coverage is to be maintained, insurers would need more risk-based capital to indemnify catastrophic losses and remain financially solvent. This coverage is purchased in the reinsurance and capital markets. The capital costs account for a substantial portion of premiums and the affordability and viability of weather insurance are subjects of ongoing research given future climate change (Charpentier, 2008; Clarke and Grenham, 2012; Maynard and Ranger, 2012).

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

10.7.3. Observed and Projected Insured Losses from Weather Hazards

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

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

Frequently Asked Questions

FAQ 10.2 | How does climate change impact insurance and financial services?

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

reflect climate variability on various time scales (Pielke and Landsea, 1999; Welker and Faust, 2013).

Studies analyzing changes in climate variables and insured losses in parallel are still rare. Variability and mean level of thunderstorm-related insured losses in the USA in the period 1970–2009 have substantially increased, while meteorological thunderstorm forcing has risen in parallel (Sander et al., 2013). The number of days that a regional insurer in southwest Germany sustains hail losses displays an upward trend since 1986, while meteorological severe storm indicators also show upward trends (Kunz et al., 2009). Although more studies find increases of large hail in Europe, general data and monitoring issues hindered assessing more than *low confidence* in observed meteorological trends (WGI AR5 Section 2.6.2.4). Corti et al. (2009) found an increase in modeled and partly observed insured subsidence losses in France over the period 1961–2002, consistent with a *likely* increase in dryness in Mediterranean regions (WGI AR5 Section 2.6.2.3). The observed rise in U.S. normalized insured flood losses (Barthel and Neumayer, 2012) may partly correspond to *very likely* increased heavy precipitation events in central North America (WGI AR5 Section 2.6.2.1), while the evidence for climate-driven changes in river floods is not compelling (WGI AR5 Section 2.6.2.2). Declining anthropogenic aerosol emissions may partly explain the recent upswing in hurricane hazard and losses (WGI AR5 Sections 2.6.3, 14.6; Table 10-4). Apart from detection, loss trends have not been conclusively attributed to anthropogenic climate change; most such discussions are not based on scientific attribution methods.

Many GCM-based projection studies agree that extreme winter storm wind speeds fall in the Mediterranean and increase in west, central, and northern Europe (WGI AR5 Section 14.6.2.2). Loss ratios—that is, insured loss divided by insured value—follow the same pattern (Schwierz et al., 2010; Donat et al., 2011; Pinto et al., 2012; see also Table 10-5). Return periods per loss level are projected to shorten in large parts of Europe, indicating more frequent high losses (Pinto et al., 2012; see Table 10-5). Projected overall losses and fatalities develop accordingly (Narita et al., 2010; IPCC, 2012). Across three modeling approaches calibrated to

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

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

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

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

Hazard	Insurance line	Region	Projected changes in future time slices relative to current climate (spatial distribution and vulnerability of insured values assumed to be unchanged over time)
Winter storm	Homeowners' insurance	Europe	Projected increases in mean annual loss ratio lie in a range from one- to two-digit percentages in time slices before and around 2050 for regions such as France, Belgium/Netherlands, UK/Ireland, Germany, and Poland, with larger increases at the end of the century. Southern European regions expect decreases, such as Portugal/Spain (SRES A1B, A2).[4,5,8,13–15,19] Currently rare and high annual loss ratios are projected to occur more often: today's 20-year, 10-year, and 5-year return periods appear strongly reduced by the end of the century for individual countries. For entire Europe they will roughly be halved (SRES A2).[16] Accordingly, return periods will have higher loss levels associated,[10,19] e.g., the 25-year loss in Germany is expected to rise by 5–41% in 2041–2070 (SRES A1B).[8,10]
River flood, maritime flood, flash flood from rainfall, melting snow	Property and business interruption insurances	Europe, North America	Germany: projected increases in mean annual insured flood loss according to a seven-member dynamical downscaling ensemble mean (SRES B1, A1B, A2) are 84% (2011–2040), 91% (2041–2070), and 114% (2071–2100).[7] United Kingdom: projected increases in mean annual insured flood loss are 8% (for a +2°C rise in global mean temperature) and 14% (for a +4°C rise), with the one-in-hundred-year loss higher by 18% and 30%, respectively.[4] Norway, Canada: losses from heavy precipitation in property and business interruption insurances in three city areas in Canada are projected to rise by 13% (2016–2035), 20% (2046–2065), and 30% (2081–2100) in a five-member ensemble mean (IS92a, SRES A2/B2, A2)[3]. In three counties across southern Norway precipitation and snow melt insurance losses are expected to be higher by approximately 10–21% (SRES A2) and 17–32% (SRES B2) at the end of the century.[9] The Netherlands: expected annual property loss caused by increasing river discharge and sea level with an assumed flood insurance system is projected to lie by 125% higher in 2040 relative to 2015 (corresponding to 24 cm sea level rise) and by 1784% higher in 2100 (85 cm sea level rise).[1]
Tropical cyclone	Foremost property insurance lines	North America, Asia	USA: three of four GCMs driving a specific tropical cyclone and loss model entail increasing insured hurricane losses over time (SRES A1B).[6] Two GCM outputs at coarser resolution for the end of the century produce contradictory results of prolonged (ECHAM5/MPIOM A2) versus shortened (MRI/JMA A1B) return periods of current loss levels.[17] Analogously, a wide range of model projections is reflected in price levels of Florida's hurricane wind insurance that are projected to change by –20% to +5% (2020s) and –28% to +10% (2040s) (under the assumptions of strained reinsurance capacity, i.e., hard market conditions, and current adaptation).[12,18] These approaches demonstrate uncertainty in the sign of change. China: projected increases of insured typhoon losses are 20% (for a +2°C rise in global mean temperature) and 32% (for a +4°C scenario), with the one-in-hundred-year loss higher by 7% and 9%, respectively.[4]
Hailstorm	Homeowners' insurance, agricultural insurances	Europe	The Netherlands: losses from outdoor farming insurance and greenhouse horticulture insurance are projected to increase by 25–29% and 116–134%, respectively, for a +1°C rise in global mean temperature. For a +2°C scenario, projected increases will be higher at 49% to 58% and 219% to 269%, respectively (statistical model).[2] Germany: projected increases in mean annual loss ratios from homeowners' insurance due to hail are 15% (2011–2040) and 47% (2041–2070) (SRES A1B, statistical model).[8]
Storms, pests, diseases	Paddy rice insurance	Asia	Japan: paddy rice insurance payouts are projected to decrease by 13% by the 2070s, on the basis of changes in standard yield and yield loss (A2).[11]

Notes: GCM = General Circulation Model; ECHAM5 = European Centre for Medium Range Weather Forecasts and (Max Planck Institute of Meteorology) Hamburg, fifth GCM generation; MRI = Meteorological Research Institute of Japan Meteorological Agency (JMA); SRES = Special Report on Emission Scenarios.

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

German insurance data, the 25-year loss is projected (SRES A1B) to change by –10% to +26% (2011–2040), +5% to +41% (2041–2070), and +45% to +58% (2071–2100) against 1971–2000, keeping exposures and damage sensitivities constant (Held et al., 2013). Although it is *unlikely* that the North Atlantic response to climate change is just a simple poleward shift of the storm track, overall confidence in the magnitude of regional storm track changes is low (WGI AR5 Section 14.6.3).

Direct losses and fatalities from flooding will increase with climate change in various locations in the absence of adequate adaptation, given *very likely* widespread increases in heavy precipitation (WGI AR5 Sections 11.3.2.5.2, 12.4.5.4; see also IPCC, 2012). This is selectively reflected in studies projecting mean annual insured heavy rainfall and flood losses to rise with climate change in the UK, the Netherlands, Germany, southern Norway, and the Canadian province of Ontario (Table 10-5).

Direct losses and fatalities from tropical cyclones will increase with exposure and may increase with the frequency of very intense cyclones in some basins (WGI AR5 Section 14.6; Nordhaus, 2010; IPCC, 2012; Peduzzi et al., 2012). Ranger and Niehoerster (2012), Kunreuther et al. (2012), and Raible et al. (2012) found insured hurricane losses change in opposite directions across a range of dynamical and statistical model projections, whereas a high-resolution approach tends to support a long-term increase (Emanuel, 2011). Here, increased probabilities of upward shifted accumulated loss might be detectable by 2025 at earliest, whereas a significant loss trend might emerge much later (Crompton et al., 2011; Emanuel, 2011).

Insured typhoon-related property losses in China are projected to increase (Dailey et al., 2009). Averaged across four GCMs, Mendelsohn et al. (2012) project rising direct losses for Central America, the Caribbean, North America, and East Asia. Narita et al. (2009) report an increase in damages and fatalities in all parts of the world.

Hailstorm insurance losses in the Netherlands (Botzen et al., 2010b) and Germany (Gerstengarbe et al., 2013) are projected to increase, consistent with more severe thunderstorms (WGI AR5 Section 12.4.5.5). Paddy rice insurance payouts in Japan are projected to decrease (Iizumi et al., 2008; see Table 10-5).

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

10.7.4. Fundamental Supply-Side Challenges and Sensitivities

10.7.4.1. High-Income Countries

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

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

The additional uncertainty induced by climate change translates into a need for more risk capital (Charpentier, 2008; Grace and Klein, 2009; Kunreuther et al., 2009). This raises insurance premiums and affects the economy (Table 10-6). Health and life insurance may also be affected through the health impacts of climate change (Hecht, 2008). Liability insurance, too, may be susceptible to climate change. So far, no damages have been awarded for greenhouse gas emissions as such, but litigation where damages are sought is pending (Heintz et al., 2009; Mills, 2009; Patton, 2011). Defense cost coverage under liability insurance in such cases depends on the specific contractual wording (Supreme Court of Virginia, USA, 2012; see Table 10-6).

10.7.4.2. Middle- and Low-Income Countries

Middle- and low-income countries account for a small share of worldwide non-life insurance: approximately 14% of premiums in 2012 (Swiss Re, 2013b). In high-income countries, some 37% of direct natural disaster losses have been covered by insurance in the period 1980–2011, about 4% in middle-income countries, and even less in low-income countries (Wirtz et al., 2013). For instance, only about 1% of direct overall losses in the 2010 floods in Pakistan were insured (Munich Re., 2011).

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

Challenges that might increase in the climate change context	Example/explanation
Failure to reflect temporal changes in hazard condition in risk management	After the devastating 2004 and 2005 hurricane seasons, the losses of Florida's homeowners' insurance accumulated since 1985 exceeded the cumulative direct premiums earned by 31%. Consequences of the upswing and peak in hurricane activity: one insurer liquidated, two seized by regulation due to insolvency; reduced coverage availability in high-risk areas.[9]
Misguided incentives additionally increasing risk	US National Flood Insurance Program (NFIP) allows for a vicious circle of built-up areas already existing within flood plains pressing authorities to construct or improve protecting levees that in turn lead to even more development attracted by NFIP premium discounts, although exposed to extreme flooding events.[11,22] In addition, the large majority of older properties situated within flood plains and accounting for 16% of losses in the period 1978–2008 pay premiums substantially below the risk-adequate level.[14; see also 1,6,7,11,15] In this respect, premium incentives to reduce residual flood risk have been missing. Policyholders residing in flood plains where flood cover was made precondition for mortgage drop the cover after only 2–4 years, accounting for missing insurance penetration and insufficient build-up of NFIP risk capital.[11,14,15] All these features, among others, account for the fact that NFIP has continuously been running a cumulative operating deficit, reaching more than US$20 billion in 2006, after the big hurricanes.[14]
Non-quantifiable uncertainties increasing risk	There is ambiguity as to what degree climate change may modify regional weather hazards—model projections are not unequivocal,[2,3] and there is uncertainty about prospects of post-disaster regulatory/jurisdictional pressures, e.g., to extend claims payments beyond the original coverage.[9] Such uncertainties materialize in risk-based capital loadings.[12]
Liability insurance impacted by new climate risk	Chances of success for claims based on CO_2 emissions in the USA seem small, owing to legal obstacles,[4,5,8,18] even though allocation schemes to overcome these hurdles are being discussed.[17,20] Defense costs could be covered by liability insurance.[20] CO_2 emissions were declared pollution (US Supreme Court/EPA). Existing and future regulation on limits for CO_2 emissions could continue to displace liability claims for CO_2 emissions and at the same time create new liability risks in case of non-compliance. These risks have not yet been adequately taken into account, somewhat similar to the early stages of environmental liability claims in the USA in the 20th century.[10,16] The Supreme Court of Virginia ruled in 2012 that coverage under liability insurance for claims based on CO_2 emissions and defense costs depends on the specific occurrence-definition underlying the contract (e.g., if the cover pertains to accident, warming due to CO_2 emissions and resulting damage does not match this definition).[19]
Share of insurance in national risk financing	In the years following weather-related disasters countries with high insurance penetration show almost no impact on sovereign deficit and increasing economic output (GDP), whereas low-penetration countries experience substantially rising government deficit and missing positive change in output.[13,21] The absence of developed insurance systems, as is the case in many middle- and low-income countries, translates into greater macroeconomic vulnerability than with developed insurance systems.

Sources: [1]Burby (2006); [2]Charpentier (2008); [3]Collier et al. (2009); [4]Ebert (2010); [5]Faure and Peeters (2011); [6]GAO (2010); [7]GAO (2011); [8]Gerrard (2007); [9]Grace and Klein (2009); [10]Hecht (2008); [11]Kousky and Kunreuther (2010); [12]Kunreuther et al. (2009); [13]Melecky and Raddatz (2011); [14]Michel-Kerjan (2010); [15]Michel-Kerjan and Kunreuther (2011); [16]Mills (2009); [17]Patton (2011); [18]Stewart and Willard (2010); [19]Supreme Court of Virginia USA (2012); [20]Taylor and Tollin (2009); [21]von Peter et al. (2012); [22]Zahran et al. (2009).

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

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

Microinsurance schemes, keeping transaction costs at the lowest operable level, mainly provide health and life insurance to households and small enterprises in low-income markets. Supply of property insurance suffers from correlated weather risks, although weather-related agricultural damages are covered. Such weather coverage is growing, typically with government and non-governmental organization (NGO) assistance or cross-subsidies from local insurers (Linnerooth-Bayer et al., 2011; Qureshi and Reinhard, 2011). These schemes may be particularly sensitive to a rise in disaster risk due to climate change (Collier et al., 2009; Leblois and Quirion, 2011; Clarke and Grenham, 2012).

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

10.7.5. Products and Systems Responding to Changes in Weather Risks

10.7.5.1. High-Income Countries

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

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

Reinsurers are key to the supply of disaster risk capital. They operate globally to diversify the regional risks of hurricanes and other disasters. Access to reinsurance enhances risk diversification of insurers. Periodic shortages in reinsurance capacity following major disasters have moderated over the last 2 decades because of easier new capital inflow (Cummins and Mahul, 2009).

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

Very large loss events, say in excess of US$100 billion, may make additional capacity desirable. These disasters can be diversified in the financial securitization market (IPCC, 2012). Natural catastrophe risks do not correlate with capital market risks and hence are attractive to institutional investors. For instance, a catastrophe bond assures the investor above-market returns as long as a parametric index (e.g., wind-based) does not exceed a threshold, but pays the insurer's loss otherwise. The catastrophe bond market reached critical mass after the hurricanes of 2004 and 2005, with some US$11 billion of risk capital in effect by June 2011 (Michel-Kerjan and Morlaye, 2008; Cummins and Weiss, 2009; see Table 10-7).

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

Response option	Example/explanation
Risk-adjusted premiums convey the risk to the insured, encouraging them to pursue adaptive measures.	Flood hazard insurance zoning systems, e.g., HORA (Austria), SIGRA (Italy), and ZÜRS (Germany), hamper development in high-risk zones by allocating adequately high premiums.[26] Prior to Germany's disastrous River Elbe flood in 2002, 48.5% of insured households had obtained information on flood mitigation or were involved in emergency networks and 28.5% implemented one of several mitigation measures compared with 33.9% and 20.5%, respectively, of uninsured households.[42] However, perceptions that motivate flood insurance uptake range from risk awareness[9] to pure peer group expectation[32]—the latter might blur the role of the risk-premiums-nexus in some societal contexts.
Conditions of insurance policies incentivizing vulnerability reduction	Premium discounts for compliance with local building codes or other prevention options[27,45]; share of the insured in claims payment by deductibles or upper coverage limits, and exclusion of systematically affected property[1,7,8,10,11,15,21]; long-term natural-hazard insurance tied to the property and linked to mortgages and loans granted for prevention measures.[27,28,36] The latter is contested by modeled high-risk capital requirements and ambiguity loadings, rendering multi-year policies relatively expensive and less flexible for the insurance market.[34]
Amplifying factors in large disaster losses included in risk models	Evacuation and systemic economic catastrophe impacts, adversely affecting regional workforce and repair capacity, or knock-on catastrophes following initial catastrophes, e.g., long-term flooding following hurricane landfall.[38]
Diversifying large disaster risk across securitization markets	Following the hurricane disasters of 2004 and 2005, securitization instruments, e.g., catastrophe bonds, industry loss warranties, and sidecars, acquired greater prominence, and have been recovering again from the market break in 2008.[16,18,20] Investors in insurance linked securities are attracted by the lack of correlation to typical financial market risks (e.g., currency risks) and the well defined loss-per-index structure. The higher transparency relative to other asset-backed securities, such as mortgage-backed securities, contributed to the better performance of catastrophe bonds following the financial crisis of 2007/2008.[16,18] As bonds typically cover large losses, the basis risk, i.e., suffering damage without parametric triggering, is reduced[44]; further reduction may be feasible by optimizing index measurements.[16] Weather derivatives are further instruments used to transfer risks to the capital markets.[17,27,37] Also, multiple-trigger "hybrid" products are available, combining a parametric trigger-based catastrophe bond with a trigger-based protection against a simultaneous drop in stock market prices, thereby hedging against a double hit from direct disaster loss and losses incurred by the asset management side.[5,18]
Index-based weather crop insurance products	Agricultural insurances predominantly cover crops, but also livestock, forestry, aquaculture, and greenhouses. Main products are indemnity-based crop insurance (covers for single perils and multiple-peril events), and index-based crop insurance.[41] The latter is available in 40% of middle-income countries, with enlarged systems beyond pilot implementation in India and Mexico, and growth in China.[23,33,40,46] Risk-based price signals may better foster adaptation if schemes are coupled with access to advanced technology, e.g., drought-resistant seed.[4,15,23,33] Various index definitions (cumulative rainfall, area-yield, etc.) and applications exist or have been proposed.[4,29,30,31] Adjusting to uncertain regional changes in temporal hazard condition is a basic challenge with climate change.[14,24,29]
Improvements in index-based weather insurance	Basis risk, i.e., weak correlation between index and damage, can be reduced if the index scheme is applied to an area-yield trigger in a region with homogeneous production potential (e.g., based on a sample) and/or to the uppermost disaster risk layer only.[14,15,22] It can be better absorbed if index insurance works at aggregate level, e.g., to cover crop-credit portfolios, cooperatives, or informal networks,[43] and if satellite-based remote-sensing technology can be used to establish plot identification and yield estimation and loss assessment.[22] Satellite-based forage estimation is already used for livestock index insurance in East Africa.[13] Pooling local schemes across climate regions under one cooperative parent organization, thus realizing central management, economics of scale, and risk diversification, can reduce capital requirements and advance performance.[6,12,35] The disaster risk layer and high start-up costs (weather data collection, risk modeling, education) necessitate subsidies from the state or donors.[15,33]
Sovereign insurance schemes	Economic theory about the public sector's risk neutrality argues (1) that risks borne publicly render the social cost of risk-bearing insignificant and (2) that disaster loss is seen small in comparison with a government's portfolio of diversified assets.[3] This theory proved inadequate if applied to relatively vulnerable small-sized middle- to low-income countries,[19] thereby rehabilitating sovereign insurance. For the Caribbean scheme CCRIF, which pools states, the reduction in premium cost per country is expected to be 45–50%.[31] Similar pooling schemes are being developed (e.g., African Risk Capacity, Pacific Catastrophe Risk Insurance Pilot).[2,39] Pooling natural catastrophe risks across an array of megacities has also been proposed.[25]

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

10.7.5.2. Middle- and Low-Income Countries

Index-based weather insurance is often considered well-suited to the agricultural sector in developing countries (Collier et al., 2009; IPCC, 2012). Payouts depend on a physical trigger, for example, cumulative rainfall at a nearby weather station, instead of the policyholder's condition. Thus, they can be timely; costly loss assessments and moral hazard are avoided; and adverse selection reduced (Barnett et al., 2008). Risk-based premiums can encourage adaptive responses (Mahul and Stutley, 2010; see Table 10-7). However, basis risk, where losses occur but no payout is triggered, provokes distrust. Misunderstanding and scaling up of pilots pose further difficulties (Patt et al., 2010; Leblois and Quirion, 2011; Clarke and Grenham, 2012). Suggested improvements include area-yield indices and coverage at aggregate levels to reduce basis risk, and a cooperative design (Biener and Eling, 2012; Clarke and Grenham, 2012; see Table 10-7). Application of indemnity-based insurance and index-based concepts depend on the insured's characteristics and the market setting (Herbold, 2013a; Swiss Re, 2013a). Insurance-linked services can strengthen farmers' resilience by seasonal-forecast-based agricultural guidance (AgroClima, 2013).

Improved building standards at high-risk sites in the Caribbean substantially reduce damages from tropical cyclones and increase benefits twofold over costs over a 20-year period, assuming scenarios of changing hazard inferred from past decades (Michel-Kerjan et al., 2013; Ou-Yang et al., 2013). Insurance coverage linked to credit for retrofitting could improve adaptation (Mechler et al., 2006).

Sovereign insurance is deemed appropriate in developing countries suffering from post-disaster financing gaps (see Section 10.7.4). Current schemes include government disaster reserve funds (FONDEN, Mexico) and pools of developing states' sovereign risks (e.g., CCRIF, Caribbean;

IPCC, 2012). In both cases, peak risk is transferred to reinsurance and catastrophe bonds (Table 10-7).

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

10.7.6.1. High-Income Countries

Theory favors an arrangement where individual risk is insured, but the non-diversifiable component of risk (that may rise with climate change) is public (Borch, 1962; Kunreuther et al., 2009). Accordingly, many high-income states have public-private arrangements involving government intervention on peak risk (Aakre et al., 2010; Bruggeman et al., 2010; Schwarze et al., 2011; Paudel, 2012), or even public statutory insurance systems (Quinto, 2011; see Table 10-8). Expected governmental post-disaster relief has been shown to counteract insurance uptake (Raschky et al., 2013). The pro-adaptive, risk-reducing features of insurance are more effective if the price reflects the risk and the pool of insureds is larger, for example, through bundled perils (Bruggeman et al., 2010; Paudel, 2012). People who cannot afford premiums can be covered by vouchers, leaving the price signal undistorted, or by subsidies (Kunreuther et al., 2009; Aakre et al., 2010; see Table 10-8).

Insurance regulation ensures availability, affordability, and solvency, but often adopts only short- to medium-term views. Because of climate change, the role of regulators has changed to include risk-adequate pricing, risk education, and risk-reduction in the long term (Hecht, 2008; Grace and Klein, 2009; Mills, 2009).

10.7.6.2. Middle- and Low-Income Countries

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

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

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

10.7.7. Financial Services

The financial industry apart from insurance is vulnerable to both slow-onset changes and to more frequent and/or intensive weather-related disasters. Equity investors potentially face a higher exposure than debt investors, due to exit conditions and a focus on longer-term returns in equity markets, but ultimately the impact on debt investors depends on the exposure of credit collateral to climate change (Stenek et al., 2010). In the short- to medium-term, the financial sector is better sheltered from climate change due to high capital mobility, an ability to hedge

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

Structural element	Example/explanation
Public–private arrangements involving government intervention on the non-diversifiable disaster risk portion	Systems with government intervention range from ex ante risk financing design, such as public monopoly natural hazard insurance (e.g., Switzerland, with inter-cantonal pool) or compulsory forms of coverage to maximize the pool of insureds (e.g., Spain, France, with unlimited state guarantee on top), to ex post financing design, such as taxation-based governmental relief funds (e.g., Austria, Netherlands). In between these boundaries rank predominantly private insurance markets, in several countries combined with governmental post-disaster ad hoc relief (e.g., Germany, Italy, UK, Poland, USA)[13]; see also [1,3,4,10,11,12,14].
Care for people who cannot afford insurance	Either by funds outside the insurance system, e.g., insurance vouchers, or by premium subsidies (particularly for the catastrophic risk portion).[1,6,14]
Public-private partnership to expedite agricultural development	Insurance improves the farmers' creditworthiness, which in turn strengthens their adaptive capacity. For instance, by means of loans farmers can step from low-yield to higher-yield cropping systems.[2,8,9]
Concepts for adaptation-oriented climate change risk management frameworks linked to United Nations Framework Convention on Climate Change (UNFCCC)	Risk prevention and risk reduction often are the starting points that can absorb many of the smaller weather risks, and various forms of insurance, including international coordination, are meant to cover all of the remaining risks.[7,15,16] A global framework, where the wealthy agree to pool risks with the most vulnerable, equals social insurance that is different from a risk-based share in insurance funds.[5]

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

against a range of business risks, and an aptitude for the development of new products to cater for changing demand in particular with respect to risk transfers and investment in growing markets (Oliver Wyman, 2007; Whalley and Yuan, 2009). In the longer-term, some risks associated with climate change will be more difficult to diversify in particular for financial institutions with local reach.

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

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

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

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

10.7.8. Summary

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

10.8. Services Other than Tourism and Insurance

Other service sectors of the economy include waste management, wholesale and retail trade, engineering, government, education, defense, and health. Contributions to the economy vary substantially by country; however, overall worldwide economic activity related to government accounts for approximately 30% of global expenditures.

10.8.1. Sectors Other than Health

The literature on the impact of climate change on other sectors of the economy is sparse (see Section SM10.1 of the on-line supplementary material). Few studies have evaluated the possible impacts of climate change, and particularly the economic impacts, on these sectors. Tamiotti et al. (2009) conducted a qualitative assessment of climate and trade. Travers and Payne (1998) and Subak et al. (2000) find that weather affects retail, mostly through transfers in the economy. Sabbioni et al. (2009) note that climate change may require a greater effort to protect cultural heritage. Chapter 12 discusses the impact of climate change on violent conflict, which has implications for military expenditures.

10.8.2. Health

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

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

Although the proportion of individuals seeking medical treatment during a disaster is typically a small subset of the total number of those affected, the additional burden on health care facilities can be significant (Hess et al., 2009). Six weather and climate events that struck the USA between 2000 and 2009 were estimated to have increased health care costs by US$740 million, reflecting more than 760,000 encounters with the health care system (Knowlton et al., 2011). Hospitalizations, with attendant costs, can increase from cases of heat stress, heat stroke, and

Frequently Asked Questions

FAQ 10.3 | Are other economic sectors vulnerable to climate change too?

Economic activities such as agriculture, forestry, fisheries, and mining are exposed to the weather and thus vulnerable to climate change. Other economic activities, such as manufacturing and services, largely take place in controlled environments and are not really exposed to climate change. However, markets connect sectors so that the impacts of climate change spill over from one activity to all others. The impact of climate change on economic development and growth also affects all sectors.

acerbations of cardiorespiratory diseases and other health conditions during heat waves (e.g., Lin et al., 2012; Astrom et al., 2013), and from the adverse health impacts of other extreme events (Sections 11.4.1-2). For example, one trauma center in the USA found a 5% increase in hourly admissions for each approximately 5°C increase in temperature (Rising et al., 2006). Individuals looking for an air-conditioned location during high ambient temperatures can further increase hospital visits (Carthey et al., 2009).

Climate change is projected to increase the burden of major worldwide causes of childhood mortality, including malnutrition, diarrheal diseases, and malaria (Sections 11.5.1-2, 11.6.1). Any increase in health burdens or risks would increase the demands for public health services (e.g., surveillance and control programs) and the demands for health care and relevant supplies (e.g., antimalarials, insecticide-treated bednets, oral rehydration). Studies estimating the costs of additional cases of climate-sensitive health outcomes focus on the costs of treatment, typically omitting the costs of providing additional health services, implementing new policies, and health actions in other sectors (Hutton, 2011). Because most climate change-related cases of adverse health outcomes are projected to occur in low-income countries, treatment costs will primarily be borne by families where governments provide limited health care (WHO, 2004). Time off from work to care for sick children could affect productivity.

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

Estimates of the costs of treating future cases of adverse health outcomes from climate change are in the range of billions of US$ annually (Ebi, 2008; Pandey, 2010). An estimate of the worldwide costs in 2030 of additional cases of malnutrition, diarrheal disease, and malaria due to climate change—assuming no population or economic growth, emissions reductions resulting in stabilization at 750 ppm CO_2-eq in 2210, and current costs of treatment in developing countries—estimated treatment costs without adaptation could be US$4 to 12 billion worldwide, depending on assumptions of the sensitivity of these health outcomes to climate change (Ebi, 2008). The costs for additional infrastructure and health care workers were not estimated, nor were the costs of additional public health services, such as surveillance and monitoring. The costs were estimated to be unevenly distributed, with most of the costs borne by developing countries, particularly in Southeast Asia and Africa, to address the projected approximately 3 to 5% increase in the number of cases of diarrheal disease and malaria from the 2002 baseline (Markandya and Chaibai, 2009). The prevalence of these diseases have since declined (http://apps.who.int/gho/data/node.main.14?lang=en; Section 11.1.1), although there is considerable uncertainty in mortality data from many low-income countries because of the low proportion of deaths covered by vital registration programs (Byass et al., 2013).

A second global estimate assumed UN population projections, strong economic growth, updated projections of the current health burden of diarrheal diseases and malaria, two climate scenarios, and updated estimates of the costs of malaria treatment (Pandey, 2010). In 2010, the average annual adaptation costs for treating diarrheal disease and malaria were estimated to be US$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 US$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 due primarily to a reduction in the baseline burden of disease and lower costs for malaria treatment.

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

Estimated additional health care costs for climate change-related cases of malaria are similar in southern Africa (van Rensburg and Blignaut, 2002). Ranges for (low-high) additional cost scenarios for the prevention and treatment of malaria in South Africa in 2025 were estimated to be approximately US$280 to 3764 million. Estimates for Botswana and Namibia are US$9 to 124 million and US$13 to 177 million, respectively. The high cost scenario for Namibia is about 4.6% of GDP. The climate change-related malaria inpatient and outpatient treatments costs at the end of the century (2080–2100) in 25 African countries[1] indicated that even marginal changes in temperature and precipitation could affect the number of malaria cases, with increases in most countries and decreases in others (Egbendewe-Mondzozo et al., 2011). The end of century treatment costs as a proportion of annual 2000 health expenditures per 1000 people would increase in the vast majority of countries, with increases of more than 20% in inpatient treatment costs for Burundi, Côte D'Ivoire, Malawi, Rwanda, and Sudan.

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

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

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

10.9. Impacts on Markets and Development

Prior sections of this chapter present the direct impacts of climate change on the economy sector by sector. There are, however, also indirect impacts, from the one sector on the rest of the economy (Section 10.9.1) and on economic growth and development (Section 10.9.2).

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

10.9.1. Effects of Markets

There are three channels through which economic impact diffuse. First, outputs of one sector are used as inputs to other sectors. For example, a change in crop yields would affect the food-processing industry. Second, products compete for the consumers' finite budget. If, for example, food becomes more expensive, a consumer would shift to cheaper food but also spend less money on other goods and services. Third, sectors compete for the primary factors of production (labor, capital, land, water). If, besides more fertilizers and irrigation, more labor is needed in agriculture to offset a drop in crop yields, less labor is available to produce other goods and services. Firms and households react to changes in relative prices, domestically and internationally. Ignoring these effects would lead to biased estimates of the impacts of climate change.

General equilibrium analysis describes how climate change impacts in one sector propagate to the rest of the economy, how impacts in one country influence other countries, and how macroeconomic conditions affect each impact (Ginsburgh and Keyzer, 1997). General equilibrium models can provide a comprehensive and internally consistent analysis of the medium-term impact of climate change on economic activity and welfare. However, these models necessarily make a number of simplifying assumptions, particularly with regard to the rationality of consumers and producers and the absence of market imperfections. Other types of economic models have yet to be applied to the estimation of indirect economic effects of climate change.

Computable general equilibrium models have long been used to study the wider economic implications of changes in crop yields. 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 (Kane et al., 1992; Reilly et al., 1994; Winters et al., 1998; Yates and Strzepek, 1998; Darwin and Kennedy, 2000; Darwin, 2004). This has been extended to land use (Lee, 2009; Ronneberger et al., 2009), water use (Kane et al., 1992; Calzadilla et al., 2011), 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 SLR (Darwin and Tol, 2001; Bosello et al., 2007b), tourism (Berrittella et al., 2006; Bigano et al., 2008), human health (Bosello et al., 2006), and energy (see Section 10.2).

Bigano et al. (2008) study the joint, global impact on tourism and coasts in the 21st century, finding that changes in tourist demand dominate the welfare impacts of SLR. Kemfert (2002) and Eboli et al. (2010) estimate the joint, global effect on the world economy of a range of climate change impacts in the 21st century, but conflate general equilibrium and growth effects. Aaheim et al. (2010) analyze the economic effects of impacts of climate change on agriculture, forestry, fishery, energy demand, hydropower production, and tourism on the Iberian Peninsula. They find positive impacts on output in some sectors (agriculture,

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electricity), negative impacts in other sectors (forestry, transport), and negligible ones in others (manufacturing, services). Ciscar et al. (2011) study the combined impact on agriculture, coasts, river floods, and tourism in the current European economy. They find an average welfare loss of 0.2 to 1.0% (depending on the SRES scenario) but there are large regional differences with losses in southern Europe and gains in northern Europe.

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

10.9.2. Aggregate Impacts

Since AR4, four new estimates of the global aggregate impact on human welfare of moderate climate change were published (Maddison and Rehdanz, 2011; Bosello et al., 2012; Roson and van der Mensbrugghe, 2012), including two estimates for warming greater than 3°C. Estimates agree on the size of the impact (small relative to economic growth), and 17 of the 20 impact estimates shown in Figure 10-1 are negative. Losses accelerate with greater warming, and estimates diverge. The new estimates have slightly widened the uncertainty about the economic impacts of climate.

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

10.9.3. Social Cost of Carbon

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

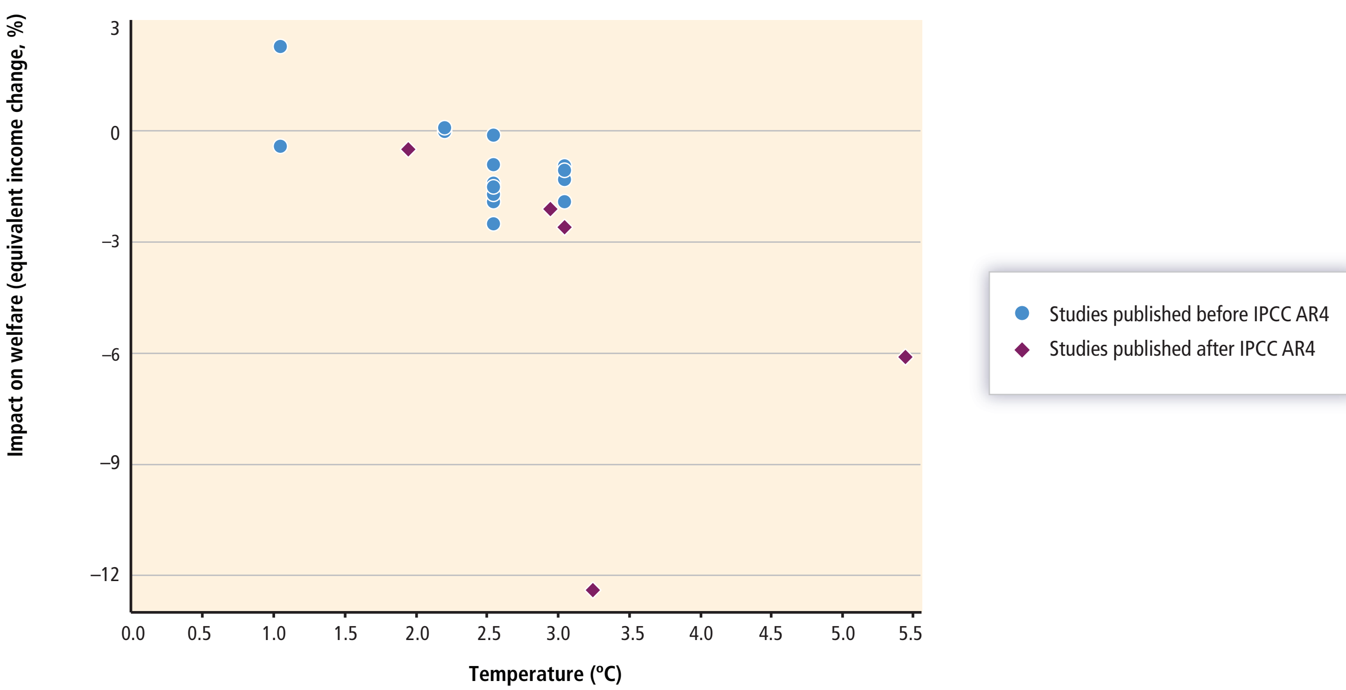

Figure 10-1 | Estimates of the total impact of climate change plotted against the assumed climate change (proxied by the increase in the global mean surface air temperature); studies published since IPCC AR4 are highlighted as diamonds; see Table SM10-1.

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

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

Sources: See Section SM10.2 of the on-line supplementary material.

PRTP = pure rate of time preference.

See Table 10-9. For comparison, the EU ETS price in July 2013 was about US$21/tC.

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

Quantitative analyses have shown that SCC estimates can vary by at least approximately two times depending on assumptions about future demographic conditions (Interagency Working Group on the Social Cost of Carbon, 2010), at least approximately three times owing to the incorporation of uncertainty (Kopp et al., 2012), and at least approximately four times owing to differences in discounting (Tol, 2011) or alternative damage functions (Ackerman and Stanton, 2012).

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

10.9.4. Effects on Growth

10.9.4.1. The Rate of Economic Growth

Climate change will also affect economic growth and development, but our understanding is limited. Fankhauser and Tol (2005) investigate four

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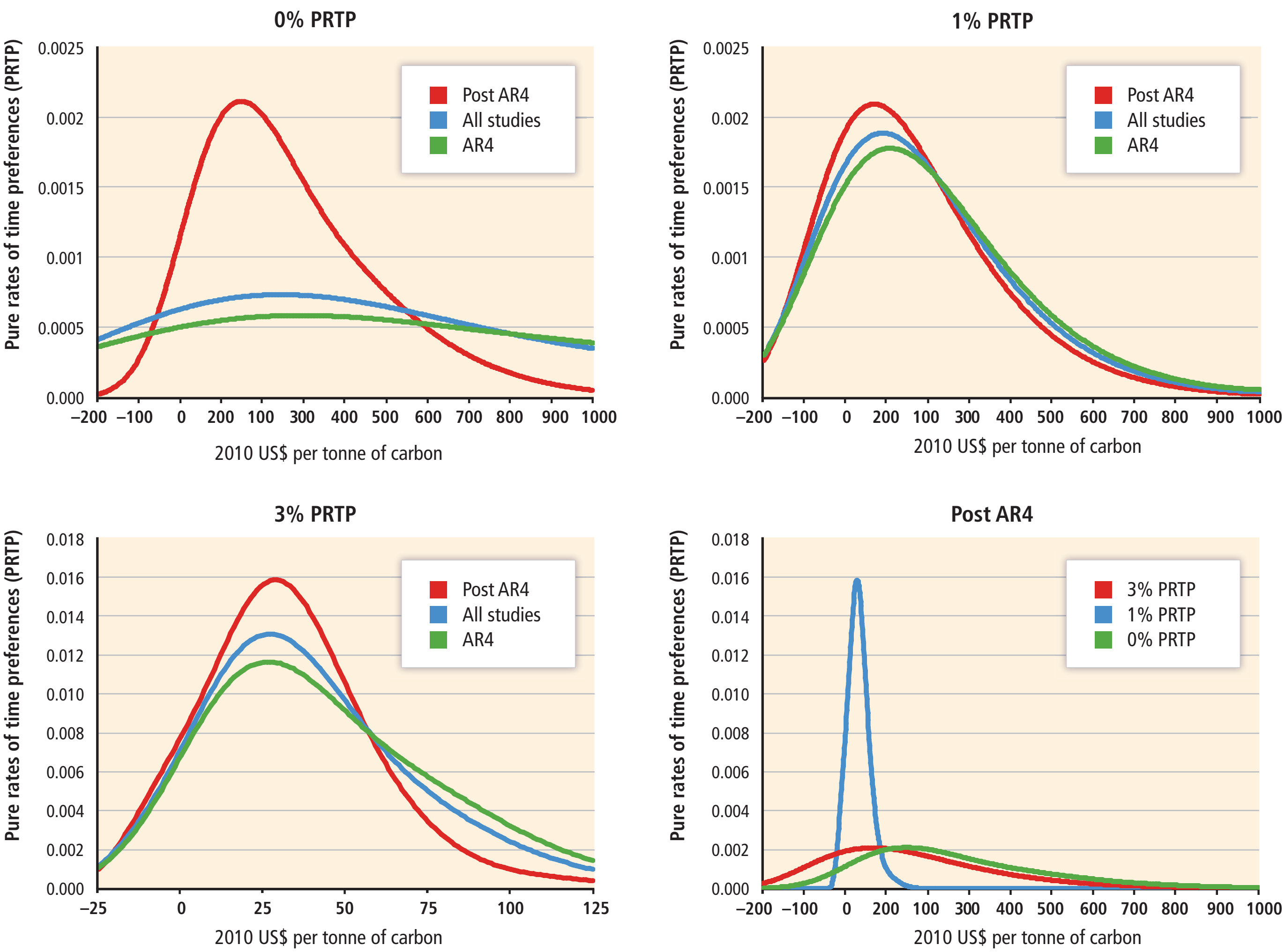

Figure 10-2 | Kernel densities of the social cost of carbon for all studies and studies before or after AR4 for three alternative pure rates of time preference (PRTP).

standard models of economic growth and three transmission mechanisms: economic production, capital depreciation, and the labor force. They find that, in three models, the fall in economic output is slightly larger than the direct impact on markets while in the fourth model (which emphasizes human capital accumulation) indirect impacts are 1.5 times as large. The difference can be understood as follows. In the three models, the impacts of climate change crowd out consumption and investment in physical capital, while in the fourth model investment in human capital is also crowded out; lower investment implies slower growth. Hallegatte (2005) reaches a similar conclusion. Hallegatte and Thery (2007), Hallegatte and Ghil (2008), and 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. In addition, Eboli et al. (2010) use a multi-sector, multi-region growth model, and find that the impact of climate change would lead to a 0.3% reduction of global GDP in 2050. Regional impacts are more pronounced, ranging from –1.0% in developing countries to +0.4% in Australia and Canada. In contrast, Garnaut (2008) finds –2.1% for Australia; the difference is due mainly to impacts on infrastructure (cf. Section 10.4). Sectoral results are varied too, with output changes ranging from +0.5% for power generation (to meet increased demand to air conditioning) to –0.7% for natural gas (as demand for space heating falls).

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

There are also statistical analyses of the relationship between climate and economic growth. Barrios et al. (2010) find that the decline in rainfall in the 20th century partly explains the economies of sub-Saharan Africa have grown more slowly than those of other developing regions. Brown et al. (2011) corroborate this. Dell et al. (2012) find that, in the second half of the 20th century, anomalously hot weather slowed down economic growth in poor countries, in both the agricultural and the industrial sectors. Dell et al. (2009) find that 1°C of warming would reduce income by 1.1% in the short run, and by 0.5% in the long run. The difference is due to adaptation. Horowitz (2009) finds a much larger effect: a 3.8% drop in income in the long run for one degree of warming. The impact of natural disasters on economic growth in the long-term is disputed, with studies reporting positive effects (Skidmore and Toya, 2002), negative effects (Raddatz, 2009), and no discernible effects (Cavallo et al., 2013).

10.9.4.2. Poverty Traps

Poverty is concentrated in the tropics and subtropics. This has led some analysts to the conclusion that a tropical climate is one in a complex of causes of poverty (which itself is a cause of poverty). We here focus on national economies, while Chapter 13 discusses groups of people in poverty. Gallup et al. (1999) emphasize the link between climate, disease, and poverty while Masters and McMillan (2001) focus on climate, agricultural pests, and poverty. Other studies (Acemoglu et al., 2001, 2002; Easterly and Levine, 2003) argue that climatic influence on development disappears if differences in human institutions (the rule of law, education, etc.) are accounted for. However, Van der Vliert (2008) demonstrates that climate affects human culture and thus institutions, but this has yet to be explored in the economic growth literature. Brown et al. (2011) find that weather affects economic growth in sub-Saharan Africa—particularly, drought decelerates growth. Jones and Olken (2010) find that exports from poor countries fall during hot years. Bloom et al. (2003) find limited support for an impact of climate (rather than weather) on past growth in a single-equilibrium model, but strong support in a multiple-equilibrium model: hot and wet conditions and large variability in rainfall reduce long-term growth in poor countries (but not in hot ones) and increase the probability of being poor.

Galor and Weil (1996) speculate about the existence of a climate-health-poverty trap. Strulik (2008), Bonds et al. (2010), Bretschger and Valente (2011), Gollin and Zimmermann (2012), and Ikefuji and Horii (2012) posit theoretical models and offer limited empirical support, while Tang et al. (2009) offers more rigorous empirical evidence. This is further supported by yet-to-be-published analyses (Gollin and Zimmermann, 2008; Ikefuji et al., 2010). Climate-related diseases such as malaria and diarrhea impair children's cognitive and physical development. This contributes to poverty in their later life so that there are limited means to protect their own children against these diseases. Furthermore, high infant mortality may induce parents to have many children so that the investment in education is spread thin. An increase in infant and child mortality and morbidity due to climate change could thus trap more people in poverty.

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 macroeconomic level, natural disasters disproportionally affect the growth rate of poor countries (Noy, 2009).

Devitt and Tol (2012) construct a model with a conflict-poverty trap, and show that climate change may exacerbate this. Bougheas et al. (1999, 2000) show that more expensive infrastructure, for example, because of frequent repairs after natural disasters, slows down economic growth and that there is a threshold infrastructure cost above which trade and specialization do not occur, suggesting another mechanism through which climate could cause a poverty trap. The implications of climate change have yet to be assessed.

10.9.5. Summary

In sum, estimates of the aggregate economic impact of climate change are relatively small but with a large downside risk. Estimates of the incremental damage per tonne of CO_2 emitted vary by two orders of magnitude, with the assumed discount rate the main driver of the differences between estimates. The literature on the impact of climate and climate change on economic growth and development has yet to reach firm conclusions. There is agreement that climate change would slow economic growth, by a little according to some studies and by a lot according to other studies. Different economies will be affected differently. Some studies suggest that climate change may trap more people in poverty.

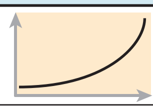
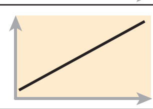
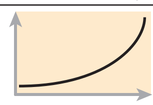
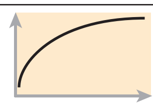
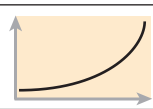
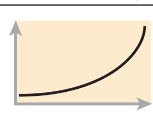
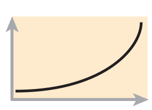
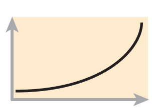
10.10. Summary; Research Needs and Priorities

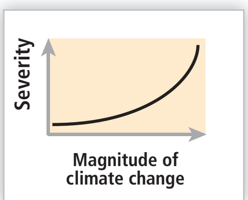
Table 10-10 summarizes the main findings. For each of the sectors discussed above, it gives the main climate drivers, the relationship between climate and impact (limited to less than linear, linear, and more than linear), the sign of the impacts (where needed split by economic actor), drivers other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

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

Based on a comprehensive assessment across economic sectors, few key sectors have been subject to detailed research. Multiple aspects of energy impacts have been assessed, but others remain to be evaluated, particularly economic impact assessments of adaptation both on existing and future infrastructure, but also the costs and benefits for future systems under differing climatic conditions. Studies focused on the impacts of

Table 10-10 | Summary of findings.

Sector	Climate change drivers	Sensitivity to climate change	Sign	Other drivers	Relative impact of climate change to other drivers
Winter tourism	• Temperature • Snow		Negative	• Population • Lifestyle • Income • Aging	Much less
Summer tourism	• Temperature • Rainfall • Cloudiness		Negative for suppliers in low altitudes and latitudes Positive for suppliers in high altitudes and latitudes Neutral for tourists	• Population • Income • Lifestyle • Aging	Much less
Cooling demand	• Temperature • Humidity • Hot spells		Positive for suppliers Negative for consumers	• Population • Income • Energy prices • Technology change	Less
Heating demand	• Temperature • Humidity • Cold spells		Negative for suppliers Positive for consumers	• Population • Income • Energy prices • Technology change	Less
Health services	• Temperature • Precipitation		Positive for suppliers Negative for consumers	• Aging • Income • Diet/lifestyle	Less
Water infrastructure and services	• Temperature • Precipitation • Storm Intensity • Seasonal Variability		Negative for water users Positive for suppliers Spatially heterogeneous	• Population • Income • Urbanization • Regulation	Less in developing countries Equal in developed countries
Transportation	• Temperature • Precipitation • Storm intensity • Seasonal variability • Freeze/thaw cycles		Negative for all users Positive for transport construction industry	• Population • Income • Urbanization • Regulation • Mode shifting • Consumer and commuter behavior	Much less in developing countries Less in developed countries
Insurance	• Temperature • Precipitation • Storm intensity • Seasonal variability • Freeze/thaw cycles		Negative for consumers Neutral for suppliers	• Population • Income • Regulation • Product innovation	Less or equal in developing countries Equal or more in developed countries



climate change on the energy sector indicate both potential benefits and detrimental impacts across developed and developing countries. In energy supply, the deployment of extraction, transport and processing infrastructure, power plants, and other installations are expected to proceed rapidly in developing countries in the coming decades to satisfy fast growing demand for energy. Designing newly deployed facilities with a view to projected changes in climate attributes and extreme weather patterns would require targeted inquiries into the impacts of climate change on the energy-related resource base, conversion, and transport technologies.

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

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

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

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

The spillover effects of the impacts of climate change in one sector on other markets are understood in principle, but the number of quantitative studies is too few to place much confidence in the numerical results. Similarly, the impact of climate and climate change on economic growth and development is not well understood, with some studies pointing to a small or negligible effect and other studies arguing for a large or dominant effect. A limited set of studies have evaluated the aggregate economic impact of climate change up to 3°C annual mean temperature rise, while only one study has evaluated larger temperature scenarios, suggesting considerable new analysis is warranted to improve confidence in the conclusions and investigation of a broader suite of Representative Concentration Pathways (RCPs).

References

Aaheim, A., H. Amundsen, T. Dokken, T. Ericson, and T. Wei, 2009: *A Macroeconomic Assessment of Impacts and Adaptation of Climate Change in Europe.* CICERO Report 2009:06, Center for International Climate and Environmental Research (CICERO), Oslo, Norway, 50 pp.

Aaheim, A., T. Dokken, S. Hochrainer, A. Hof, E. Jochem, R. Mechler, and D.P. van Vuuren, 2010: National responsibilities for adaptation strategies: lessons from four modelling framework. In: *Making Climate Change Work for Us: European Perspectives on Adaptation and Mitigation Strategies* [Hulme, M. and H. Neufeldt (eds.)]. Cambridge University Press, Cambridge, UK, pp. 87-112.

Aaheim, A., R.K. Chaturvedi, and A.D. Sagadevan, 2011a: Integrated modelling approaches to analysis of climate change impacts on forests and forest management. *Mitigation and Adaptation Strategies for Global Change*, **16(2)**, 247-266.

Aaheim, A., R. Gopalakrishnan, R.K. Chaturvedi, N.H. Ravindranath, A.D. Sagadevan, N. Sharma, and T. Wei, 2011b: A macroeconomic analysis of adaptation to climate change impacts on forests in India. *Mitigation and Adaptation Strategies for Global Change*, **16(2)**, 229-245.

Aakre, S., I. Banaszak, R. Mechler, D. Rübbelke, A. Wreford, and H. Kalirai, 2010: Financial adaptation to disaster risk in the European Union. *Mitigation and Adaptation Strategies for Global Change*, **15**, 721-736.

ABI, 2005: *Financial Risks of Climate Change*. Association of British Insurers (ABI) Report based on research by Climate Change Management in collaboration with Metroeconomica and in partnership with AIR Worldwide Corporation, ABI, London, UK, 39 pp.

Acemoglu, D., S. Johnson, and J.A. Robinson, 2001: The colonial origins of comparative development: an empirical investigation. *American Economic Review*, **91(4)**, 1369-1401.

Acemoglu, D., S. Johnson, and J.A. Robinson, 2002: Reversal of fortune: geography and institutions in the making of the modern world income distribution. *Quarterly Journal of Economics*, **117(4)**, 1231-1294.

Ackerman, F. and E.A. Stanton, 2012: Climate risks and climate prices: revisiting the social cost of carbon. *Economics: The Open-Access, Open-Assessment E-Journal*, **6(10)**, doi:10.5018/economics-ejournal.ja.2012-10.

Acosta-Moreno, R., J. Skea, A. Gacuhi, D.L. Greene, W. Moomaw, T. Okita, A. Riedacker, and T.V. Lien, 1995: Industry, energy, and transportation: impacts and adaptation. In: *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change* [Watson, R.T., M.C. Zinyowera, and R.H. Moss (eds.)]. Cambridge University Press, Cambridge, UK, New York, NY, USA, and Melbourne, Australia, pp. 365-398.

Adger, W.N., S. Agrawala, M.M.Q. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smit, and K. Takahashi, 2007: Assessment of adaptation practices, options, constraints and capacity. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 717-743.

Aerts, J.C.J.H. and W.J.W. Botzen, 2011: Climate change impacts on pricing long-term flood insurance: a comprehensive study for the Netherlands. *Global Environmental Change*, **21**, 1045-1060.

AgroClima, 2013: *AgroClima Informática Avanzada SA de CV*. AgroClima Informática Avanzada SA de CV (AgroClima), a ProAgro subsidiary specializing in climate information, Mexico, DF, Mexico, www.agroclima.com.mx/.

Allard, M., A. Fortier, D. Sarrazin, F. Calmels, D. Fortier, D. Chaumont, J.P. Savard, and Tarussov A., 2007: *L'Impact du Réchauffement Climatique sur les Aéroports du Nunavik: Caractéristiques du Pergélisol et Caractérisation des Processus de*

Dégradation des Pistes. Ressources naturelles Canada (Natural Resources Canada), Ottawa, ON, Canada, 184 pp.

Allison, E.H., A.L. Perry, M.-C. Badjeck, W.N. Adger, K. Brown, D. Conway, A.S. Halls, G.M. Pilling, J.D. Reynolds, N.L. Andrew, and N.K. Dulvy, 2009: Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, **10(2)**, 173-196.

Álvarez-Díaz, M. and J. Rosselló-Nadal, 2010: Forecasting British tourist arrivals in the Balearic Islands using meteorological variables. *Tourism Economics*, **16(1)**, 153-168.

Amelung, B. and A. Moreno, 2012: Costing the impact of climate change on tourism in Europe: results of the PESETA project. *Climatic Change*, **112(1)**, 83-100.

Amelung, B., S. Nicholls, and D. Viner, 2007: Implications of global climate change for tourism flows and seasonality. *Journal of Travel Research*, **45(3)**, 285-296.

Amengual, A., V. Homar, R. Romero, S. Alonso, and C. Ramis, 2012: Projections of the climate potential for tourism at local scales: application to Platja de Palma, Spain. *International Journal of Climatology*, **32(14)**, 2095-2107.

Anthoff, D. and R.S.J. Tol, 2013a: Climate policy under fat-tailed risk: an application of FUND. *Annals of Operations Research*, doi:10.1007/s10479-013-1343-2.

Anthoff, D. and R.S.J. Tol, 2013b: The uncertainty about the social cost of carbon: a decomposition analysis using FUND. *Climatic Change*, **117(3)**, 515-530.

Antonioni, G., S. Bonvicini, G. Spadoni, and V. Cozzani, 2009: Development of a framework for the risk assessment of Na-Tech accidental events. *Reliability Engineering and System Safety*, **94(9)**, 1442-1450.

Apipattanavis, S., K. Sabol, K.R. Molenaar, B. Rajagopalan, Y. Xi, B. Blackard, and S. Patil, 2010: Integrated framework for quantifying and predicting weather-related highway construction delays. *Journal of Construction Engineering and Management*, **136(11)**, 1160-1168.

Arkell, B.P. and G.J.C. Darch, 2006: Impact of climate change on London's transport network. *Municipal Engineer*, **159(ME4)**, 231-237.

Arndt, C. and M. Bacou, 2000: Economy-wide effects of climate variability and climate prediction in Mozambique. *American Journal of Agricultural Economics*, **82(3)**, 750-754.

Arndt, C., J. Thurlow, S. Kenneth, P. Chinowsky, A. Kuriakose, J. Neumann, and R. Nicholls, 2012: Impacts of climate change on development paths for Mozambique. *Review of International Economics*.

Arrow, K.J. and R.C. Lind, 1970: Uncertainty and the evaluation of public investment decisions. *The American Economic Review*, **60(3)**, 364-378.

Astrom, C., H. Orru, J. Rocklöv, G. Strandberg, K.L. Ebi, and B. Forsberg, 2013: Heat-related respiratory hospital admissions in Europe in a changing climate: a health impact assessment. *BMJ Open*, **3(1)**, e001842, doi:10.1136/bmjopen-2012-001842.

Banks, L.L., M.B. Shah, and M.E. Richards, 2007: Effective healthcare system response to consecutive Florida hurricanes. *American Journal of Disaster Medicine*, **2(6)**, 285-295.

Barlas, T.K. and G.A.M. Van Kuik, 2010: Review of state of the art in smart rotor control research for wind turbines. *Progress in Aerospace Sciences*, **46**, 1-27.

Barnett, B.J., C.B. Barrett, and J.R. Skees, 2008: Poverty traps and index-based risk transfer products. *World Development*, **36(10)**, 1766-1785.

Barredo, J.I., D. Sauri, and M.C. Llasat, 2012: Assessing trends in insured losses from floods in Spain 1971-2008. *Natural Hazards and Earth System Sciences*, **12(5)**, 1723-1729, doi:10.5194/nhess-12-1723-2012.

Barrieu, P. and H. Loubergé, 2009: Hybrid cat bonds. *The Journal of Risk and Insurance*, **76(3)**, 547-578.

Barrios, S., L. Bertinelli, and E. Strobl, 2010: Trends in rainfall and economic growth in Africa: a neglected cause of the African growth tragedy. *Review of Economics and Statistics*, **92(2)**, 350-366.

Barthel, F. and E. Neumayer, 2012: A trend analysis of normalized insured damage from natural disasters. *Climatic Change*, **113**, 215-237, doi:10.1007/s10584-011-0331-2.

Barthelmie, R.J., F. Murray, and S.C. and Pryor, 2008: The economic benefit of short-term forecasting for wind energy in the UK electricity market. *Energy Policy*, **36**, 1687-1696.

Becken, S., 2005: Harmonising climate change adaptation and mitigation: the case of tourist resorts in Fiji. *Global Environmental Change*, **15(4)**, 381-393.

Becken, S. and J. Hay, 2007: *Tourism and Climate Change: Risks and Opportunities.* Channel View Publications, Bristol, UK, 352 pp.

Becker, A., S. Inoue, M. Fischer, and B. Schwegler, 2011: Climate change impacts on international seaports: knowledge, perceptions, and planning efforts among port adminstrators. *Climatic Change*, **10(1-2)**, 5-29.

Belle, N. and B. Bramwell, 2005: Climate change and small island tourism: policy maker and industry perspectives in Barbados. *Journal of Travel Research*, **44(1)**, 32-41.

Bengtsson, L., K. Hodges, and E. Roeckner, 2006: Storm tracks and climate change. *Journal of Climate*, **19**, 3518-3543.

Berrittella, M., A. Bigano, R. Roson, and R.S.J. Tol, 2006: A general equilibrium analysis of climate change impacts on tourism. *Tourism Management*, **27(5)**, 913-924.

Bicknell, S. and P. McManus, 2006: The canary in the coalmine: Australian ski resorts and their response to climate change. *Geographical Research*, **44(4)**, 386-400.

Biener, C. and M. Eling, 2012: Insurability in microinsurance markets: an analysis of problems and potential solutions. *The Geneva Papers*, **37(1)**, 77-107, doi:10.1057/gpp.2011.29.

Bigano, A., J.M. Hamilton, and R.S.J. Tol, 2006: The impact of climate on holiday destination choice. *Climatic Change*, **76(3-4)**, 389-406.

Bigano, A., J.M. Hamilton, and R.S.J. Tol, 2007: The impact of climate change on domestic and international tourism: a simulation study. *Integrated Assessment*, **7(1)**, 25-49.

Bigano, A., F. Bosello, R. Roson, and R.S.J. Tol, 2008: Economy-wide impacts of climate change: a joint analysis for sea level rise and tourism. *Mitigation and Adaptation Strategies for Global Change*, **13(8)**, 765-791.

Block, P. and K.M. Strzepek, 2012: Power ahead: meeting Ethiopia's energy needs under a changing climate. *Review of International Economics*, **6(3)**, 476-488.

Bloom, A., V. Kotroni, and K. Lagouvardos, 2008: Climate change impact of wind energy availability in the Eastern Mediterranean using the regional climate model PRECIS. *Natural Hazards and Earth System Sciences*, **8**, 1249-1257.

Bloom, D.E., D. Canning, and J. Sevilla, 2003: Geography and poverty traps. *Journal of Economic Growth*, **8(4)**, 355-378.

Bonds, M.H., D.C. Keenan, P. Rohani, and J.D. Sachs, 2010: Poverty trap formed by the ecology of infectious diseases. *Proceedings of the Royal Society B*, **277(1685)**, 1185-1192.

Borch, K., 1962: Equilibrium in a reinsurance market. *Econometrica*, **30(3)**, 424-444.

Bosello, F., R. Roson, and R.S.J. Tol, 2006: Economy-wide estimates of the implications of climate change: human health. *Ecological Economics*, **58(3)**, 579-591.

Bosello, F., E. De Cian, and R. Roson, 2007a: *Climate Change, Energy Demand and Market Power in a General Equilibrium Model of the World Economy*. CMCC Research Paper No. 10, Centro Euro-Mediterraneo per i Cambiamenti Climatici, Climate Impacts and Policy Division (CMCC), Lecce, Italy,16 pp.

Bosello, F., R. Roson, and R.S.J. Tol, 2007b: Economy-wide estimates of the implications of climate change: sea level rise. *Environmental and Resource Economics*, **37(3)**, 549-571.

Bosello, F., C. Carraro, and E. De Cian, 2009: *An Analysis of Adaptation as a Response to Climate Change*. Working Paper No. 26 Department of Economics, Ca' Foscari University of Venice, Venice, Italy, 60 pp.

Bosello, F., F. Eboli, and R. Pierfederici, 2012: Assessing the economic impacts of climate change. *Review of Energy Environment and Economics*, **Re3**, doi:10.7711/feemre3.2012.02.002.

Botzen, W.J.W. and J.C.J.M. van den Bergh, 2008: Insurance against climate change and flooding in the Netherlands: present, future, and comparison with other countries. *Risk Analysis*, **28(2)**, 413-426.

Botzen, W.J.W. and J.C.J.M. van den Bergh, 2009: Bounded rationality, climate risks, and insurance: is there a market for natural disasters? *Land Economics*, **85(2)**, 265-278.

Botzen, W.J.W. and J.C.J.M. van den Bergh, 2012: Monetary valuation of insurance against flood risk under climate change. *International Economic Review*, **53(3)**, 1005-1025.

Botzen, W.J.W., J.C.J.H. Aerts, and J.C.J.M. van den Bergh, 2009: Willingness of homeowners to mitigate climate risk through insurance. *Ecological Economics*, **68**, 2265-2277.

Botzen, W.J.W., J.C.J.M. van den Bergh, and L.M. Bouwer, 2010a: Climate change and increased risk for the insurance sector: a global perspective and an assessment for the Netherlands. *Natural Hazards*, **52**, 577-598.

Botzen, W.J.W., L.M. Bouwer, and J.C.J.M. van den Bergh, 2010b: Climate change and hailstorm damage: empirical evidence and implications for agriculture and insurance. *Resource and Energy Economics*, **32**, 341-362.

Bougheas, S., P.O. Demetriades, and E.L.W. Morgenroth, 1999: Infrastructure, transport costs and trade. *Journal of International Economics*, **47(1)**, 169-189.

Bougheas, S., P.O. Demetriades, and T.P. Mamuneas, 2000: Infrastructure, specialization, and economic growth. *Canadian Journal of Economics*, **33(2)**, 506-522.

Bourdeau, P., 2009: From après-ski to après-tourism: the Alps in transition? Reflections based on the French situation. *Revue de Geographie Alpine*, **97(3)**, rga.revues.org/1049.
Bouwer, L.M., 2011: Have disaster losses increased due to anthropogenic climate change? *Bulletin of the American Meteorological Society*, **92**, 39-46.
Bouwer, L.M., R.P. Crompton, E. Faust, P. Höppe, and R.A. Pielke Jr., 2007: Confronting disaster losses. *Science*, **318(5851)**, 753.
Boyd, R. and M.E. Ibarraran, 2009: Extreme climate events and adaptation: an exploratory analysis of drought in Mexico. *Environment and Development Economics*, **14**, 371-395.
Brander, L.M., K. Rehdanz, R.S.J. Tol, and P.H.J. van Beukering, 2012: The economic impact of ocean acidification on coral reefs. *Climate Change Economics*, **3(1)**, 1-29.
Breisinger, C., T. Zhu, P. Al Riffai, G. Nelson, R. Robertson, J. Funes, and D. Verner, 2013: Global and local economic impacts of climate change in Syria and options for adaptation. *Climate Change Economics*, **4(1**), doi:10.1142/S2010007813500024.
Bretschger, L. and S. Valente, 2011: Climate change and uneven development. *Scandinavian Journal of Economics*, **113(4)**, 825-845.
Brimble, M. and J. Stewart, 2009: The financial sector and climate change risks, opportunities and overall preparedness. In: *APABIS 2009: Proceedings of the Asia Pacific Academy of Business in Society Conference: Finding Solutions to Global Problems through Stakeholder Engagement, New Social Partnerships and Strategic Alliances for a Sustainable Enterprise Economy, 5 – 6 November 2009, Brisbane, Australia*. Asia Pacific Academy of Business in Society (APABIS), Hamilton, New Zealand, doi:10.2139/ssrn.1460676.
Brown, C., R. Meeks, K. Hunu, and W. Yu, 2011: Hydroclimate risk to economic growth in sub-Saharan Africa. *Climatic Change*, **106(4)**, 621-647.
Bruggeman, V., M.G. Faure, and K. Fiore, 2010: The government as reinsurer of catastrophe risks. *The Geneva Papers*, **35**, 369-390.
Buchholz, W. and M. Schymura, 2012: Expected utility theory and the tyranny of catastrophic risks. *Ecological Economics*, **77**, 234-239.
Buckley, L.B. and M.S. Foushee, 2012: Footprints of climate change in US national park visitation. *International Journal of Biometeorology*, **56(6)**, 1173-1177.
Bujosa, A. and J. Rosselló, 2012: Climate change and summer mass tourism: the case of Spanish domestic tourism. *Climatic Change*, **117(1-2)**, 363-375.
Burby, J.R., 2006: Hurricane Katrina and the paradoxes of government disaster policy: bringing about wise governmental decisions for hazardous areas. *The ANNALS of the American Academy of Political and Social Science*, **604**, 171-191.
Buzinde, C.N., D. Manuel-Navarrete, D. Kerstetter, and M. Redclift, 2010a: Representations and adaptation to climate change. *Annals of Tourism Research*, **37(3)**, 581-603.
Buzinde, C.N., D. Manuel-Navarrete, E.E. Yoo, and D. Morais, 2010b: Tourists' perceptions in a climate of change: eroding destinations. *Annals of Tourism Research*, **37(2)**, 333-354.
Byass, P., d.C. Maximilian, J.G. Wendy, L. Lucie, M. Affette, A.S. Osman, M.T. Stephen, and Z. Basia, 2013: Reflections on the global burden of disease 2010 estimates. *PLoS Med*, **10(7)**, e1001477, doi:10.1371/journal.pmed.1001477.
Bye, T., A. Bruvoll, and F.R. Aune, 2008: Inflow shortages in deregulated power markets – reasons for concern? *Energy Economics*, **30(4)**, 1693-1711.
Callaway, J.M., D.B. Louw, and M. Hellmuth, 2012: Benefits and costs of measures for coping with water and climate change: Berg River Basin, South Africa. In: *Climate Change Adaptation in the Water Sector* [Ludwig, F., P. Kabat, H. van Schaik, and M. van der Valk (eds.)]. Earthscan, London, UK and Sterling, VA, USA, pp. 205-226.
Calzadilla, A., K. Rehdanz, and R.S.J. Tol, 2011: Trade liberalization and climate change: a computable general equilibrium analysis of the impacts on global agriculture. *Water*, **3(2)**, 526-550.
Candel, F.M., 2007: Climate change and the global insurance industry: impacts and problems in Latin America. *The Geneva Papers*, **32**, 29-34.
Carter, M.R., P.D. Little, T. Mogues, and W. Negatu, 2007: Poverty traps and natural disasters in Ethiopia and Honduras. *World Development*, **35(5)**, 835-856.
Carthey, J., V. Chandra, and M. Loosemore, 2009: Adapting Australian health facilities to cope with climate-related extreme weather events. *Journal of Facilities Management*, **7**, 36-51.
Cavallo, E., E. Galiani, I. Noy, and J. Pantano, 2013: Catastrophic natural disasters and economic growth. *Review of Economics and Statistics*, **95(5)**, 1549-1561.
Cavan, G., J.F. Handley, J. Aylen, K. Albertson, J. McMorrow, S. Lindley, and D. McEvoy, 2006: Climate change and the visitor economy in the uplands. *International Journal of Biodiversity Science and Management*, **2(3)**, 170-173.
CCSP, 2007: *Effects of Climate Change on Energy Production and Use in the United States* [Wilbanks, T.J. (coordinating author), V. Bhatt, D.E. Bilello, S.R. Bull, J. Ekmann, W.C. Horak, Y.J. Huang, M.D. Levine, M.J. Sale, D.K. Schmalzer, and M.J. Scott (authors)]. U.S. Climate Change Science Program Synthesis and Assessment Product 4.5, Report by the U.S. Climate Change Science Program (CCSP) and the Subcommittee on Global Change Research, U.S. Department of Energy, Office of Biological & Environmental Research, Washington, DC, USA, 144 pp.
CCSP, 2008: *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I* [Potter, J., V. Burkett, M. Savonis, and D. Dokken (eds.)]. U.S. Climate Change Science Program Synthesis and Assessment Product 4.7, Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, U.S. Department of Transportation, Washington, DC, USA, 445 pp.
City of Chicago, 2008: *Chicago Climate Action Plan: Our City*, *Our Future.* City of Chicago, Chicago Climate Task Force (CCTF), Chicago, IL, USA, 56 pp.
Ceron, J.-P. and G. Dubois, 2005: The potential impacts of climate change on French tourism. *Current Issues in Tourism*, **8(2-3)**, 125-139.
Changnon, S.A., 2005: Economic impacts of climate conditions in the United States: past, present, and future – an editorial essay. *Climatic Change*, **68(1-2)**, 1-9.
Changnon, S.A., 2007: Catastrophic winter storms: an escalating problem. *Climatic Change*, **84**, 131-139.
Changnon, S.A., 2008: Assessment of flood losses in the United States. *Journal of Contemporary Water Research & Education*, **138**, 38-44.
Changnon, S.A., 2009a: Characteristics of severe Atlantic hurricanes in the United States: 1949-2006. *Natural Hazards*, **48**, 329-337.
Changnon, S.A., 2009b: Increasing major hail losses in the U.S. *Climatic Change*, **96(1-2)**, 161-166.
Channing, A., P Chinowsky, S Robinson, K. Strzepek, F. Tarp, and J. Thurlow, 2012: Economic development under climate change. *Review of International Economics*, **16(3)**, 369-377, DOI: 10.1111/j.1467-9361.2012.00668.x
Chantarat, S., A.G. Mude, C.B. Barrett, and M.R. Carter, 2013: Designing index-based livestock insurance for managing asset risk in northern Kenya. *The Journal of Risk and Insurance*, **80(1)**, 205-237.
Chapman, L., 2007: Transport and climate change: a review. *Journal of Transport Geography*, **15**, 354-367.
Charpentier, A., 2008: Insurability of climate risks. *The Geneva Papers*, **33**, 91-109.
Chen, C.-C., D. Gillig, and B.A. McCarl, 2001: Effects of climatic change on a water dependent regional economy: a study of the Texas Edwards Aquifer. *Climatic Change*, **49(4)**, 397-409.
Cheng, C.S., Q. Li, G. Li, and H. Auld, 2012: Climate change and heavy rainfall-related water damage insurance claims and losses in Ontario, Canada. *Journal of Water Resource and Protection*, **4(2)**, 49-62, doi:10.4236/jwarp.2012.42007.
Chinowsky, P. and C. Arndt, 2012: Climate change and roads: a dynamic stressor–response model. *Review of Development Economics*, **16(3)**, 448-462.
Chinowsky, P., K.M. Strzepek, P. Larsen, and A. Opdahl, 2010: Adaptive climate response cost models for infrastructure. *ASCE Journal of Infrastructure Systems*, **16**, 173-181.
Chinowsky, P., C. Hayles, A. Schwwikert, N. Strzepek, K.M. Strzepek, and C.A. Schlosser, 2011: Climate change: comparative impact on developing and developed countries. *The Engineering Project Organization Journal*, **1(1)**, 67-80.
Chinowsky, P.S., A.E. Schweikert, N.L. Strzepek, and K.M. Strzepek, 2013: *Infrastructure and Climate Change: Impacts and Adaptations for the Zambezi River Valley.* UNU-WIDER Working Paper, WP/2013/041, United Nations University-World Institute for Development Economics Research (UNU-WIDER), Helsinki, Finland, 14 pp.
Choi, O. and A. Fisher, 2003: The impacts of socioeconomic development and climate change on severe weather catastrophe losses: Mid-Atlantic Region (MAR) and the U.S. *Climatic Change*, **58(1-2)**, 149-170.
Ciscar, J.-C., A. Iglesias, L. Feyen, L. Szabó, D. Van Regemorter, B. Amelung, R. Nicholls, P. Watkiss, O.B. Christensen, R. Dankers, L. Garrote, C.M. Goodess, A. Hunt, A. Moreno, J. Richards, and A. Soria, 2011: Physical and economic consequences of climate change in Europe. *Proceedings of the National Academy of Sciences of the United States of America*, **108(7)**, 2678-2683.
Clarke, D.J. and D. Grenham, 2012: Microinsurance and natural disasters: challenges and options. *Environmental Science & Policy*, **27(Suppl. 1)**, S89-S98.
Cogan, D.G., M. Good and E. McAteer, 2008: *Corporate Governance and Climate Change: The Banking Sector.* Ceres Report produced by the RiskMetrics Group, Ceres, Boston, MA, USA, 55 pp.

10

Collier, B., J. Skees, and B. Barnett, 2009: Weather index insurance and climate change: opportunities and challenges in lower income countries. *The Geneva Papers*, **34**, 401-424.

Cooley, S.R. and S.C. Doney, 2009: Anticipating ocean acidification's economic consequences for commercial fisheries. *Environmental Research Letters*, **4(2)**, doi:10.1088/1748-9326/4/2/024007.

Coombes, E.G., A.P. Jones, and W.J. Sutherland, 2009: The implications of climate change on coastal visitor numbers: a regional analysis. *Journal of Coastal Research*, **25(4)**, 981-990.

Corti, T., V. Muccione, P. Köllner-Heck, D. Bresch, and S.I. Seneviratne, 2009: Simulating past droughts and associated building damages in France. *Hydrology and Earth System Sciences*, **13**, 1739-1747.

Courbage, C., M. Orie, and W.R. Stahel, 2012: 2011 Thai floods and insurance. In: *The Geneva Reports – Risk and Insurance Research No. 5. Extreme Events and Insurance: 2011 annus horribilis* [Courbage, C. and W.R. Stahel (eds.)]. The Geneva Association, The International Association for the Study of Insurance Economics, Geneva, Switzerland, pp. 121-132.

Crompton, R.P. and K.J. McAneney, 2008: Normalised Australian insured losses from meteorological hazards: 1967-2006. *Environmental Science & Policy*, **11**, 371-378.

Crompton, R.P., R.A.J. Pielke, and K.J. McAneney, 2011: Emergence timescales for detection of anthropogenic climate change in US tropical cyclone loss data. *Environmental Research Letters*, **6(1)**, 014003, doi:10.1088/1748-9326/6/1/014003.

Cruz, A.M. and E. Krausmann, 2013: Vulnerability of the oil and gas sector to climate change and extreme weather events. *Climatic Change*, **121(1)**, 41-53.

Cummins, J.D., 2012: CAT bonds and other risk-linked securities: product design and evolution of the market. In: *The Geneva Reports – Risk and Insurance Research No. 5. Extreme Events and Insurance: 2011 annus horribilis* [Courbage, C. and W.R. Stahel (eds.)]. The Geneva Association, The International Association for the Study of Insurance Economics, Geneva, Switzerland, pp. 39-61.

Cummins, J.D. and O. Mahul, 2009: *Catastrophe Risk Financing in Developing Countries: Principles for Public Intervention.* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 268 pp.

Cummins, J.D. and M.A. Weiss, 2009: Convergence of insurance and financial markets: hybrid and securitized risk-transfer solutions. *The Journal of Risk and Insurance*, **76(3)**, 493-545.

Dailey, P., M. Huddleston, S. Brown, and D. Fasking, 2009: *The Financial Risks of Climate Change: Examining the Financial Implications of Climate Change using Climate Models and Insurance Catastrophe Risk Models.* ABI Research Paper No. 19, Report by AIR Worldwide Corporation and the Met Office, The Association of British Insurers, London, UK, 107 pp.

Damigos, D., 2012: Monetizing the impacts of climate change on the Greek mining sector. *Mitigation and Adaptation Strategies for Global Change*, **17(8)**, 865-878.

Darwin, R.F., 2004: Effects of greenhouse gas emissions on world agriculture, food consumption, and economic welfare. *Climatic Change*, **66(1-2)**, 191-238.

Darwin, R.F. and D. Kennedy, 2000: Economic effects of CO_2 fertilization of crops: transforming changes in yield into changes in supply. *Environmental Modeling and Assessment*, **5**, 157-168.

Darwin, R.F. and R.S.J. Tol, 2001: Estimates of the economic effects of sea level rise. *Environmental and Resource Economics*, **19(2)**, 113-129.

Dasgupta, S., M. Huq, H. Khan, Z. Ahmed, N. Mukherjee, M. Khan, and K. Pandey, 2010: *Vulnerability of Bangladesh to Cyclones in a Changing Climate: Potential Damages and Adaptation Cost.* Policy Research Working Paper No. 5280, The World Bank, Development Research Group, Environment and Energy Team, Washington, DC, USA, 54 pp.

Daugherty, D.J., D.L. Buckmeier, and P.K. Kokkanti, 2011: Sensitivity of recreational access to reservoir water level variation: an approach to identify future access needs in reservoirs. *North American Journal of Fisheries Management*, **31(1)**, 63-69.

Dawson, J. and D. Scott, 2010: Climate change and tourism in the great lakes region: a summary of risks and opportunities. *Tourism in Marine Environments*, **6(2-3)**, 119-132.

Dawson, J. and D. Scott, 2013: Managing for climate change in the alpine ski sector. *Tourism Management*, **35**, 244-254.

Dawson, J., D. Scott, and G. McBoyle, 2009: Climate change analogue analysis of ski tourism in the northeastern USA. *Climate Research*, **39(1)**, 1-9, doi:10.3354/cr00793.

Day, J., N. Chin, S. Sydnor, and K. Cherkauer, 2013: Weather, climate, and tourism performance: a quantitative analysis. *Tourism Management Perspectives*, **5**, 51-56.

De Bruin, K., R.B. Dellink, A. Ruijs, L. Bolwidt, A. Van Buuren, J. Graveland, R.S. De Groot, P.J. Kuikman, S. Reinhard, and R.P. Roetter, 2009: Adapting to climate change in The Netherlands: an inventory of climate adaptation options and ranking of alternatives. *Climatic Change*, **95(1-2)**, 23-45.

de Cian, E., E. Lanzi, and R. Roson, 2013: Seasonal temperature variations and energy demand: a panel cointegration analysis for climate change impact assessment. *Climatic Change*, **116(3-4)**, 805-825.

De Freitas, C.R., D. Scott, and G. McBoyle, 2008: A second generation climate index for tourism (CIT): specification and verification. *International Journal of Biometeorology*, **52(5)**, 399-407.

de Lucena, A.F.P., R. Schaeffer, and A.S. Szklo, 2010: Least-cost adaptation options for global climate change impacts on the Brazilian electric power system. *Global Environmental Change*, **20(2)**, 342-350.

de Nooij, M., R. Lieshout, and C. Koopmans, 2009: Optimal blackouts: empirical results on reducing the social cost of electricity outages through efficient regional rationing. *Energy Economics*, **31(3)**, 342-347.

Dell, J.J. and P. Pasteris, 2010: Adaptation in the oil and gas industry to projected impacts of climate change. In: *SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, 2010, 12-14 April, Rio de Janeiro, Brazil*. Vol. 1, Society of Petroleum Engineers (SPE), Richardson, TX, USA, pp. 333-348.

Dell, M., B.F. Jones, and B.A. Olken, 2009: Temperature and income: reconciling new cross-sectional and panel estimates. *American Economic Review*, **99(2)**, 198-204.

Dell, M., B.F. Jones, and B.A. Olken, 2012: Temperature shocks and economic growth: evidence from the last half century. *American Economic Journal: Macroeconomics*, **4(3)**, 66-95.

Denstadli, J.M., J.K.S. Jacobsen, and M. Lohmann, 2011: Tourist perceptions of summer weather in Scandinavia. *Annals of Tourism Research*, **38(3)**, 920-940.

Devitt, C. and R.S.J. Tol, 2012: Civil war, climate change, and development: a scenario study for sub-Saharan Africa. *Journal of Peace Research*, **49(1)**, 129-145.

DOE, 2007: *Concentrating Solar Power Commercial Application Study: Reducing Water Consumption of Concentrating Solar Power Electricity Generation.* U.S. Department of Energy (DOE) Report to Congress, DOE, Washington, DC, USA, 24 pp.

DOE, 2009: *An Analysis of the Effects of Drought Conditions on Electric Power Generation in the United States.* DOE/NETL-2009/1365, U.S. Department of Energy (DOE) and National Energy Technology Laboratory (NREL), DOE, Washington, DC, USA, 32 pp.

DOE, 2013: *U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather.* DOE/PI-0013, U.S. Department of Energy, Office of Policy and International Affairs (DOE-PI) and the National Energy Technology Laboratory (NREL), DOE, Washington, DC, USA, 81 pp.

Donat, M.G., G.C. Leckebusch, S. Wild, and U. Ulbrich, 2011: Future changes in European winter storm losses and extreme wind speeds detected from GCM and RCM multi-model simulations. *Natural Hazards and Earth System Sciences*, **11**, 1351-1370.

Doney, S.C., V.J. Fabry, R.A. Feely, and J.A. Kleypas, 2009: Ocean acidification: the other CO_2 problem. *Annual Review of Marine Science*, **1**, 169-192.

Dore, M. and I. Burton, 2001: *The Costs of Adaptation to Climate Change in Canada: A Stratified Estimate by Sectors and Regions – Social Infrastructure.* Climate Change Laboratory, Brock University, St Catharines, ON, Canada, 338 pp.

DOT, 2002: *The Potential Impacts of Climate Change on Transportation*. Federal Research Partnership Workshop October 1-2, 2002 held at the Brookings Institution, Washington, DC, USA, Summary and Discussion Papers, U.S. Department of Transportation Center for Climate Change and Environmental Forecasting (DOT), Washington, DC, USA, 263 pp.

Droogers, P., 2009: *Climate Change and Hydropower*, *Impact and Adaptation Costs: Case Study Kenya.* FutureWater Report 85, FutureWater, Wageningen, Netherlands, 27 pp.

Dunne, J., S. R., and J. J., 2013: Reductions in labour capacity from heat stress under climate warming. *Nature Climate Change*, **3(3)**, 1-4.

Duus-Otterström, G. and S.C. Jagers, 2011: Why (most) climate insurance schemes are a bad idea. *Environmental Politics*, **20(3)**, 322-339, doi:10.1080/09644016.2011.573354.

Easterly, W. and R. Levine, 2003: Tropics, germs, and crops: how endowments influence economic development. *Journal of Monetary Economics*, **50(1)**, 3-39.

Ebert, I., 2010: Legal aspects of U.S. claims based on greenhouse gas emissions. In: *Liability for Climate Change? Experts' Views on a Potential Emerging Risk.* Munich Re, Munich, Germany, pp. 14-15.

Ebi, K.L., 2008: Adaptation costs for climate change-related cases of diarrhoeal disease, malnutrition, and malaria in 2030. *Globalization and Health*, **4(9)**, doi:10.1186/1744-8603-4-9.

Ebinger, J. and W. Vergara, 2011: *Climate Impacts on Energy Systems: Key Issues for Energy Sector Adaptation.* The International Bank for Reconstruction and Development / The World Bank and Energy Sector Management Assistance Program (ESMAP), The World Bank, Washington, DC, USA, 178 pp.

Eboli, F., R. Parrado, and R. Roson, 2010: Climate-change feedback on economic growth: explorations with a dynamic general equilibrium model. *Environment and Development Economics*, **15(5)**, 515-533.

Eide, A., 2008: An integrated study of economic effects of and vulnerabilities to global warming on the Barents Sea cod fisheries. *Climatic Change*, **87(1-2)**, 251-262.

Eide, A. and K. Heen, 2002: Economic impacts of global warming. A study of the fishing industry in North Norway. *Fisheries Research*, **56(3)**, 261-274.

Eijgelaar, E., C. Thaper, and P. Peeters, 2010: Antarctic cruise tourism: the paradoxes of ambassadorship, "last chance tourism" and greenhouse gas emissions. *Journal of Sustainable Tourism*, **18(3)**, 337-354.

Eisenack, K. and R. Stecker, 2012: A framework for analyzing climate change adaptations as actions. *Mitigation and Adaptation Strategies for Global Change*, **17(3)**, 243-260.

Eisenack, K., R. Stecker, D. Reckien, and E. Hoffmann, 2012: Adaptation to climate change in the transport sector: a review of actions and actors. *Mitigation and Adaptation Strategies for Global Change*, **17**, 451-469.

Ekman, J., 2013: Climate change impacts on coal from resource assessment through to environmental remediation. *Climatic Change*, **21(1)**, 27-39.

Elsasser, H. and R. Bürki, 2002: Climate change as a threat to tourism in the Alps. *Climate Research*, **20(3)**, 253-257.

Emanuel, K., 2011: Global warming effects on U.S. hurricane damage. *Weather, Climate and Society*, **3(4)**, 261-268.

Endler, C. and A. Matzarakis, 2010a: Climatic potential for tourism in the Black Forest, Germany – winter season. *International Journal of Biometeorology*, **55(3)**, 339-351.

Endler, C. and A. Matzarakis, 2010b: Analysis of high-resolution simulations for the Black Forest region from a point of view of tourism climatology – a comparison between two regional climate models (REMO and CLM). *Theoretical and Applied Climatology*, **103(3-4)**, 427-440.

Endler, C. and A. Matzarakis, 2011: Climate and tourism in the Black Forest during the warm season. *International Journal of Biometeorology*, **55(2)**, 173-186.

Endler, C., K. Oehler, and A. Matzarakis, 2010: Vertical gradient of climate change and climate tourism conditions in the Black Forest. *International Journal of Biometeorology*, **54(1)**, 45-61.

EPA, 2001: *Technical Development Document for the Final Regulations Addressing Cooling Water Intake Structures for the New Facilities.*, EPA-821-R-01-036, Office of Water, U.S. Environmental Protection Agency (EPA), Washington, DC, USA, 269 pp.

Eskeland, G.S. and T.K. Mideksa, 2010: Electricity demand in a changing climate. *Mitigation and Adaptation Strategies for Global Change*, **15(8)**, 877-897.

Falk, M., 2013: Impact of long-term weather on domestic and foreign winter tourism demand. *International Journal of Tourism Research*, **15(1)**, 1-17, doi:10.1002/jtr.865.

Fankhauser, S. and R.S.J. Tol, 2005: On climate change and economic growth. *Resource and Energy Economics*, **27(1)**, 1-17.

Fant, C., Y. Gebretsadik, and K.M. Strzepek, 2013: Impact of climate change on crops, irrigation, and hydropower in the Zambezi River Basin. UNU-WIDER Working Paper No. 2013/039, Helsinki, Finland, 26 pp. ISBN 978-92-9230-61-616-8.

Farbotko, C., 2010: 'The global warming clock is ticking so see these places while you can': voyeuristic tourism and model environmental citizens on Tuvalu's disappearing islands. *Singapore Journal of Tropical Geography*, **31(2)**, 224-238.

Faure, M.G. and M. Peeters (eds.), 2011: *Climate Change Liability*. Edward Elgar Publishing, Cheltenham, UK, 304 pp.

Feeley III, T.J., T.J. Skone, G.J. Stiegel Jr, A. McNemar, M. Nemeth, B. Schimmoller, J.T. Murphy, and L. Manfredo, 2008: Water: a critical resource in the thermoelectric power industry. *Energy*, **33(1)**, 1-11.

Feyen, L., R. Dankers, K. Bódis, P. Salamon, and J.I. Barredo, 2012: Fluvial flood risk in Europe in present and future climates. *Climatic Change*, **112(1)**, 47-62.

FHWA, 2006: *Long-Term Pavement Performance (LTPP) Data Analysis Support: National Pooled Fund Study TPF-5(013) – Effects of Multiple Freeze Cycles and Deep Frost Penetration on Pavement Performance and Cost*. Publication No. FHWA-HRT-06-121, U.S. Department of Transportation, Federal Highway Administration (FHWA), Washington, DC, USA, 244 pp.

Fischer, G., T. Francesco, V. Harrij van, and W. David, 2007: Climate change impacts on irrigation water requirements: effects of mitigation, 1990-2080. **74(7)**, 1083-1107.

Ford, J.D., T. Pearce, J. Prno, F. Duerden, L.B. Ford, M. Beaumier, and T. Smith, 2010: Perceptions of climate change risks in primary resource use industries: a survey of the Canadian mining sector. *Regional Environmental Change*, **10(1)**, 65-81.

Ford, J.D., T. Pearce, J. Prno, F. Duerden, L. Berrang Ford, T.R. Smith, and M. Beaumier, 2011: Canary in a coal mine: perceptions of climate change risks and response options among Canadian mine operations. *Climatic Change*, **109(3-4)**, 399-415.

Førland, E.J., J.K. Steen Jacobsen, J.M. Denstadli, M. Lohmann, I. Hanssen-Bauer, H.O. Hygen, and H. Tømmervik, 2012: Cool weather tourism under global warming: comparing Arctic summer tourists' weather preferences with regional climate statistics and projections. *Tourism Management*, **36**, 567-579.

Förster, H. and J. Lilliestam, 2009: Modeling thermoelectric power generation in view of climate change. *Regional Environmental Change*, **10(4)**, 327-338.

Forster, J., P.W. Schuhmann, I.R. Lake, A.R. Watkinson, and J.A. Gill, 2012: The influence of hurricane risk on tourist destination choice in the Caribbean. *Climatic Change*, **114(3-4)**, 745-768.

Furrer, B., J. Hamprecht, and V.H. Hoffmann, 2012: Much Ado about Nothing? How Banks Respond to Climate Change. *Business & Society*, **51(1)**, 62-88.

Füssel, H.-M., 2010: Modeling impacts and adaptation in global IAMs. *Wiley Interdisciplinary Reviews: Climate Change*, **1(2)**, 288-303.

Gabrielsen, K., T. Bye, and F.R. Aune, 2005: *Climate Change-Lower Electricity Prices and Increasing Demand: An Application to the Nordic Countries*. Discussion Paper No. 430, Statistics Norway, Research Department, Kongsvinger, Norway, 34 pp.

Gallup, J.L., J.D. Sachs, and A.D. Mellinger, 1999: Geography and economic development. *International Regional Science Review*, **22(2)**, 179-232.

Galor, O. and D.N. Weil, 1996: The gender gap, fertility, and growth. *American Economic Review*, **86(3)**, 374-387.

GAO, 2010: *National Flood Insurance Program: Continued Actions needed to address Financial and Operational Issues.* GAO-10-1063T, Testimony before the Subcommittee on Housing and Community Opportunity, Committee on Financial Services, House of Representatives, United States Government Accountability Office (GAO), Washington, DC, USA, 22 pp.

GAO, 2011: *Flood Insurance: Public Policy Goals Provide a Framework for Reform.* GAO-11-429T, Testimony before the Subcommittee on Insurance, Housing, and Community Opportunity, Committee on Financial Services, House of Representatives, United States Government Accountability Office (GAO), Washington, DC, USA, 15 pp.

Garnaut, R., 2008: *The Garnaut Climate Change Review: Final Report.* Cambridge University Press, Port Melbourne, Australia, 634 pp.

Garvey, S.D., 2010: Structural capacity and the 20 MW wind turbine. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, **224(8)**, 1083-1115.

Garza-Gil, M.D., J. Torralba-Cano, and M.M. Varela-Lafuente, 2011: Evaluating the economic effects of climate change on the European sardine fishery. *Regional Environmental Change*, **11(1)**, 87-95.

German Insurance Association, 2011: *Auswirkungen des Klimawandels auf die Schadensituation in der deutschen Versicherungswirtschaft. Kurzfassung Hochwasser.* Studie im Auftrag des Gesamtverbandes der Deutschen Versicherungswirtschaft e.V., Produced by Potsdam Institute for Climate Impact Research (PIK), Free University of Berlin (FUB), University of Cologne (Germany), Institute for Applied Water, and Geoinformatics (IAWG) for the German Insurance Association (Gesamtverband der Deutschen Versicherungswirtschaft), GDV, Berlin, Germany, 29 pp.

Gerrard, B.G. (ed.), 2007: *Global Climate Change and U.S. Law*. American Bar Association, Chicago, IL, USA, 784 pp.

Gerstengarbe, F.-W., P.C. Werner, H. Österle, and O. Burghoff, 2013: Winter storm- and summer thunderstorm- related loss events with regard to climate change in Germany. *Theoretical and Applied Climatology*, **114(3-4)**, 715-724, doi:10.1007/s00704-013-0843-y.

Ghesquiere, F. and O. Mahul, 2007: *Sovereign Natural Disaster Insurance for Developing Countries: A Paradigm Shift in Catastrophe Risk Financing*. Policy Research Working Paper, 4345, The World Bank Hazard Risk Management Unit Latin America and Caribbean Region and the Financial Markets for Social Safety Net Department, Financial and Private Sector Development Vice Presidency, The World Bank, Washington, DC, USA, 24 pp.

Giannakopoulos, C., E. Kostopoulou, K.V. Varotsos, K. Tziotziou, and A. Plitharas, 2011: An integrated assessment of climate change impacts for Greece in the near future. *Regional Environmental Change*, **11(4)**, 829-843.

Gibbons, J.H., 2012: Technology and innovation. In: *Energy for Development: Resources*, *Technologies*, *Environment* [Toth, F.L. (ed.)]. Kluwer, Dordrecht, Netherlands, pp. 141-148.

Ginsburgh, V. and M.A. Keyzer, 1997: *The Structure of Applied General Equilibrium Models.* The MIT Press, Cambridge, MA, USA, 555 pp.

Glauber, J.W., 2004: Crop insurance reconsidered. *American Journal of Agricultural Economics*, **86(5)**, 1179-1195.

Gollin, D. and C. Zimmermann, 2008: *Malaria: Disease Impacts and Long-Run Income Differences.* IZA Discussion Paper No. 2997, Forschungsinstitut zur Zukunft der Arbeit Institute for the Study of Labor (IZA), IZA, Bonn, Germany, 25 pp.

Gollin, D. and C. Zimmermann, 2012: Global climate change and the resurgence of tropical disease: an economic approach. *Mathematical Population Studies*, **19(1)**, 51-62.

Golombek, R., S.A.C. Kittelsen, and I. Haddeland, 2011: Climate change: impacts on electricity markets in Western Europe. *Climatic Change*, **113(2)**, 357-370.

Gómez-Martín, M.B., 2006: Climate potential and tourist demand in Catalonia (Spain) during the summer season. *Climate Research*, **32(1)**, 75-87.

Gössling, S. and C.M. Hall, 2006: Uncertainties in predicting tourist flows under scenarios of climate change. *Climatic Change*, **79(3-4)**, 163-173.

Gössling, S., M. Bredberg, A. Randow, E. Sandström, and P. Svensson, 2006: Tourist perceptions of climate change: a study of international tourists in Zanzibar. *Current Issues in Tourism*, **9(4-5)**, 419-435.

Gössling, S., D. Scott, C.M. Hall, J.-P. Ceron, and G. Dubois, 2012: Consumer behaviour and demand response of tourists to climate change. *Annals of Tourism Research*, **39(1)**, 36-58.

Grace, M.F. and R.W. Klein, 2009: The perfect storm: hurricanes, insurance, and regulation. *Risk Management and Insurance Review*, **12(1)**, 81-124.

Graff Zivin, J. and M.J. Neidell, 2010: *Temperature and the Allocation of Time: Implications for Climate Change.* NBER Working Paper 15717, National Bureau of Economic Research (NBER), Washington, DC, USA, 40 pp.

Grey, D. and C.W. Sadoff, 2007: Sink or swim? Water security for growth and development. *Water Policy*, **9(6)**, 545-571.

Guha-Sapir, D., F. Vos, R. Below, and S. Ponserre, 2012: *Annual Disaster Statistical Review 2011: The Numbers and Trends.* Centre for Research on the Epidemiology of Disasters (CRED), Institute of Health and Society (IRSS), Université catholique de Louvain – Brussels, Belgium, 42 pp.

Gusmao, D., 2010: Case-study 2: European airports and sea level rise. In: "*Challenges of Growth" – Environmental Update Study: Climate Adaptation Case Studies* [Thomas, C. and A.J. Drew (eds.)]. European Organisation for the Safety of Air Navigation (EUROCONTROL), Brussels, Belgium, pp. 71-91.

Guy Carpenter, 2011: *Global Reinsurance Outlook, Points of Inflection – Positioning for Change in a Challenging Market.* Guy Carpenter & Company, LLC, New York, NY, USA, 72 pp.

Hall, C.M., 2006: New Zealand tourism entrepreneur attitudes and behaviours with respect to climate change adaptation and mitigation. *International Journal of Innovation and Sustainable Development*, **1(3)**, 229-237.

Hall, J.W., P.B. Sayers, and R.J. Dawson, 2005: National-scale assessment of current and future flood risk in England and Wales. *Natural Hazards*, **36(1-2)**, 147-164.

Hallegatte, S., 2005: The long time scales of the climate-economy feedback and the climatic cost of growth. *Environmental Modeling and Assessment*, **10(4)**, 277-289.

Hallegatte, S. and P. Dumas, 2009: Can natural disasters have positive consequences? Investigating the role of embodied technical change. *Ecological Economics*, **68(3)**, 777-786.

Hallegatte, S. and M. Ghil, 2008: Natural disasters impacting a macroeconomic model with endogenous dynamics. *Ecological Economics*, **68(1-2)**, 582-592.

Hallegatte, S. and D. Thery, 2007: Are the economic impacts of climate change underestimated? *Revue d'Economie Politique*, **117(4)**, 507-522.

Hamilton, J.M., 2007: Coastal landscape and the hedonic price of accommodation. *Ecological Economics*, **62(3-4)**, 594-602.

Hamilton, J.M. and R.S.J. Tol, 2007: The impact of climate change on tourism in Germany, the UK and Ireland: a simulation study. *Regional Environmental Change*, **7(3)**, 161-172.

Hamilton, J.M., D.J. Maddison, and R.S.J. Tol, 2005a: Effects of climate change on international tourism. *Climate Research*, **29(3)**, 245-254.

Hamilton, J.M., D.J. Maddison, and R.S.J. Tol, 2005b: Climate change and international tourism: a simulation study. *Global Environmental Change*, **15(3)**, 253-266.

Hamilton, L.C., C. Brown, and B.D. Keim, 2007: Ski areas, weather and climate: time series models for New England case studies. *International Journal of Climatology*, **27(15)**, 2113-2124.

Hamlet, A.F., S.Y. Lee, K.E.B. Mickelson, and M.M. Elsner, 2010: Effects of projected climate change on energy supply and demand in the Pacific Northwest and Washington State. *Climatic Change*, **102(1-2)**, 103-128.

Hamzah, J., A. Habibah, A. Buang, K. Jusoff, M.E. Toriman, M.J. Mohd. Fuad, A.C. Er, and A.M. Azima, 2012: Flood disaster, impacts and the tourism providers' responses: the Kota Tinggi experience. *Advances in Natural and Applied Sciences*, **6(1)**, 26-32.

Hanewinkel, M., D.A. Cullmann, M.-J. Schelhaas, G.-J. Nabuurs, and N.E. Zimmermann, 2013: Climate change may cause severe loss in the economic value of European forest land. *Nature Climate Change*, **3(3)**, 203-207.

Harrison, S.J., S.J. Winterbottom, and C. Sheppard, 1999: The potential effects of climate change on the Scottish tourist industry. *Tourism Management*, **20(2)**, 203-211.

Haug, O., X.K. Dimakos, J.F. Vardal, M. Aldrin, and E. Meze-Hausken, 2011: Future building water loss projections posed by climate change. *Scandinavian Actuarial Journal*, **2011(1)**, 1-20, doi:10.1080/03461230903266533.

Haugen, J.E. and T. Iversen, 2008: Response in extremes of daily precipitation and wind from a downscaled multi- model ensemble of anthropogenic global climate change scenarios. *Tellus A*, **60(3)**, 411-426.

Hecht, S.B., 2008: Climate change and the transformation of risk: insurance matters. *UCLA Law Review*, **55**, 1559-1620.

Hein, L., M.J. Metzger, and A. Moreno, 2009: Potential impacts of climate change on tourism: a case study for Spain. *Current Opinion in Environmental Sustainability*, **1(2)**, 170-178.

Heintz, J.E., M.H. Kanemitsu, and E. Scanlan, 2009: Insurance coverage for climate change suits: the battle has begun. *Environmental Claims Journal*, **21(1)**, 29-51.

Held, H., F.-W. Gerstengarbe, T. Pardowitz, J.F. Pinto, U. Ulbrich, K. Born, M.G. Donat, M.K. Karremann, G.C. Leckebusch, P. Ludwig, K.M. Nissen, H. Österle, B.F. Prahl, P.C. Werner, D.J. Befort, and O. Burghoff, 2013: Projections of global warming-induced impacts on winter storm losses in the German private household sector. *Climatic Change*, **121(2)**, 195-207.

Henderson, J., C. Rodgers, R. Jones, J. Smith, K. Strzepek, and J. Martinich, 2013: Economic impacts of climate change on water resources in the coterminous United States. *Mitigation and Adaptation Strategies for Global Change*, doi:10.1007/s11027-013-9483-x.

Hendrikx, J. and E.Ö. Hreinsson, 2012: The potential impact of climate change on seasonal snow in New Zealand: part II – industry vulnerability and future snow-making potential. *Theoretical and Applied Climatology*, **110(4)**, 619-630.

Hendrikx, J., E.Ö. Hreinsson, M.P. Clark, and A.B. Mullan, 2012: The potential impact of climate change on seasonal snow in New Zealand: part I – an analysis using 12 GCMs. *Theoretical and Applied Climatology*, **110(4)**, 607-618.

Hendrikx, J., C. Zammit, E.Ö. Hreinsson, and S. Becken, 2013: A comparative assessment of the potential impact of climate change on the ski industry in New Zealand and Australia. *Climatic Change*, **119(3-4)**, 965-978.

Herbold, J., 2013a: New approaches to agricultural insurance in developing economies. In: *Finance for Food: Towards New Agricultural and Rural Finance* [Köhn, D. (ed.)]. Kreditanstalt für Wiederaufbau (KfW), Springer, Heidelberg, Gemany (in press).

Herbold, J., 2013b: Index insurance in agriculture – the (re)insurer's perspective. In: *The Challenges of Index-Based Insurance for Food Security in Developing Countries* [Gommes, R. and F. Kayitakire (eds.)]. Proceedings of a technical workshop organised by the EC Joint Research Centre (JRC) and the International Research Institute for Climate and Society (IRI, Earth Institute, Columbia University), JRC Ispra, Italy, 2 and 3 May 2012, European Union Publication Office, Luxembourg, Luxembourg, pp. 47-54.

Hertin, J., F. Berkhout, D.M. Gann, and J. Barlow, 2003: Climate change and the UK house building sector: perceptions, impacts and adaptive capacity. *Building Research and Information*, **31(3-4)**, 278-290.

Herweijer, C., N. Ranger, and R.E.T. Ward, 2009: Adaptation to climate change: threats and opportunities for the insurance industry. *The Geneva Papers*, **34**, 360-380.

Hess, U. and P. Hazell, 2009: Sustainability and scalability of index-based insurance for agriculture. In: *Innovations in Insuring the Poor* [Vargas Hill, R. and M. Torrero (eds.)]. The International Food Policy Research Institute (IFPRI), Washington, DC, USA, pp. 13-14.

Hess, J.J., K.L. Heilpern, T.E. Davis, and H. Frumkin, 2009: Climate change and emergency medicine: impacts and opportunities. *Academic Emergency Medicine*, **16(8)**, 782-794.

Hill, M., A. Wallner, and J. Furtado, 2010: Reducing vulnerability to climate change in the Swiss Alps: a study of adaptive planning. *Climate Policy*, **10(1)**, 70-86.

Hilmi, N., D. Allemand, S. Dupont, A. Safa, G. Haraldsson, P.A.L.D. Nunes, C. Moore, C. Hattam, S. Reynaud, J.M. Hall-Spencer, M. Fine, C. Turley, R. Jeffree, J. Orr, P.L. Munday, and S.R. Cooley, 2013: Towards improved socio-economic assessments of ocean acidification's impacts. *Marine Biology*, **160(8)**, 1773-1787.

Hines, P., J. Apt, and S. Talukdar, 2009: Large blackouts in North America: historical trends and policy implications. *Energy Policy*, **37(12)**, 5249-5259.

Hochrainer, S., R. Mechler, and D. Kull, 2010: Micro-insurance against drought risk in changing climate. Assessing demand and supply considerations. *International Journal of Climate Strategies and Management*, **2(2)**, 148-166.

Hochrainer, S. and R. Mechler, 2011: Natural disaster risk in Asian megacities: a case for risk pooling? *Cities*, **28**, 53-61.

Hoffmann, B., U. Müller, S. Häfele, and U. Karl, 2010: Analysis of the impact of changing hydro-meteorological parameters on the electricity production of once-through cooled thermal power plants in Germany – a System Dynamics modelling approach. In: *Proceedings of the International Conference on Energy, Environment and Health – Optimisation of Future Energy Systems* [Siggaard-Andersen, M.-L. and E. Kaas (eds.)]. CEEH Scientific Report No. 9, July, 2011, Proceedings of the conference at Carlsberg Academy, Copenhagen, Denmark, May 31 -June 2, 2010, organized by the Centre for Energy Environment and Health (CEEH), the REBECa project (Renewable Energy in the transport sector - using Biofuels as Energy Carriers), and the CEESA project (Coherent Energy and Environmental System Analysis), CEEH, Earth and Planetary Science, University of Copenhagen, Copenhagen, Denmark, pp. 36-42.

Hoffmann, V.H., D.C. Sprengel, A. Ziegler, M. Kolb, and B. Abegg, 2009: Determinants of corporate adaptation to climate change in winter tourism: an econometric analysis. *Global Environmental Change*, **19(2)**, 256-264.

Honeyborne, R., 2009: *Flat Plate versus Evacuated Tube Solar Collectors.* International Technology Sourcing (ITS), Solar Division, ITS Solar, Cape Town, South Africa.

Hope, C.W., 2013: Critical issues for the calculation of the social cost of CO_2: why the estimates from PAGE09 are higher than those from PAGE2002. *Climatic Change*, **117**, 531-543.

Hope, C.W. and M. Hope, 2013: The social cost of CO_2 in a low-growth world. *Nature Climate Change*, **3**, 722-724.

Hopkins, D., J.E.S. Higham, and S. Becken, 2012: Climate change in a regional context: relative vulnerability in the Australasian skier market. *Regional Environmental Change*, **13(2)**, 449-458.

Horowitz, J.K., 2009: The income-temperature relationship in a cross-section of countries and its implications for predicting the effects of global warming. *Environmental and Resource Economics*, **44(4)**, 475-493.

Hsiang, S.M., 2010: Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. *Proceedings of the National Academy of Sciences of the United States of America*, **107(35)**, 15367-15372.

Hübler, M., G. Klepper, and S. Peterson, 2008: Costs of climate change. The effects of rising temperatures on health and productivity in Germany. *Ecological Economics*, **68(1-2)**, 381-393.

Huebner, A., 2012: Public perceptions of destination vulnerability to climate change and implications for long-haul travel decisions to small island states. *Journal of Sustainable Tourism*, **20(7)**, 939-951.

Hughes, G., P. Chinowsky, and K. Strzepek, 2010: The costs of adaptation to climate change for water infrastructure in OECD countries. *Utilities Policy*, **18(3)**, 142-153.

Hunt, A. and P. Watkiss, 2010: Climatic change impacts and adaptation in cities: a review of the literature. *Climatic Change*, **104(1)**, 13-49.

Hurd, B. and M. Rouhi-Rad, 2013: Estimating economic effects of changes in climate and water availability. *Climatic Change*, **117(3)**, 575-584.

Hurd, B.H., M. Callaway, J. Smith, and P. Kirshen, 2004: Climatic change and U.S. water resources: from modeled watershed impacts to national estimates. *Journal of the American Water Resource Association*, **40(1)**, 129-148.

Hutton, G., 2011: The economics of health and climate change: key evidence for decision making. *Globalization and Health*, **7(18)**, doi:10.1186/1744-8603-7-18.

Hwang, I.C., F. Reynès, and R.S.J. Tol, 2013: Climate policy under fat-tailed risk: an application of Dice. *Environmental and Resource Economics*, **56**, 415-436, doi:10.1007/s10640-013-9654-y .

IAEA, 2011: *Core Knowledge on Instrumentation and Control Systems in Nuclear Power Plants.* IAEA Nuclear Energy Series No. NP-T-3.12, International Atomic Energy Agency (IAEA), Vienna, Austria, 141 pp.

Ibarra, E.M., 2011: The use of webcam images to determine tourist-climate aptitude: favourable weather types for sun and beach tourism on the Alicante coast (Spain). *International Journal of Biometeorology*, **55(3)**, 373-385.

IEA, 2008: *World Energy Outlook 2008.* Organization for Economic Cooperation and Development (OECD) and International Energy Agency (IEA), Paris, France, 569 pp.

IEA, 2009: *World Energy Outlook 2009.* Organization for Economic Cooperation and Development (OECD) and International Energy Agency (IEA), Paris, France, 691 pp.

IEA, 2010a: *World Energy Outlook 2010.* Organization for Economic Cooperation and Development (OECD) and International Energy Agency (IEA), Paris, France, 731 pp.

IEA, 2010b: *Energy Technology Perspectives 2010.* Organization for Economic Cooperation and Development (OECD) and International Energy Agency (IEA), Paris, France, 706 pp.

IEA, 2012: *World Energy Outlook 2012.* Organization for Economic Cooperation and Development (OECD) and International Energy Agency (IEA), Paris, France, 668 pp.

Iizumi, T., M. Yokozawa, Y. Hayashi, and F. Kimura, 2008: Climate change impact on rice insurance payouts in Japan. *Journal of Applied Meteorology and Climatology*, **47**, 2265-2278.

Ikefuji, M., J. Magnus, and H. Sakamoto, 2010: *Climate Change*, *Economic Growth*, *and Health.* Discussion Paper No. 2010-86, Tilburg University Center for Economic Research, Amsterdam, Netherland, 39 pp.

Ikefuji, M. and R. Horii, 2012: Natural disasters in a two-sector model of endogenous growth. *Journal of Public Economics*, **96(9-10)**, 784-796.

Interagency Working Group on the Social Cost of Carbon, 2010: *Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866.* February, 2010, The Interagency Working Group (IAW) on the Social Cost of Carbon (SCC), United States Government, Washington, DC, USA, 51 pp.

Interagency Working Group on the Social Cost of Carbon, 2013: *Technical Support Document – Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis – under Executive Order 12866.* The Interagency Working Group (IAW) on the Social Cost of Carbon (SCC), United States Government, Washington, DC, USA, 21 pp.

IPCC, 2005: *IPCC Special Report on Carbon Dioxide Capture and Storage.* Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 442 pp.

IPCC, 2011: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation.* Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, and C. von Stechow (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1075 pp.

IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 582 pp.

Isaac, M. and D. Van Vuuren, 2009: Modelling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy*, **37**, 507-521.

Jiang, M., E. Wong, L.M. Klint, T. DeLacy, and D. Dominey-Howes, 2012: Tourism adaptation to climate change –analysing the policy environment of Fiji. *International Journal of Tourism Policy*, **4(3)**, 238-260.

Jochem, E.S., T. Barker, G. Catenazzi, W. Eichhammer, T. Fleiter, A. Held, N. Helfrich, M. Jakob, P. Criqui, S. Mima, L. Quandt, A. Peters , M. Ragwitz, U. Reiter, F. Reitze, M. Schelhaas, S. Scrieciu, and H. Turton, 2009: *Report of the Reference and 2°C Scenario for Europe.* Project No. 018476-GOCE, Deliverable D-M1.2 of the ADAM project (Adaptation and Mitigation Strategies: Supporting European Climate Policy), Fraunhofer Institute for Systems and Innovation Research (ISI), Karlsruhe, Germany, 231 pp.

Jones, B.F. and B.A. Olken, 2010: Climate shocks and exports. *American Economic Review*, **100(2)**, 454-459.
Jones, B., D. Scott, and H.A. Khaled, 2006: Implications of climate change for outdoor event planning: a case study of three special events in Canada's National Capital Region. *Event Management*, **10(1)**, 63-76.
Jopp, R., T. DeLacy, J. Mair, and M. Fluker, 2013: Using a regional tourism adaptation framework to determine climate change adaptation options for Victoria's Surf Coast. *Asia Pacific Journal of Tourism Research*, **18(1-2)**, 144-164.
Jorgenson, D., R. Goettle, B. Hurd, and J. and Smith, 2004: *U.S. Market Consequences of Global Climate Change.* Pew Center on Global Climate Change, Arlington, VA, USA, 44 pp.
Kabat, P., H. van Schaik, and B. Appleton, 2003: *Climate Changes the Water Rules: How Water Managers can cope with Today's Climate Variability and Tomorrow's Climate Change.* Dialogue on Water and Climate (DWC), International Secretariat of DWC, Wageningen, Netherlands, 105 pp.
Kane, S., J.M. Reilly, and J. Tobey, 1992: An empirical study of the economic effects of climate change on world agriculture. *Climatic Change*, **21(1)**, 17-35.
Karl, T.R., J.M. Melillo, and T.C. Peterson (eds.), 2009: *Global Climate Change Impacts in the United States.* State of the Knowledge Report by the U.S. Global Change Research Program, Cambridge University Press, New York, NY, USA, 188 pp.
Kemfert, C., 2002: An integrated assessment model of economy-energy-climate – the Model WIAGEM. *Integrated Assessment*, **3(4)**, 281-298.
Khosla, V., 2008: *Scalable Electric Power from Solar Energy.* Breaking the Climate Deadlock Briefing Paper, The Climate Group, Brussels, Belgium, 19 pp.
Kingwell, R. and I. Farré, 2009: Climate change impacts on investment in crop sowing machinery. *Australian Journal of Agricultural and Resource Economics*, **53(2)**, 265-284.
Kirkinen, J., A. Martikainen, H. Holttinen, I. Savolainen, O. Auvinen, and S. Syri, 2005: *Impacts on the Energy Sector and Adaptation of the Electricity Network Business under a Changing Climate in Finland*. Finnish Environment Institute (SKYE) Mimeographs No. 340, FINADAPT Working Paper 10, FINADAPT Consortium co-ordinated at SYKE as a part of the Finnish Environmental Cluster Research Programme, co-ordinated by the Finnish Ministry of the Environment, Helsinki, Finland, 36 pp.
Kirshen, P., M. Ruth, and W. Anderson, 2006: Climate's long-term impacts on urban infrastructures and services: the case of Metro Boston. In: *Regional Climate Change and Variability: Impacts and Responses* [Ruth, M., K. Donaghy, and P. Kirshen (eds.)]. New Horizons in Regional Science Series, Edward Elgar Publishers, Northampton, MA, USA, pp. 190-252.
Kirshen, P., K. Knee, and M. Ruth, 2008a: Climate change and coastal flooding in Metro Boston: impacts and adaptation strategies. *Climatic Change*, **90(4)**, 453-473.
Kirshen, P., M. Ruth, and W. Anderson, 2008b: Interdependencies of urban climate change impacts and adaptation strategies: a case study of Metropolitan Boston USA. *Climatic Change*, **86(1-2)**, 105-122.
Kjellstrom, T., R.S. Kovats, S.J. Lloyd, T. Holt, and R.S. Tol, 2009: The direct impact of climate change on regional labor productivity. *Archives of Environmental & Occupational Health*, **64(4)**, 217-227.
Kjellstrom, T., B. Lemke, and M. Otto, 2013: Mapping occupational heat exposure and effects in South-East Asia: ongoing time trends 1980-2009 and future estimates to 2050. *Industrial Health*, **51**, 56-67.
Klint, L.M., M. Jiang, A. Law, T. DeLacy, S. Filep, E. Calgaro, D. Dominey-Howes, and D. Harrison, 2012: Dive tourism in Luganville, Vanuatu: shocks, stressors, and vulnerability to climate change. *Tourism in Marine Environments*, **8(1-2)**, 91-109.
Knowlton, K., M. Rotkin-Ellman, L. Geballe, W. Max, and M.S. Gina, 2011: Six climate change-related events in the United States accounted for about $14 billion in lost lives and health costs. *Health Affairs*, **30(11)**, 2167-2176.
Koch, H., S. Vögele, M. Kaltofen, and U. Grünewald, 2012: Trends in Water availability for power plants-scenario analyses for the German Capital Berlin. *Climatic Change*, **110(3-4)**, 879-899.
Koetse, M. and P. Rietveld, 2009: The impact of climate change and weather on transport: an overview of empirical findings. *Transportation Research Part D: Transport and Environment*, **14(3)**, 205-221.
Kong, C., J. Bang, and Y. Sugiyama, 2005: Structural investigation of composite wind turbine blade considering various load cases and fatigue life. *Energy*, **30**, 2101-2114.
Kopp, R.E., A. Golub, N.O. Keohane, and C. Onda, 2012: The influence of the specification of climate change damages on the social cost of carbon. *Economics: The Open-Access, Open-Assessment E-Journal*, **6**, 2012-13, doi:10.5018/economics-ejournal.ja.2012-13.
Kousky, C. and R. Cooke, 2012: Explaining the failure to insure catastrophic risks. *The Geneva Papers*, **37(2)**, 206-227, doi:10.1057/gpp.2012.14.
Kousky, C. and H. Kunreuther, 2010: Improving flood insurance and flood-risk management: insights from St. Louis, Missouri. *Natural Hazards Review*, **11(4)**, 162-172.
Krausmann, E. and F. Mushtaq, 2008: A qualitative Natech damage scale for the impact of floods on selected industrial facilities. *Natural Hazards*, **46(2)**, 179-197.
Krekt, A.H., T.J. van der Laan, R.A.E. van der Meer, B. Turpin, O.E. Jonkeren, A. van der Toorn, E. Mosselman, J. van Meijeren, and T. Groen, 2011: *Climate Change and Inland Waterway Transport: Impacts on the Sector*, *the Port of Rotterdam and Potential Solutions.* Research Project HSRR08, National Research Programme Knowledge for Climate, Secretariat of the Knowledge for Climate Programme, University of Utrecht, Utrecht, Netherlands, 74 pp.
Kron, W., 2009: Flood insurance: from clients to global financial markets. *Journal of Flood Risk Management*, **2**, 68-75, doi:10.1111/j.1753-318X.2008.01015.x.
Kron, W., 2012: Changing flood risk – a re-insurer's viewpoint. In: *Changes in Flood Risk in Europe* [Kundzewicz, Z.W. (ed.)]. International Association of Hydrological Sciences, Wallingford, UK, pp. 459-490.
Kron, W. and G. Berz, 2007: Flood disasters and climate change: trends and options – a (re-)insurer's view. In: *Global Change: Enough Water for All?* [Lozán, J.L., H. Graßl, P. Hupfer, L. Menzel, and C.-D. Schönwiese (eds.). Wissenschaftliche Auswertungen, Hamburg, Germany, pp. 268-273.
Kron, W., M. Steuer, P. Loew, and A. Wirtz, 2012: How to deal properly with a natural catastrophe database – analysis of flood losses. *Natural Hazards and Earth System Sciences*, **12**, 535-550.
Kulshreshtha, S.N., 2011: Climate change, prairie agriculture, and prairie economy: the new normal. *Canadian Journal of Agricultural Economics*, **59(1)**, 19-44.
Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller, T. Oki, Z. Sen and I.A. Shiklomanov , 2007: Freshwater resources and their management. In: *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Metz, B., O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 173-210.
Kunreuther, H.C. and E.O. Michel-Kerjan, 2009: The development of new catastrophe risk markets. *Annual Review of Resource Economics*, **1**, 119-139.
Kunreuther, H.C., E.O. Michel-Kerjan, N.A. Doherty, M.R. Grace, R.W. Klein, and M.V. Pauly, 2009: *At War with the Weather: Managing Large-Scale Risks in a New Era of Catastrophes.* The Massachusetts Institute of Technology (MIT) Press, Cambridge, MA, USA and London, UK, pp. 416.
Kunreuther, H.C., E.O. Michel-Kerjan, and N. Ranger, 2012: Insuring future climate catastrophes. *Climatic Change*, **118(2)**, 339-354.
Kunz, K., J. Sander, and C. Kottmeier, 2009: Recent trends of thunderstorm and hailstorm frequency and their relation to atmospheric characteristics in southwest Germany. *International Journal of Climatology*, **29**, 2283-2297.
Kurtz, S., J. Granata, and M. Quintana, 2009: Photovoltaic reliability R&D toward a solar-powered world. In: *Proceedings of SPIE: Reliability of Photovoltaic Cells, Modules, Components, and Systems II* [Dhere, N.G., J.H. Wohlgemuth, and D.T. Ton (eds.)]. Proceedings of the International Society for Optics and Photonics (SPIE), Vol. 7412, SPIE, Bellingham, WA, USA, Article No. 7412 0Z, doi:10.1117/12.825649.
Kurtz, S., K. Whitfield, G. TamizhMani, M. Koehl, D. Miller, J. Joyce, J. Wohlgemuth, N. Bosco, M. Kempe, and T. Zgonena, 2011: Evaluation of high temperature exposure of photovoltaic modules. *Progress in Photovoltaics: Research and Applications*, **19(8)**, 954-965.
Landauer, M., U. Pröbstl, and W. Haider, 2012: Managing cross-country skiing destinations under the conditions of climate change – scenarios for destinations in Austria and Finland. *Tourism Management*, **33(4)**, 741-751.
Larsen, P., S. Goldsmith, O. Smith, M. Wilson, K. Strezpek, P. Chinowsky, and B. Saylor, 2008: Estimating future costs for Alaska public infrastructure at risk from climate change. *Global Environmental Change*, **18**, 442-457.
Lavin, P.G., 2003: *Asphalt Pavements: A Practical Guide to Design, Production, and Maintenance for Architects and Engineers*. Spon Press, London, UK and New York, NY, USA, 444 pp.
Le Floc'h, P., J.-C. Poulard, O. Thébaud, F. Blanchard, J. Bihel, and F. Steinmetz, 2008: Analyzing the market position of fish species subject to the impact of long-term changes: a case study of French fisheries in the Bay of Biscay. *Aquatic Living Resources*, **21(3)**, 307-316.

Leblois, A. and P. Quirion, 2013: Agricultural insurances based on meteorological indices: realizations, methods and research challenges. *Meteorological Applications*, **20(1)**, 1-9, doi:10.1002/met.303.

Leckebusch, G.C., U. Ulbrich, L. Fröhlich, and J.G. Pinto, 2007: Property loss potentials for European midlatitude storms in a changing climate. *Geophysical Research Letters*, **34(5)**, doi:10.1029/2006GL027663.

Leckebusch, G.C., A. Weimer, J.G. Pinto, M. Reyers, and P. Speth, 2008: Extreme wind storms over Europe in present and future climate: a cluster analysis approach. *Meteorologische Zeitschrift*, **17(1)**, 67-82.

Lee, D.M. and K.S. Lyon, 2004: A dynamic analysis of the global timber market under global warming: an integrated modeling approach. *Southern Economic Journal*, **70(3)**, 467-489.

Lee, H.-L., 2009: The impact of climate change on global food supply and demand, food prices, and land use. *Paddy and Water Environment*, **7(4)**, 321-331.

Leiva, A.J. and J.R. Skees, 2008: Using irrigation insurance to improve water usage of the Rio Mayo irrigation system in Northwestern Mexico. *World Development*, **36(12)**, 2663-2678.

Lemmen, D. and F. Warren, 2010: *Climate Change Impacts and Adaptation: A Canadian Perspective* [Lemmen, D. and F. Warren (eds.)]. Government of Canada, Climate Change Impacts and Adaptation Directorate, Natural Resources Canada, Ottawa, ON, Canada, 174 pp.

Lin, S., H. Wan-Hsiang, V.Z. Alissa, S. Shubhayu, L. George, and H. Syni-An, 2012: Excessive heat and respiratory hospitalizations in New York State: estimating current and future public health burden related to climate change. *Environmental Health Perspectives*, **120(12)**, 1571-1577, doi: 10.1289/ehp.1104728.

Lin, T.-P. and A. Matzarakis, 2008: Tourism climate and thermal comfort in Sun Moon Lake, Taiwan. *International Journal of Biometeorology*, **52(4)**, 281-290.

Lin, T.-P. and A. Matzarakis, 2011: Tourism climate information based on human thermal perception in Taiwan and Eastern China. *Tourism Management*, **32(3)**, 492-500.

Link, P.M. and R.S.J. Tol, 2009: Economic impacts on key Barents Sea fisheries arising from changes in the strength of the Atlantic thermohaline circulation. *Global Environmental Change*, **19(4)**, 422-433.

Linnerooth-Bayer, J. and R. Mechler, 2009: *Insurance against Losses from Natural Disasters in Developing Countries.* DESA Working Paper No. 85, ST/ESA/2009/DWP/85, United Nations Department of Economic and Social Affairs (UN DESA), New York, NY, USA, 35 pp.

Linnerooth-Bayer, J., K. Warner, C. Bals, P. Höppe, I. Burton, T. Loster, and A. Haas, 2009: Insurance, developing countries and climate change. *The Geneva Papers*, **34**, 381-400.

Linnerooth-Bayer, J., R. Mechler, and S. Hochrainer-Stigler, 2011: Insurance against losses from natural disasters in developing countries – evidence, gaps and the way forward. *Journal of Integrated Disaster Risk Management*, **1(1)**, 59-81, doi:10.5595/idrim.2011.0013.

Linnerud, K., T.K. Mideksa, and G.S. Eskeland, 2011: The impact of climate change on nuclear power supply. *Energy Journal*, **32(1)**, 149-168.

Lise, W. and R.S.J. Tol, 2002: Impact of climate on tourist demand. *Climatic Change*, **55(4)**, 429-449.

Lo, A.J., 2013: The likelihood of having flood insurance increases with social expectations. *Area*, **45(1)**, 70-76.

Lu, C., M.T. Schneider, P. Gubbins, K. Leach-Kemon, D. Jamison, and C.J. Murray, 2010: Public financing of health in developing countries: a cross-national systematic analysis. *The Lancet*, **375(9723)**, 1375-1387.

Macknick, J., R. Newmark, G. Heath, and K.C. Hallett, 2011: *A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies*. Technical Report NREL/TP-6A20-50900. National Renewable Energy Laboratory, Golden, CO, USA, 21 pp. http://www.nrel.gov/docs/fy11osti/50900.pdf.

Maddison, D., 2001: In search of warmer climates? The impact of climate change on flows of British tourists. *Climatic Change*, **49(1-2)**, 193-208.

Maddison, D. and K. Rehdanz, 2011: The impact of climate on life satisfaction. *Ecological Economics*, **70(12)**, 2437-2445.

Mahul, O. and C.J. Stutley, 2010: *Government Support to Agricultural Insurance: Challenges and Options for Developing Countries.* The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 219 pp.

Makki, S.S. and A. Somwaru, 2001: Evidence of adverse selection in crop insurance markets. *The Journal of Risk and Insurance*, **68(4)**, 685-708.

Mansur, E.T., R.O. Mendelsohn, and W. Morrison, 2005: *A Discrete-Continuous Choice Model of Climate Change Impacts on Energy*. Yale SOM Working Paper ES-43, Yale School of Management and School of Forestry and Environmental Studies, New Haven, CT, USA, 45 pp.

Markandya, A. and A. Chaibai, 2009: Valuing climate change impacts on human health: empirical evidence from the literature. *International Journal of Environmental Resources and Public Health*, **6**, 759-786.

Markoff, M.S. and A.C. Cullen, 2008: Impact of climate change on Pacific northwest hydropower. *Climatic Change*, **87**, 451-469.

Masters, W.A. and M.S. McMillan, 2001: Climate and scale in economic growth. *Journal of Economic Growth*, **6(3)**, 167-186.

Matzarakis, A. and C. Endler, 2010: Climate change and thermal bioclimate in cities: impacts and options for adaptation in Freiburg, Germany. *International Journal of Biometeorology*, **54(4)**, 479-483.

Matzarakis, A., T. Georgiadis, and F. Rossi, 2007: Thermal bioclimate analysis for Europe and Italy. *Il Nuovo Cimento*, **30(6)**, 623-632, doi:10.1393/ncc/i2007-10268-0.

Matzarakis, A., E. Rudel, M. Zygmuntowski, and E. Koch, 2010: Bioclimatic maps for tourism purposes. *Physics and Chemistry of the Earth*, **35(1-2)**, 57-62.

Matzarakis, A., M. Hämmerle, C. Endler, S. Muthers, and E. Koch, 2012: Assessment of tourism and recreation destinations under climate change conditions in Austria. *Meteorologische Zeitschrift*, **21(2)**, 157-165.

Maynard, T. and N. Ranger, 2012: What role for "long-term insurance" in adaptation? An analysis of the prospects for and pricing of multi-year insurance contracts. *The Geneva Papers*, **37(2)**, 318-339.

McBoyle, G., D. Scott, and B. Jones, 2007: Climate change and the future of snowmobiling in non-mountainous regions of Canada. *Managing Leisure*, **12(4)**, 237-250.

McColl, L., 2012: *Assessing the Potential Impact of Climate Change on the UK's Electricity Network*. Met Office, Exeter, UK, 2 pp.

McDermott, G. and O. Nilsen, 2013: *Electricity Prices*, *River Temperatures and Cooling Water Scarcity.* IZA Discussion Paper No. 6482, Institute for the Study of Labour (IZA), Bonn, Germany, 38 pp.

McGoodwin, J.R., 2007: Effects of climatic variability on three fishing economies in high-latitude regions: implications for fisheries policies. *Marine Policy*, **31(1)**, 40-55.

McIlgorm, A., 2010: Economic impacts of climate change on sustainable tuna and billfish management: insights from the Western Pacific. *Progress in Oceanography*, **86(1-2)**, 187-191.

Mechler, R., J. Linnerooth-Bayer, and D. Peppiatt, 2006: *Disaster Insurance for the Poor? A Review of Microinsurance for Natural Disaster Risks in Developing Countries.* ProVention Consortium and International Institute for Applied Systems Analysis (IIASA) Study, ProVention, Geneva, Switzerland and IIASA, Laxenburg, Austria, 31 pp.

Melecky, M. and C. Raddatz, 2011: *How Do Governments Respond after Catastrophes? Natural-Disaster Shocks and the Fiscal Stance*. Policy Research Working Paper No. 5564, The World Bank, Private & Financial Sectors Development Sector Unit, Europe and Central Asia Region, Washington, DC, USA, 25 pp.

Mendelsohn, R., K. Emanuel, S. Chonabayashi, and L. Bakkensen, 2012: The impact of climate change on global tropical cyclone damage. *Nature Climate Change*, **2**, 205-209.

Mendoza, R.U., 2009: A proposal for an Asian rice insurance mechanism. *Global Economy Journal*, **9(1)**, 6, doi:10.2202/1524-5861.1454.

Mercer, 2011: *Climate Change Scenarios – Implications for Strategic Asset Allocation.* Mercer, LLC, Carbon Trust, UK, and International Finance Corporation (IFC), Mercer, LLC, New York, NY, USA, 124 pp.

Merino, G., M. Barange, and C. Mullon, 2010: Climate variability and change scenarios for a marine commodity: modelling small pelagic fish, fisheries and fishmeal in a globalized market. *Journal of Marine Systems*, **81(1-2)**, 196-205.

Meze-Hausken, E., A. Patt, and S. Fritz, 2009: Reducing climate risk for micro-insurance providers in Africa: a case study of Ethiopia. *Global Environmental Change*, **19**, 66-73.

Michel-Kerjan, E.O., 2010: Catastrophe economics: the national flood insurance program. *Journal of Economic Perspectives*, **24(4)**, 165-186.

Michel-Kerjan, E. and H. Kunreuther, 2011: Redesigning flood insurance. *Science*, **333**, 408-409.

Michel-Kerjan, E. and F. Morlaye, 2008: Extreme events, global warming, and insurance-linked securities: how to trigger the tipping point. *The Geneva Papers*, **33**, 153-176.

Michel-Kerjan, E., S. Hochrainer-Stigler, H. Kunreuther, H. Kunreuther, J. Linnerooth-Bayer, R. Mechler, R. Muir-Wood, N. Ranger, P. Vaziri, and M. Young, 2013: Catastrophe risk models for evaluating disaster risk reduction investments in developing countries. *Risk Analysis*, **33(6)**, 984-999.
Middelkoop, H., K. Daamen, D. Gellens, W. Grabs, J.C.J. Kwadijk, H. Lang, B.W.A.H. Parmet, B. Schädler, J. Schulla, and K. Wilke, 2001: Impact of climate change on hydrological regimes and water resources management in the Rhine basin. *Climatic Change*, **49(1-2)**, 105-128.
Mideksa, T.K. and S. Kallbekken, 2010: The impact of climate change on the electricity market: a review. *Energy Policy*, **38(7)**, 3579-3585.
Mika, J., 2013: Changes in weather and climate extremes: phenomenology and empirical approaches. *Climatic Change*, **121(1)**, 15-26.
Millerd, F., 2010: The potential impacts of climate change on Great Lakes international shipping. *Climatic Change*, **104(3-4)**, 629-652.
Millner, A., 2013: On welfare frameworks and catastrophic climate risks. *Journal of Environmental Economics and Management*, **65(2)**, 310-325.
Mills, B.N. and J. Andrey, 2002: Climate change and transportation: potential interactions and impacts. In: *The Potential Impacts of Climate Change on Transportation*. Federal Research Partnership Workshop October 1-2, 2002, held at the Brookings Institution, Washington, DC, USA, Summary and Discussion Papers, U.S. Department of Transportation Center for Climate Change and Environmental Forecasting (DOT), Washington, DC, USA, pp. 77-88.
Mills, E., 2009: A global review of insurance industry responses to climate change. *The Geneva Papers*, **34**, 323-359.
Mills, E., 2012: The Greening of insurance. *Science*, **338**, 1424-1425.
Moen, J. and P. Fredman, 2007: Effects of climate change on alpine skiing in Sweden. *Journal of Sustainable Tourism*, **15(4)**, 418-437.
Mogaka, H., S. Gichere, and R. Davis, 2006: *Climate Variability and Water Resources Degradation in Kenya: Improving Water Resources Development and Management.* World Bank Working Paper No. 69, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 105 pp.
Moiseyev, A., B. Solberg, A.M.I. Kallio, and M. Lindner, 2011: An economic analysis of the potential contribution of forest biomass to the EU RES target and its implications for the EU forest industries. *Journal of Forest Economics*, **17(2)**, 197-213.
Monti, A., 2012: Public-private initiatives to cover extreme events. In: *The Geneva Reports – Risk and Insurance Research No.5. Extreme Events and Insurance: 2011 annus horribilis* [Courbage, C. and W.R. Stahel (eds.)]. The Geneva Association, The International Association for the Study of Insurance Economics, Geneva, Switzerland, pp. 27-38.
Moreno, A., 2010: Mediterranean tourism and climate (change): a survey-based study. *Tourism and Hospitality*, *Planning and Development*, **7(3)**, 253-265.
Moreno, A., B. Amelung, and L. Santamarta, 2008: Linking beach recreation to weather conditions: a case study in Zandvoort, Netherlands. *Tourism in Marine Environments*, **5(2-3)**, 111-119.
Moreno, A. and B. Amelung, 2009: Climate change and tourist comfort on Europe's beaches in summer: a reassessment. *Coastal Management*, **37(6)**, 550-568.
Morrison, C. and C. Pickering, 2012: Limits to climate change adaptation: case study of the Australian Alps. *Geographical Research*, **51(1)**, 11-25.
Muir-Wood, R. and P. Grossi, 2008: The catastrophe modeling response to Hurricane Katrina. In: *Climate Extremes and Society* [Diaz, H.F. and R.J. Murnane (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 296-319.
Mukheibir, P., 2013: Potential consequences of projected climate change impacts on hydroelectricity generation. *Climatic Change*, **121(1)**, 67-78.
Muller, M., 2007: Adapting to climate change: water management for urban resilience. *Environment and Urbanization*, **19(1)**, 99-113.
Munich Re, 2005: *Weather Catastrophes and Climate Change: Is There Still Hope for Us?* Münchener Rückversicherungs-Gesellschaft, Munich Reinsurance Company (Munich Re), Munich, Germany, 264 pp.
Munich Re, 2011: *Topics Geo: Natural Catastrophes 2010: Analyses*, *Assessments*, *Positions.* Muenchener Rückversicherungs-Gesellschaft, Munich Reinsurance Company (Munich Re), Munich, Germany, 40 pp.
Munich Re, 2013: *Topics Geo: Natural Catastrophes 2012: Analyses, Assessments, Positions.* Muenchener Rückversicherungs-Gesellschaft, Munich Reinsurance Company (Munich Re), Munich, Germany, 60 pp.
Narita, D., R.S.J. Tol, and D. Anthoff, 2009: Damage costs of climate change through intensification of tropical cyclone activities: an application of FUND. *Climate Research*, **39(2)**, 87-97.
Narita, D., R.S.J. Tol, and D. Anthoff, 2010: Economic costs of extratropical storms under climate change: an application of FUND. *Journal of Environmental Planning and Management*, **53(3)**, 371-384.
Narita, D., K. Rehdanz, and R.S.J. Tol, 2012: Economic costs of ocean acidification: a look into the impacts on global shellfish production. *Climatic Change*, **113(3-4)**, 1049-1063.
Nassopoulos, H., P. Dumas, and S. Hallegatte, 2012: Adaptation to an uncertain climate change: cost benefit analysis and robust decision making for dam dimensioning. *Climatic Change*, **114(3-4)**, 497-508.
National Research Council, 2008: *Potential Impacts of Climate Change on U.S. Transportation*. Transportation Research Board Special Report 290. Committee on Climate Change and U.S. Transportation, Transportation Research Board (TRB) and Division on Earth and Life Studies, National Research Council of the National Academies, TRB, Washington, DC, USA, 280 pp.
Nelson, G., M. Rosegrant, J. Koo, R. Robertson, T. Sulser, R. Zhu, C. Ringler, S. Msangi, A. Palazzo, M. Batka, M. Magalhaes, R. Valmonte-Santos, M. Ewing, and D. Lee, 2009: *Climate Change Impact on Agriculture and Costs of Adaptation.* IFPRI Food Policy Report, International Food Policy Research Institute (IFPRI), Washington, DC, USA, 30 pp.
Nemry, F. and H. Demirel, 2012: *Impacts of Climate Change on Transport: A Focus on Road and Rail Transport Infrastructures*. JRC Scientific and Policy Reports, European Commission, Joint Research Centre, and Institute for Prospective Technological Studies, Publications Office of the European Union, Luxembourg, Luxembourg, 89 pp.
NETL, 2007: *Potential Impacts of Climate Change on the Energy Sector.* DOE/NETL-403/101807, U.S. Government, National Energy Technology Laboratory (NETL), Pittsburgh, PA, USA, 51 pp.
Neumann, J., J. Price, P. Chinowsky, L. Wright, L. Ludwig, R. Streeter, R. Jones, J. Smith, B. Perkins, L. Jantarasami, and J. Martinich, 2013: Climate change risks to United States infrastructure: impacts on coastal development, roads, bridges, and urban drainage. *Climatic Change*, doi:10.1007/s10584-013-1037-4.
Niesing, B., 2004: WIND provides storm warnings. *Fraunhofer Magazine*, **1**, 20-21.
Nordhaus, W. D., 2010: The economics of hurricanes and implications of global warming. *Climate Change Economics*, **1(1)**, 1-20, DOI: 10.1142/S2010007810000054.
Nordhaus, W.D., 2011: The economics of tail events with an application to climate change. *Review of Environmental Economics and Policy*, **5(2)**, 240-257.
Norton, B., 2006: Anatomy of a solar collector: developments in materials, components and efficiency improvements in solar thermal collector systems. *Refocus*, **7(3)**, 32-35.
Noy, I., 2009: The macroeconomic consequences of disasters. *Journal of Development Economics*, **88(2)**, 221-231.
Ntelekos, A.A., M. Oppenheimer, J.A. Smith, and A.J. Miller, 2010: Urbanization, climate change and flood policy in the United States. *Climatic Change*, **103(3)**, 597-616.
Nursey-Bray, M. and T. Miller, 2012: Ports and climate change: building skills in climate change adaptation, Australia. In: *Climate Change and the Sustainable Use of Water Resources* [Filho, W.L. (ed.)]. Springer-Verlag, Berlin and Heidelberg, Germany, pp. 273-282.
Nyaupane, G.P. and N. Chhetri, 2009: Vulnerability to climate change of nature-based tourism in the Nepalese Himalayas. *Tourism Geographies*, **11(1)**, 95-119.
Oliver Wyman, 2007: *Climate Change: Risks and Opportunities for Global Financial Services.* Oliver Wyman, Ltd., New York, NY, USA, 58 pp.
Olonscheck, M., A. Holsten, and J.P. Kropp, 2011: Heating and cooling energy demand and related emissions of the German residential building stock under climate change. *Energy Policy*, **39(9)**, 4795-4806.
Ott, H.E. and C. Richter, 2008: *Anpassung an den Klimawandel – Risiken und Chancen für deutsche Unternehmen*. Wuppertal Papers No. 171, Brief analysis for the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Project: Economic Opportunities Of International Climate Policy (FKZ 90511504), Wuppertal Institit für Klima, Umwelt, Energie GmbH, Wuppertal, Germany, 26 pp.
Ou-Yang, C., H. Kunreuther, and E. Michel-Kerjan, 2013: An economic analysis of climate adaptations to hurricane risk in St. Lucia. *The Geneva Papers*, **38**, 521-546.
Pandey, K., 2010: *Costs of Adapting to Climate Change for Human Health in Developing Countries.* World Bank Development and Climate Change Discussion Paper No.11, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 19 pp.
Pang, S.F.H., B. McKercher, and B. Prideaux, 2013: Climate change and tourism: an overview. *Asia Pacific Journal of Tourism Research*, **18(1-2)**, 4-20.

Parkpoom, S., G.P. Harrison, and J.W. Bialek, 2005: Climate and weather uncertainty in the electricity industry. *International Energy Journal*, **6(1)**, 455-464.

Patt, A., P. Suarez, and U. Hess, 2010: How do small-holder farmers understand insurance, and how much do they want it? Evidence from Africa. *Global Environmental Change*, **20**, 153-161.

Patt, A., Pfenninger S., and J. Lilliestam, 2013: Vulnerability of solar energy infrastructure and output to climate change. *Climatic Change*, **121(1)**, 93-102.

Patton, L., 2011: Why insurers *should* focus on climate risk issues. In: *Risk Management*, *(SC5), June 2011*. The Geneva Association, The International Association for the Study of Insurance Economics, Geneva, Switzerland, pp. 5-15, www.genevaassociation.org/media/185056/ga2011-rmsc5.pdf.

Paudel, Y., 2012: A comparative study of public – private catastrophe insurance systems: lessons from current practices. *The Geneva Papers*, **37(2)**, 257-285, doi:10.1057/gpp.2012.16.

Pearce, T.D., J.D. Ford, J. Prno, F. Duerden, J. Pittman, M. Beaumier, L. Berrang-Ford, and B. Smit, 2011: Climate change and mining in Canada. *Mitigation and Adaptation Strategies for Global Change*, **16(3)**, 347-368.

Pechan, A. and K. Eisenack, 2013: *The Impact of Heat Waves on Electricity Spot Markets.* Oldenburg Economic Discussion Paper V-357-13, Oldenburg University, Oldenburg, Germany, 31 pp.

Peduzzi, P., B. Chatenoux, H. Dao, A. De Bono, C. Herold, J. Kossin, F. Mouton, and O. Nordbeck, 2012: Global trends in tropical cyclone risk. *Nature Climate Change*, **2**, 289-294, doi:10.1038/NCLIMATE1410.

Pejovic, T., V. Williams, R. Noland, and R. Toumi, 2009: Factors affecting the frequency and severity of airport weather delays and the implications of climate change for future delays. *Journal of the Transportation Research Board*, **2139**, 97-106.

Perch-Nielsen, S.L., 2010: The vulnerability of beach tourism to climate change – an index approach. *Climatic Change*, **100(3)**, 579-606.

Perch-Nielsen, S.L., B. Amelung, and R. Knutti, 2009: Future climate resources for tourism in Europe based on the daily Tourism Climatic Index. *Climatic Change*, **103(3-4)**, 363-381.

Perez-Garcia, J., L.A. Joyce, A.D. Mcguire, and X. Xiao, 2002: Impacts of climate change on the global forest sector. *Climatic Change*, **54(4)**, 439-461.

Phelan, L., R. Taplin, A. Henderson-Sellers, and G. Albrecht, 2011: Ecological viability or liability? Insurance system responses to climate risk. *Environmental Policy and Governance*, **21**, 112-130.

Pickering, C.M. and R.C. Buckley, 2010: Climate response by the ski industry: the shortcomings of snowmaking for Australian resorts. *Ambio*, **39(5-6)**, 430-438.

Pickering, C.M., J.G. Castley, and M. Burtt, 2010: Skiing less often in a warmer world: attitudes of tourists to climate change in an Australian ski resort. *Geographical Research*, **48(2)**, 137-147.

Pielke, R.A.J. and M.W. Downton, 2000: Precipitation and damaging floods: trends in the United States, 1932-97. *Journal of Climate*, **13(20)**, 3625-3637.

Pielke, R.A.J. and C.W. Landsea, 1999: La Nina, El Nino, and Atlantic hurricane damages in the United States. *Bulletin of the American Meteorological Society*, **80**, 2027-2033.

Pinto, J.G., E.L. Fröhlich, G.C. Leckebusch, and U. Ulbrich, 2007: Changing European storm loss potentials under modified climate conditions according to ensemble simulations of the ECHAM5/MPI-OM1 GCM. *Natural Hazards and Earth System Sciences*, **7**, 165-175.

Pinto, J.G., C.P. Neuhaus, G.C. Leckebusch, M. Reyers, and M. Kerschgens, 2009: Estimation of wind storm impacts over Western Germany under future climate conditions using a statistical-dynamical downscaling approach. *Tellus A*, **62**, 188-201.

Pinto, J.G., M.K. Karremann, K. Born, P.M. Della-Marta, and M. Klawa, 2012: Loss potentials associated with European windstorms under future climate conditions. *Climate Research*, **54(1)**, 1-20, doi:10.3354/cr01111.

Pons-Pons, M., P.A. Johnson, M. Rosas-Casals, B. Sureda, and E. Jover, 2012: Modeling climate change effects on winter ski tourism in Andorra. *Climate Research*, **54(3)**, 197-207.

Potocka, I. and A. Zajadacz, 2009: Weather and climate as elements of tourism space controlling the demand for and forms of tourist activity. *Quaestiones Geographicae*, **(28 A1)**, 53-64.

Pouta, E., M. Neuvonen, and T. Sievänen, 2009: Participation in cross-country skiing in Finland under climate change: application of multiple hierarchy stratification perspective. *Journal of Leisure Research*, **41(1)**, 91-108.

Prabhakar, S.V.R.K., G.S. Rao, K. Fukuda, and S. Hayashi, 2013: Promoting risk insurance in the Asia-Pacific region lessons from the ground for the future climate regime under UNFCCC. In: *Climate Change Adaption in Practice: From Strategy Development to Implementation* [Schmidt-Thome, T. and J. Klein (eds.)]. John Wiley & Sons, Ltd., Hoboken, NJ, USA, pp. 303-323.

Prideaux, B. and K.E. Mcnamara, 2012: Turning a global crisis into a tourism opportunity: the perspective from Tuvalu. *International Journal of Tourism Research*, **15(6)**, 583-594.

Pryor, S.C. and R.J. Barthelmie, 2010: Climate change impacts on wind energy: a review. *Renewable and Sustainable Energy Reviews*, **14(1)**, 430-437.

Pryor, S.C. and R.J. Barthelmie, 2011: Assessing climate change impacts on the near-term stability of the wind energy resource over the USA. *Proceedings of the National Academy of Sciences of the United States of America*, **108**, 8167-8171.

Pryor, S.C. and R.J. Barthelmie, 2013: Assessing the vulnerability of wind energy to climate change and extreme events. *Climatic Change*, **121(1)**, 79-91.

Pryor, S.C. and J.T. Schoof, 2010: Importance of the SRES in projections of climate change impacts on near-surface wind regimes. *Meteorologische Zeitschrift*, **19(3)**, 267-274.

Pryor, S.C., J.T. Schoof, and R.J. Barthelmie, 2006: Winds of change? Projections of near-surface winds under climate change scenarios. *Geophysical Research Letters*, **33(11)**, L11702, doi:10.1029/2006GL026000.

Pryor, S.C., R.J. Barthelmie, N.E. Clausen, M. Drews, N. MacKellar, and E. Kjellström, 2011: Analyses of possible changes in intense and extreme wind speeds over northern Europe under climate change scenarios. *Climate Dynamics*, **38**, 189-208.

Qin, D., C. Yiyu, and L. Xueyong, 2005: *Evolution of Climate and Environment in China* (in Chinese). *Science Press*, **1**, 562 pp.

Qiu, L. and W.A. Nixon, 2008: Effects of adverse weather on traffic crashes: systematic review and meta-analysis. *Journal of the Transportation Research Board*, **2055(1)**, 139-146.

Quinto, C., 2011: *Insurance Systems in Times of Climate Change: Insurance of Buildings against Natural Hazards.* Springer, Berlin, Germany, 180 pp.

Qureshi, Z. and D. Reinhard (eds.), 2011: *Making Insurance Work for the Poor*. Proceedings of the 6th International Microinsurance Conference 2010, November 9-11, 2010, Manila, Philippines, Munich Re Foundation in cooperation with the Microinsurance Network, Munich Re Foundation, Munich, Germany, 89 pp.

Raddatz, C., 2009: *The Wrath of God – Macroeconomic Costs of Natural Disasters.* Policy Research Working Paper 5039, The Word Bank Development Research Group, Macroeconomics and Growth Team, The World Bank, Washington, DC, USA, 35 pp.

Raible, C.C., S. Kleppek, M. Wüest, D.N. Bresch, A. Kitoh, H. Murakami, and T.F. Stocker, 2012: Atlantic hurricanes and associated insurance loss potentials in future climate scenarios: limitations of high-resolution AGCM simulations. *Tellus A*, **64**, 15672, doi:10.3402/tellusa.v64i0.15672.

Ramakrishnan, S.K., 2011: Adaptation cost of diarrhea and malaria in 2030 for India. *Indian Journal of Occupational and Environmental Medicine*, **15(2)**, 64-67.

Ranger, N. and F. Niehoerster, 2012: Deep uncertainty in long-term hurricane risk: scenario generation and implications for future climate experiments. *Global Environmental Change*, **22(3)**, 703-712.

Raschky, P.A., R. Schwarze, M. Schwindt, and F. Zahn, 2013: Uncertainty of governmental relief and the crowding out of flood insurance. *Environmental and Resource Economics*, **54**, 179-200.

Ravishankar, N., P. Gubbins, R.J. Cooley, K. Leach-Kemon, C.M. Michaud, T.J. Dean, and J.M. Christopher, 2009: Financing of global health: tracking development assistance for health from 1990 to 2007. *Lancet*, **373(9681)**, 2113-2124.

Raymond, C.M. and G. Brown, 2011: Assessing spatial associations between perceptions of landscape value and climate change risk for use in climate change planning. *Climatic Change*, **104(3-4)**, 653-678.

Reed, D.A., 2008: Electric utility distribution analysis for extreme winds. *Journal of Wind Engineering and Industrial Aerodynamics*, **96(1)**, 123-140.

Reilly, J.M., N. Hohmann, and S. Kane, 1994: Climate change and agricultural trade: who benefits, who loses? *Global Environmental Change*, **4(1)**, 24-36.

Reilly, J.M., S. Paltsev, B. Felzer, X. Wang, D.W. Kicklighter, J.M. Melillo, R.G. Prinn, M. Sarofim, A.P. Sokolov, and C. Wang, 2007: Global economic effects of changes in crops, pasture, and forests due to changing climate, carbon dioxide, and ozone. *Energy Policy*, **35**, 5370-5383.

Reinhold, T., B. O'Connor, and C. Iskowitz, 2012: Reducing vulnerabilities through science. In: *Severe Weather in North America. Perils*, *Risks*, *Insurance* [Kron, W. and F. Wöst (eds.)]. Munich Re, Munich, Germany, pp. 197-225.

Guoyu, G.Y., 1996: Global climate changes and the tourism of China. *Journal of Chinese Geography*, **6(2)**, 97-102.

10

Richardson, R.B. and J.B. Loomis, 2005: Climate change and recreation benefits in an alpine national park. *Journal of Leisure Research*, **37(3)**, 307-320.

Richter, C., S. Teske, and R. Short, 2009: *Concentrating Solar Power: Global Outlook 2009 – Why Renewable Energy is Hot.* Greenpeace International, Amsterdam, Netherlands, ESTALA, Brussels, Belgium, and IEA SolarPaces, Tabernas, Spain, 87 pp.

Rising, W.R., J.A. O'Daniel, and C.S. Roberts, 2006: Correlating weather and trauma admissions at a level I trauma center. *Journal of Trauma – Injury*, *Infection and Critical Care*, **60(5)**, 1096-1110.

Robinson, S., K. Strzepek, and R. Cervigni, 2013: *The Cost of Adapting to Climate Change in Ethiopia*. Ethiopia Strategy Support Program II Working Paper 53, IFPRI ESSP WP 53, 2013.

Ronneberger, K., M. Berrittella, F. Bosello, and R.S.J. Tol, 2009: KLUM@GTAP: introducing biophysical aspects of land-use decisions into a computable general equilibrium model, a coupling experiment. *Environmental Modeling and Assessment*, **14(2)**, 149-168.

Roson, R. and D. van der Mensbrugghe, 2012: Climate change and economic growth: impacts and interactions. *International Journal of Sustainable Economy*, **4(3)**, 270-285.

Rossello, J., 2011: North Atlantic Oscillation influences on European airline traffic. *Transportation Research Part D: Transport and Environment*, **16(2)**, 183-187.

Rosselló-Nadal, J., A. Riera-Font, and V. Cárdenas, 2010: The impact of weather variability on British outbound flows. *Climatic Change*, 105(1-2), 281-292.

Rübbelke, D.T.G. and S. Vögele, 2010: *Impacts of Climate Change on European Critical Infrastructures: The Case of the Power Sector*. Basque Centre for Climate Change (BC3) Working Paper 2010-08, BC3, Bilbao, Spain, 20 pp.

Rübbelke, D. and S. Vögele, 2013: Short-term distributional consequences of climate change impacts on the power sector: who gains and who loses? *Climatic Change*, **116(2)**, 191-206.

Rummukainen, M., 2013: Climate change: changing means and changing extremes. *Climatic Change*, **121(1)**, 3-13.

Rutty, M. and D. Scott, 2010: Will the Mediterranean become "too hot" for tourism? A reassessment. *Tourism and Hospitality*, *Planning and Development*, **7(3)**, 267-281.

Ryley, T. and L. Chapman (eds.), 2012: *Transport and Sustainability, Vol. 2: Transport and Climate Change*. Emerald Group Publishing, Ltd., Bingley, UK, 396 pp.

Saarinen, J. and K. Tervo, 2006: Perceptions and adaptation strategies of the tourism industry to climate change: the case of Finnish nature-based tourism entrepreneurs. *International Journal of Innovation and Sustainable Development*, **1(3)**, 214-228.

Saarinen, J., W.L. Hambira, J. Atlhopheng, and H. Manwa, 2012: Tourism industry reaction to climate change in Kgalagadi South District, Botswana. *Development Southern Africa*, **29(2)**, 273-285.

Sabbioni, C., M. Cassar, P. Brimblecombe, and R.A. Lefevre, 2009: Vulnerability of cultural heritage to climate change. *Pollution Atmospherique*, **(202)**, 157-169.

Sailor, D.J., M. Smith, and M. Hart, 2008: Climate change implications for wind power resources in the Northwest United States. *Renewable Energy*, **33(11)**, 2393-2406.

Sander, J., J.F. Eichner, E. Faust, and M. Steuer, 2013: Rising variability in thunderstorm-related U.S. losses as a reflection of changes in large-scale thunderstorm forcing. *Weather, Climate, and Society*, **5**, 317-331, doi:10.1175/WCAS-D-12-00023.1.

Schaefli, B., D. Balin Talamba, and A. Musy, 2007: Quantifying hydrological modeling errors through a mixture of normal distributions. *Journal of Hydrology*, **332**, 303-315.

Schmidt, P., R. Steiger, and A. Matzarakis, 2012: Artificial snowmaking possibilities and climate change based on regional climate modeling in the Southern Black Forest. *Meteorologische Zeitschrift*, **21(2)**, 167-172.

Schreider, S.Y., D.I. Smith, and A.J. Jakeman, 2000: Climate change impacts on urban flooding. *Climatic Change*, **47(1-2)**, 91-115.

Schwarze, R. and G.G. Wagner, 2007: The political economy of natural disaster insurance: lessons from the failure of a proposed compulsory insurance scheme in Germany. *European Environment*, **17(6)**, 403-415.

Schwarze, R., H. Schwindt, H. Weck-Hannemann, P. Raschky, F. Zahn, and G.G. Wagner, 2011: Natural hazard insurance in Europe: tailored responses to climate change are needed. *Environmental Policy and Governance*, **21**, 14-30.

Schwierz, C., P. Köllner-Heck, E. Zenklusen-Mutter, D.N. Bresch, P.-L. Vidale, M. Wild, and C. Schär, 2010: Modelling European winter wind storm losses in current and future climate. *Climatic Change*, **101(3-4)**, 485-514.

Scott, D. and B. Jones, 2006: The impact of climate change on golf participation in the Greater Toronto Area (GTA): a case study. *Journal of Leisure Research*, **38(3)**, 363-380.

Scott, D. and B. Jones, 2007: A regional comparison of the implications of climate change for the golf industry in Canada. *Canadian Geographer*, **51(2)**, 219-232.

Scott, D. and G. McBoyle, 2007: Climate change adaptation in the ski industry. *Mitigation and Adaptation Strategies for Global Change*, **12(8)**, 1411-1431.

Scott, D., G. McBoyle, and B. Mills, 2003: Climate change and the skiing industry in southern Ontario (Canada): exploring the importance of snowmaking as a technical adaptation. *Climate Research*, **23(2)**, 171-181.

Scott, D., G. McBoyle, A. Minogue, and B. Mills, 2006: Climate change and the sustainability of ski-based tourism in eastern North America: a reassessment. *Journal of Sustainable Tourism*, **14(4)**, 376-398.

Scott, D., B. Jones, and J. Konopek, 2007: Implications of climate and environmental change for nature-based tourism in the Canadian Rocky Mountains: a case study of Waterton Lakes National Park. *Tourism Management*, **28(2)**, 570-579.

Scott, D., G. McBoyle, and A. Minogue, 2007: Climate change and Quebec's ski industry. *Global Environmental Change*, **17(2)**, 181-190.

Scott, D., J. Dawson, and B. Jones, 2008a: Climate change vulnerability of the US Northeast winter recreation- tourism sector. *Mitigation and Adaptation Strategies for Global Change*, **13(5-6)**, 577-596.

Scott, D., S. Gössling, and C.R. De Freitas, 2008b: Preferred climates for tourism: case studies from Canada, New Zealand and Sweden. *Climate Research*, **38(1)**, 61-73.

Scott, D., S. Gössling, and C.M. Hall, 2012a: International tourism and climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **3(3)**, 213-232.

Scott, D., M.C. Simpson, and R. Sim, 2012b: The vulnerability of Caribbean coastal tourism to scenarios of climate change related sea level rise. *Journal of Sustainable Tourism*, **20(6)**, 883-898.

Scott, M., S. Gupta, E. Jáuregui, J. Nwafor, D. Satterthwaite, W. Wanasinghe, and M. Yoshino, 2001: Human settlements, energy and industry. In: *Climate Change 2001: Impacts*, *Adaptation*, *and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 381-416.

Seo, J. and O. Mahul, 2009: *The Impact of Climate Change on Catastrophe Risk Model. Implications for Catastrophe Risk Markets in Developing Countries*. Policy Research Working Paper 4959, A joint product of the World Bank Global Facility for Disaster Reduction and Recovery Unit, Sustainable Development Network Vice Presidency, and the Global Capital Markets Development Department, Financial and Private Sector Development Vice Presidency, The World Bank, Washington, DC, USA, 16 pp.

Seppala, R., A. Buck, and P. Katila (eds.), 2009: *Adaptation of Forests and People to Climate Change – A Global Assessment Report.* IUFRO World Series Vol. 22, International Union of Forest Research Organizations (IUFRO), IUFRO, Helsinki, Finland, 224 pp.

Serquet, G. and M. Rebetez, 2011: Relationship between tourism demand in the Swiss Alps and hot summer air temperatures associated with climate change. *Climatic Change*, **108(1-2)**, 291-300.

Shaw, W.D. and J.B. Loomis, 2008: Frameworks for analyzing the economic effects of climate change on outdoor recreation. *Climate Research*, **36(3)**, 259-269.

Sherement, O. and A. Lucas, 2009: Global loss diversification in the insurance sector. *Insurance: Mathematics and Economics*, **44(3)**, 415-425, doi:10.1016/j.insmatheco.2008.12.001.

Shih, C., S. Nicholls, and D.F. Holecek, 2009: Impact of weather on downhill ski lift ticket sales. *Journal of Travel Research*, **47(3)**, 359-372.

Sieber, J., 2013: Impacts of, and adaptation options to, extreme weather events and climate change concerning thermal power plants. *Climatic Change*, **121(1)**, 55-66.

Skidmore, M. and H. Toya, 2002: Do natural disasters promote long-term growth? *Economic Inquiry*, **40(4)**, 664-687.

Smith, A.B. and R.W. Katz, 2013: US billion-dollar weather and climate disasters: data sources, trends, accuracy and biases. *Natural Hazards*, **67(2)**, 387-410, doi:10.1007/s11069-013-0566-5.

Sohngen, B. and R. Mendelsohn, 1997: A dynamic model of forest carbon storage in the United States during climatic change. *Critical Reviews in Environmental Science and Technology*, **27(SI)**, S309-S321.

Sohngen, B. and R. Mendelsohn, 1998: Valuing the impact of large-scale ecological change in a market: the effect of climate change on U.S. timber. *American Economic Review*, **88(4)**, 686-710.

Sohngen, B., R. Mendelsohn, and R. Sedjo, 2001: A global model of climate change impacts on timber markets. *Journal of Agricultural and Resource Economics*, **26(2)**, 326-343.

Steger, C., S. Kotlarski, T. Jonas, and C. Schär, 2012: Alpine snow cover in a changing climate: a regional climate model perspective. *Climate Dynamics*, **41(3-4)**, 735-754.

Steiger, R., 2010: The impact of climate change on ski season length and snowmaking requirements in Tyrol, Austria. *Climate Research*, **43(3)**, 251-262.

Steiger, R., 2012: Scenarios for skiing tourism in Austria: integrating demographics with an analysis of climate change. *Journal of Sustainable Tourism*, **20(6)**, 867-882.

Steiger, R. and M. Mayer, 2008: Snowmaking and climate change: future options for snow production in Tyrolean ski resorts. *Mountain Research and Development*, **28(3-4)**, 292-298.

Stenek, V., J.C. Amado, and R. Connell, 2010: *Climate Risk and Financial Institutions: Challenges and Opportunities* [Kamins, R., A. Hidalgo, V. Stenek, and R. Connell (eds.)]. International Finance Corporation (IFC), World Bank Group, Washington, DC, USA, 120 pp.

Stewart, E.J., S.E.L. Howell, D. Draper, J. Yackel, and A. Tivy, 2007: Sea ice in Canada's Arctic: implications for cruise tourism. *Arctic*, **60(4)**, 370-380.

Stewart, W. and D. Willard, 2010: Kivalina v. ExxonMobil dismissed by Federal trial court. In: *Liability for Climate Change? Experts' Views on a Potential Emerging Risk*. Munich Re, Munich, Germany, pp. 11-13.

Strulik, H., 2008: Geography, health, and the pace of demo-economic development. *Journal of Development Economics*, **86(1)**, 61-75.

Strzepek, K., Y. Gary, N. James, and B. Brent, 2010: Characterizing changes in drought risk for the United States from climate change. *Environmental Research Letters*, **5**, 044012, doi:10.1088/1748-9326/5/4/044012.

10

Strzepek, K., B. Boehlert, A. McCluskey, W. Farmer, J. Neumann, and M. Fuchs, 2011: *Assessment of the Impacts of Climate Change on Multi-Sector Investment Opportunities in the Zambezi River Basin.* IEC Report to The World Bank, World Bank, Washington, DC, USA, pp.

Strzepek, K., J. Smith, J. Martinich, J. Neumann, B. Boehlert, M. Hejazi, J. Henderson, C. Wobus, K. Calvin, D. Johnson, J. R., E. Monier, J. Strzepek, and J. Yoon, 2013: Climate change impacts on water resources in the United States. *Climatic Change*, (under review).

Subak, S., J.P. Palutikof, M.D. Agnew, S.J. Watson, C.G. Bentham, M.G.R. Cannell, M. Hulme, S. McNally, J.E. Thornes, D. Waughray, and J.C. Woods, 2000: The impact of the anomalous weather of 1995 on the U.K. economy. *Climatic Change*, **44(1-2)**, 1-26.

Supreme Court of Virginia, USA, 2012: Declaratory judgment following rehearing. In: *The AES Corporation v. Steadfast Insurance Company, Record No.100764: Opinion by Justice S. Bernard Goodwyn, April 20, 2012*. Supreme Court of Virginia, USA, Richmond, VA, USA, www.courts.state.va.us/opinions/opnscwp/1100764r.pdf.

Sweeney, M., A. Gasca, M. Garcia-Lopez, and A.C. Palmer, 2005: Pipelines and landslides in rugged terrain: a database, historic risks and pipeline vulnerability. In: *International Conference on Terrain and Geohazard Challenges Facing Onshore Oil and Gas Pipelines: Evaluation, Routing, Design, Construction, Operation* [Sweeney, M. (ed.)]. Institution of Civil Engineers in coordination with BP Exploration, Thomas Telford, Ltd., London, UK, pp. 641-659.

Swiss Re, 2013a: *SIGMA No. 1/2013: Partnering for Food Security in Emerging Markets.* Economic Research & Consulting, Swiss Reinsurance Company, Ltd. (Swiss Re), Zürich, Switzerland, 40 pp.

Swiss Re, 2013b: *SIGMA No. 3/2013: World Insurance in 2012: Progressing on the Long and Winding Road to Recovery*. Economic Research & Consulting, Swiss Reinsurance Company, Ltd. (Swiss Re), Zürich, Switzerland, 42 pp.

Swiss Re, 2013c: *SIGMA No. 2/2012: Natural Catastrophes and Man-Made Disasters in 2012: A Year of Extreme Weather Events in the US*. Economic Research & Consulting, Swiss Reinsurance Company, Ltd. (Swiss Re), Zürich, Switzerland, 44 pp.

Tamiotti, L., R. Teh, V. Kalucoglu, A. Olhoff, B. Simmons, and H. Abaza, 2009: *Trade and Climate Change.* World Trade Organization (WTO) and the United Nations Environment Programme (UNEP), WTO, Geneva, Switzerland, 166 pp.

Tang, K.K., D. Petrie, and D.S.P. Rao, 2009: The income-climate trap of health development: a comparative analysis of African and Non-African countries. *Social Science and Medicine*, **69(7)**, 1099-1106.

Taylor, R.J. and H.M. Tollin, 2009: Insurance market for global warming heats up: old products and new policies respond to climate change risks. *Environmental Claims Journal*, **21(3)**, 247-261.

Taylor, T. and R.A. Ortiz, 2009: Impacts of climate change on domestic tourism in the UK: a panel data estimation. *Tourism Economics*, **15(4)**, 803-812.

Tervo, K., 2008: The operational and regional vulnerability of winter tourism to climate variability and change: the case of the Finnish nature-based tourism entrepreneurs. *Scandinavian Journal of Hospitality and Tourism*, **8(4)**, 317-332.

Thieken, A.H., T. Petrow, H. Kreiblich, and B. Merz, 2006: Insurability and mitigation of flood losses in private households in Germany. *Risk Analysis*, **26**, 383-395.

Tol, R.S.J., 2008: Why worry about climate change? A research agenda. *Environmental Values*, **17(4)**, 437-470.

Tol, R.S.J., 2011: The social cost of carbon. *Annual Review of Resource Economics*, **3**, 419-443.

Tol, R.S.J., 2013: Targets for global climate policy: an overview. *Journal of Economic Dynamics and Control*, **37(5)**, 911-928.

Towler, E., B. Raucher, B. Rajagopalan, A. Rodriguez, D. Yates, and R. Summers, 2011: Incorporating climate uncertainty in a cost assessment for a new municipal source water. *Journal of Water Resources Planning and Management*, **138(5)**, 396-402.

Trærup, S.L.M., 2012: Informal networks and resilience to climate change impacts: a collective approach to index insurance. *Global Environmental Change*, **22**, 255-267.

Trærup, S.L.M., R.A. Ortiz, and A. Markandya, 2011: The costs of climate change: a study of cholera in Tanzania. *International Journal of Environmental Research and Public Health*, **8(12)**, 4386-4405.

Travers, J. and V.G. Payne, 1998: The impact of climate change on traditional seasonal ranges for High Street women's wear in England. *Journal of Fashion Marketing and Management*, **2(4)**, 370-382.

Troccoli, A. (ed.), 2010: *Management of Weather and Climate Risk in the Energy Industry*. Springer, Dordrecht, Netherlands, 330 pp.

Tsai, H.-T., C.-J. Tseng, S.-Y. Tzeng, T.-J. Wu, and J.-d. Day, 2012: The impacts of natural hazards on Taiwan's tourism industry. *Natural Hazards*, **62(1)**, 83-91.

Turton, S., T. Dickson, W. Hadwen, B. Jorgensen, T. Pham, D. Simmons, P. Tremblay, and R. Wilson, 2010: Developing an approach for tourism climate change assessment: evidence from four contrasting Australian case studies. *Journal of Sustainable Tourism*, **18(3)**, 429-447.

UNCTAD, 2009: *Multi-Year Expert Meeting on Transport and Trade Facilitation: Maritime Transport and the Climate Change Challenge, 16 – 18 February 2009, Geneva, Summary of Proceedings.* UNCTAD/DTL/TLB/2009/1 United Nations Conference on Trade and Development (UNCTAD), Geneva, Switzerland, 47 pp.

UNDP, 2011: The economic impacts of climate change on energy demand for space heating and cooling. In: *Assessing the Economic Impact of Climate Change – National Case Studies*. United Nations Development Program (UNDP), New York, NY, USA, pp. 37-56.

UNECE and UNCTAD, 2010: *Note by the United Nations Economic Commission for Europe (UNECE) and United Nations Conference on Trade and Development (UNCTAD) Secretariats.* Proceedings of Joint Workshop on Climate Change Impacts on International Transport Networks, 7 – 8 September 2010, Geneva, ECE/TRANS/WP.5/2010/3, UNECE and UNCTAD, Geneva, Switzerland, 14 pp.

UNFCCC, 2007: *Investment and Financial Flows to Address Climate Change.* United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany, 272 pp.

URS, 2010: *Adapting Energy, Transport, and Water Infrastructure to the Long-Term Impacts of Climate Change, Summary Report.* Reference No. RMP/5456, Report by URS Corporation, Ltd. for the UK Government's cross-departmental Infrastructure and Adaptation Project, URS Corporation, Ltd., London, UK, 16 pp.

Uyarra, M.C., I.M. Côté, J.A. Gill, R.R.T. Tinch, D. Viner, and A.R. Watkinson, 2005: Island-specific preferences of tourists for environmental features: implications of climate change for tourism-dependent states. *Environmental Conservation*, **32(1)**, 11-19.

van den Berg, M., 2010: Household income strategies and natural disasters: dynamic livelihoods in rural Nicaragua. *Ecological Economics*, **69(3)**, 592-602.

Van den Bergh, R. and M. Faure, 2006: Compulsory insurance of loss to property caused by natural disasters: competition or solidarity? *World Competition*, **29(1)**, 25-54.

Van der Vliert, E., 2008: *Climate, Affluence, and Culture*. Cambridge University Press, New York, NY, USA, 253 pp.

Van Nostrand, J.M. and J.G. Nevius, 2011: Parametric insurance: using objective measures to address the impacts of natural disasters and climate change. *Environmental Claims Journal*, **23(3-4)**, 227-237.

van Rensburg, J.J.J. and J.N. Blignaut, 2002: The economic impact of an increasing health risk due to global warming. In: *Forum for Economics and Environment – First Conference Proceedings.* Economics for Environment Forum (Econ4Env), Cape Town, South Africa, pp. 117-141, citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.199.630&rep=rep1&type=pdf.

Van Vliet, M.T.H., J.R. Yearsley, F. Ludwig, S. Vögele, D.P. Lettenmaier, and P. Kabat, 2012: Vulnerability of US and European electricity supply to climate change. *Nature Climate Change*, **2(9)**, 676-681.

Vergara, W., A. Deeb, A. Valencia, R. Bradley, B. Francou, A. Zarzar, A. Grunwaldt, and S. Haeussling, 2007: Economic impacts of rapid glacier retreat in the Andes. *Eos, Transactions American Geophysical Union*, **88(25)**, 261-268.

Vlasova, L.V. and G.S. Rakitina, 2010: Natural risks management in the Gas Transmission System (GTS) of Russia and the contribution of climate services under global climate change. In: *Management of Weather and Climate Risk in the Energy Industry* [Troccoli, A. (ed.)]. Springer, Bilthoven, Netherlands, pp. 315-325.

von Peter, G., S. von Dahlen, and S. Saxena, 2012: *Unmitigated Disasters? New Evidence on the Macroeconomic Cost of Natural Catastrophes*. BIS Working Paper No. 394, Monetary and Economic Department of the Bank for International Settlements, Basel, Switzerland, 38 pp.

Walter, A., K. Keuler, D. Jacob, R. Knoche, A. Block, S. Kotlarski, G. Muller-Westermeier, D. Rechid, and W. Ahrens, 2006: A high resolution reference data set of German wind velocity 1951-2001 and comparison with regional climate model results. *Meteorologische Zeitschrift*, **15**, 585-596.

Wang, S., Y. He, and X. Song, 2010: Impacts of climate warming on Alpine glacier tourism and adaptive measures: a case study of Baishui Glacier No. 1 in Yulong Snow Mountain, Southwestern China. *Journal of Earth Science*, **21(2)**, 166-178.

Ward, A.M., 2013: The effect of weather on grid systems and the reliability of electricity supply. *Climatic Change*, **121(1)**, 103-113.

Ward, R.E.T., C. Herweijer, N. Patmore, and R. Muir-Wood, 2008: The role of insurers in promoting adaptation to the impacts of climate change. *The Geneva Papers*, **33**, 133-139.

Ward, P.J., K.M. Strzepek, W.P. Pauw, L.M. Brander, G.A. Hughes, and J.C.J.H. Aerts, 2010: Partial costs of global climate change adaptation for the supply of raw industrial and municipal water: a methodology and application. *Environmental Research Letters*, **5(4)**, 044011, doi:10.1088/1748-9326/5/4/044011.

Warner, K. and A. Spiegel, 2009: Climate change and emerging markets: the role of the insurance industry in climate change management. In: *The Geneva Reports – Risk and Insurance Research No. 2. The Insurance Industry and Climate Change – Contribution to the Global Debate*. The Geneva Association, The International Association for the Study of Insurance Economics, Geneva, Switzerland, pp. 83-95.

Warner, K., S. Kreft, M. Zissner, P. Höppe, C. Bals, T. Loster, J. Linnerooth-Bayer, S. Tschudi, E. Gurenko, A. Haas, S. Young, P. Kovacs, A. Dlugolecki, and A. Oxley, 2012: *Insurance Solutions in the Context of Climate Change-Related Loss and Damage: Needs, Gaps, and Roles of the Convention in addressing Loss and Damage.* UNU-EHS Publication Series Policy Brief No. 6, Munich Climate Insurance Initiative (MCII) hosted by United Nations University-Institute for Environment and Human Security (UNU-EHS), Bonn, Germany, 47 pp.

Watkiss, P. and A. Hunt, 2012: Projection of economic impacts of climate change in sectors of Europe based on bottom up analysis: human health. *Climatic Change*, **112(1)**, 101-126.

Weitzman, M.L., 2009: On modeling and interpreting the economics of catastrophic climate change. *Review of Economics and Statistics*, **91(1)**, 1-19.

Welker, C. and E. Faust, 2013: Tropical cyclone-related socio-economic losses in the western North Pacific region. *Natural Hazards and Earth System Sciences*, **13**, 115-124, doi:10.5194/nhess-13-115-2013.

Whalley, J. and Y. Yuan, 2009: Global financial structure and climate change. *Journal of Financial Transformation*, **25**, 161-168.

Whitehead, J.C., B. Poulter, C.F. Dumas, and O. Bin, 2009: Measuring the economic effects of sea level rise on shore fishing. *Mitigation and Adaptation Strategies for Global Change*, **14(8)**, 777-792.

WHO, 2004: *Evaluation of the Costs and Benefits of Water and Sanitation Improvements at the Global Level.* WHO/SDE/WSH/04.04, Water, Sanitation and Health Protection of the Human Environment, World Health Organization (WHO), Geneva, Switzerland, 87 pp.

Wilbanks, T.J., P. Romero Lankao, M. Bao, F. Berkhout, S. Cairncross, J.-P. Ceron, M. Kapshe, R. Muir-Wood, and R. Zapata-Marti, 2007: Industry, settlement and society. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson (ed.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 357-390.

Wilcox, R., J. Syroka, F. Kassam, and S. Mapfumo, 2010: *African Risk Capacity (ARC) Briefing Book.* The African Risk Capacity (ARC) Project initiated by the African Union Commission, Department of Rural Economy and Agriculture, and the United Nations World Food Programme (WFP), ARC, Johannesburg, South Africa, 48 pp.

Williams, E., 2013: Economy-wide and sectoral implications of climate change and extreme weather impacts on the energy sector. In: *Climate Change Impacts on the Energy Sector*. Interim Report, International Atomic Energy Agency (IAEA), Vienna, Austria, pp. 18-33.

Williams, E. and F.L. Toth, 2013: Nuclear power: impacts of climate change and extreme weather. In: *Climate Change Impacts on the Energy Sector.* Interim Report, International Atomic Energy Agency (IAEA), Vienna, Austria, pp. 1-17.

Williams, P.D. and M.M. Joshi, 2013: Intensification of winter transatlantic aviation turbulence in response to climate change. *Nature Climate Change*, **3**, 644-648.

Wilson, K.J., J. Falkingham, H. Melling, and R. De Abreu, 2004: Shipping in the Canadian Arctic: other possible climate change scenarios. In: *IGARSS, 2004. Proceedings of the 2004 IEEE International Geoscience and Remote Sensing Symposium: Science for Society, Exploring and Managing a Changing Planet, Anchorage, Alaska, 20 – 24 September 2004*. Institute of Electrical and Electronics Engineers (IEEE), New York, NY, USA, pp. 1853-1856.

Winkler, J., L. Dueñas-Osorio, R. Stein, and D. Subramanian, 2010: Performance assessment of topologically diverse power systems subjected to hurricane events. *Reliability Engineering and System Safety*, **95(4)**, 323-336.

Winters, P., R. Murgai, E. Sadoulet, A. De Janvry, and G. Frisvold, 1998: Economic and welfare impacts of climate change on developing countries. *Environmental and Resource Economics*, **12(1)**, 1-24.

Wirtz, A., P. Löw, T. Mahl, and S. Yildirim, 2013: Hitting the poor – public private partnerships as an option: impact of natural catastrophes in economies at various stages of development. In: *Extreme Natural Hazards, Disaster Risks and Societal Implications* [Ismail-Zadeh, A., J. Fucugauchi, A. Kijko, K. Takeuchi, and I. Zaliapin (eds.)]. Cambridge University Press, Cambridge, UK (in press).

Wobus, C., M. Lawson, R. Jones, J. Smith, and J. Martinich, 2013: Estimating monetary damages from flooding in the United States under a changing climate. *Journal of Flood Risk Management* (in press), doi:10.1111/jfr3.12043.

Wolfsegger, C., S. Gössling, and D. Scott, 2008: Climate change risk appraisal in the Austrian ski industry. *Tourism Review International*, **12(1)**, 13-23.

World Bank, 2006: *Ethiopia: Managing Water Resources to Maximize Sustainable Growth.* Country Water Resources Assistance Strategy, The International Bank for Reconstruction and Development / The World Bank, Washington, DC, USA, 91 pp.

World Bank, 2013: *Pacific Catastrophe Risk Insurance Pilot. Regional Financial Protection Against Natural Disasters for Pacific Island States*. Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI), 4 pp. http://siteresources.worldbank.org/EXTDISASTER/Resources/8308420-1361321776050/Pacific-Catastrophe-Risk-Insurance-Pilot_4pager_12Feb13.pdf.

Wright, L., P. Chinowsky, K. Strzepek, R. Jones, R. Streeter, J.B. Smith, J.-M. Mayotte, A. Powell, L. Jantarasami, and W. Perkins, 2012: Estimated effects of climate change on flood vulnerability of U.S. bridges. *Mitigation and Adaptation Strategies for Global Change*, **17(8)**, 939-955.

WTO and UNEP, 2008: *Climate Change and Tourism – Responding to Global Challenges.* World Tourism Organization (WTO) and United Nations Environment Programme (UNEP), WTO, Madrid, Spain, 256 pp.

WTTC, 2011: *Travel & Tourism 2011.* World Travel and Tourism Council (WTTC), London, UK, 40 pp.

Yates, D.N. and K.M. Strzepek, 1998: An assessment of integrated climate change impacts on the agricultural economy of Egypt. *Climatic Change*, **38(3)**, 261-287.

Yazdi, S.K. and A. Fashandi, 2010: The economic effects of climate change on fisheries and aquaculture. In: *2010 International Conference on Environmental Engineering and Applications (ICEEA 2010)*. Proceedings of a meeting held 10 – 12 September 2010, Singapore, Institute of Electrical and Electronics Engineers (IEEE), New York, NY, USA, pp. 335-340.

Yohe, G.W., 2008: A research agenda to improve economic estimates of the benefits of climate change policies. *Integrated Assessment*, **8(1)**, 1-17.

Yu, G., Z. Schwartz, and J.E. Walsh, 2009a: A weather-resolving index for assessing the impact of climate change on tourism related climate resources. *Climatic Change*, **95(3-4)**, 551-573.

10

Yu, G., S. Zvi, and J.E. Walsh, 2009b: Effects of climate change on the seasonality of weather for tourism in Alaska. *Arctic*, **62(4)**, 443-457.

Zachariadis, T., 2010: Forecast of electricity consumption in Cyprus up to the year 2030: The potential impact of climate change. *Energy Policy*, **38(2)**, 744-750.

Zahran, S., S. Weiler, S.D. Brody, M.K. Lindell, and W.E. Highfield, 2009: Modeling national flood insurance policy holding at the county scale in Florida, 1999-2005. *Ecological Economics*, **68(10)**, 2627-2636.

Zaninović, K. and A. Matzarakis, 2009: The bioclimatological leaflet as a means conveying climatological information to tourists and the tourism industry. *International Journal of Biometeorology*, **53(4)**, 369-374.

Zhu, J., 2011: Evaluation of an insurance scheme based on the weather index – a case study of Anhui Province. *The Chinese Economy*, **44(6)**, 56-72.

Zimmerman, F.J. and M.R. Carter, 2003: Asset smoothing, consumption smoothing and the reproduction of inequality under risk and subsistence constraints. *Journal of Development Economics*, **71(2)**, 233-260.