Chapter 1

Modelling the economic consequences of climate change

This chapter first presents a brief discussion of the main categories of climate change impacts. It then introduces the methodology used to identify how climate impacts affect economic growth. It highlights how the costs of inaction until 2060 can be assessed using a production function approach to link climate change impacts to specific drivers of growth in the dynamic general equilibrium model ENV-Linkages; and how and why this is complemented by a more stylised integrated assessment modelling of long-term impacts using the AD-DICE model. The chapter ends with a description of how the production function approach is used to model the various impacts in ENV-Linkages.

1.1. Introduction

Evidence is growing that changes in the climate system are contributing to a range of biophysical and economic impacts that are already affecting the economy (e.g. see the latest reports of the Intergovernmental Panel on Climate Change: IPCC, 2013, 2014a,b; see also Dell et al., 2009, 2013). Future impacts are expected to be much larger (IPCC, 2014a). A certain amount of climate change is already locked-in, and there are considerable and cascading uncertainties with regard to future emissions of greenhouse gases, the resulting changes in climate, and the resulting biophysical and socioeconomic impacts. It can therefore reasonably be asked what value a modelling analysis of the economic consequences of climate change at a global level can offer policy makers. After all, a combination of these uncertainties and the necessary simplifications of any model representation of the global economy mean that the absolute magnitude of one point estimate of a specific impact of climate change on the economy will be less interesting than the interactions in the economic system that they induce.

The particular value of this exercise is to produce a carefully caveated account of the costs of not mitigating the global emissions trajectory and, conversely, the benefits associated with action. Policies aiming to limit climate change impacts will have global economic consequences (even if the policies are not applied globally). As its name suggests, the ENV-linkages model is designed to shed light on *linkages* – on the way physical impacts can affect patterns of production leading to changes in the composition of growth regionally and sectorally. While the magnitude and distribution of these changes is uncertain, modelling provides some clues to long-run trends and mechanisms that link climate change impacts and economic activity. These at least should be valuable in informing attempts to manage the significant and accumulating risk of serious climatic disruption.

The report presents results from modelling the feedbacks of climate change damages on economic growth for the coming decades. It paints a picture of a world in which a dynamic global economy internalises the damages of climate change. In the process it continues to deliver huge gains in global output and, unevenly, living standards. What it cannot tell us is how fragile or leveraged those living standards will be given the increasing risk of costly extreme events and non-linear change that accompany that growth process.

The impacts of climate change will play out over a very long time period. Given the large uncertainties in projecting its course and impacts, the costs of inaction cannot be subjected to a simple cost benefit analysis. Rather, any comparison of the costs and benefits of different policy mixes needs to be based on an assessment of risks that incorporates the inter-temporal dimension of the problem. For this reason, the report goes no further than providing a stylised assessment of some of the main benefits of policy action, including both mitigation and adaptation policies is included.

There is extensive literature on the economic impacts of climate change (e.g. Nordhaus, 1994, 2007, 2010; Tol, 2005; Stern, 2007; Agrawala et al., 2011) and on modelling the costs of policy action (e.g. OECD, 2012). In-depth regional studies on the consequences of climate change also exist, most notably the Garnaut Review for Australia (Garnaut, 2008, 2011), the Risky Business study for the USA (Risky Business Project, 2014), the Peseta project for the European Union (Ciscar et al., 2011, 2014) and the COIN study for Austria (Steininger et al., 2015). Some literature has also attempted to quantify the costs of inaction and benefits of policy action on climate change. Most notably, the Stern Review (2007) concludes that climate change could reduce welfare by an amount equivalent to a *permanent* reduction in consumption per capita of between 5% and 20%. The size of the effects of climate impacts on the economy is, however, still the subject of debate, as confirmed by Working Group II of the IPCC (2014a) which concludes that economic impact estimates produced over the past in the past two decades "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)" (IPCC, 2014a).

Most of these studies have a stylised, aggregated representation of the economy. Typical modelling studies that focus on projections of climate change impacts over time include highly aggregated Integrated Assessment Models (IAMs), in which climate damages in different sectors are aggregated and used to re-evaluate welfare in the presence of climate change. Comparing such models is difficult, as each tends to include different impact categories, but it is clear that they vary widely in their projections for the global macroeconomic consequences for specific impacts (e.g. US Interagency Working Group, 2010; 2013). A much smaller strand of literature uses computable general equilibrium (CGE) models to examine the economic implications of climate change impacts in specific sectors, often using a comparative static approach (e.g. Bosello et al., 2006; 2007). Box 1.1 briefly introduces the main differences between these types of models. More recently, CGE models have also been used to study the economy-wide impacts of climate change in a dynamic setting (see Eboli et al., 2010; Bosello et al., 2012; Roson and Van der Mensbrugghe, 2012; Bosello and Parrado, 2014; Dellink et al., 2014).

Box 1.1. **Computable general equilibrium and integrated asessment models**

The two main types of models used for assessing the economic consequences of climate change are Computable General Equilibrium (CGE) models and Integrated Assessment models (IAM).

CGE models focus on the relations between different economic actors and contain a full description of the economic system using multiple economic sectors: households supply production factors (labour, capital, land) and consume goods and services, while firms transform the production factors, with intermediate deliveries from other sectors, into the output of goods and services. In a multi-regional CGE model all economies are linked through international trade. For assessing climate change damages, the detailed description of the economy allows for a detailed representation of those impacts of climate change that are primarily affecting markets, such as changes in crop yields, health expenditures, labour productivity and energy demand.

Box 1.1. **Computable general equilibrium and integrated asessment models** *(cont.)*

IAMs focus more on describing the interactions between the economic and biophysical system, i.e. how economic activity leads to environmental pressure, and how environmental feedbacks affect the economy. Many IAMS that have been used for policy advice (such as DICE, FUND and PAGE) are highly aggregated and contain only a cursory description of the economy. Other IAMs have much greater detail in the description of the biophysical system, often at the expense of lacking feedbacks from the biophysical system to the economy. The more stylised nature of IAMs make them more suited to describe a wider range of climate change impacts in an aggregated fashion.

In principle, there is no clear distinction between both types of models: enhanced CGE models such as ENV-Linkages describe emissions from economic activity in detail and contain feedbacks from the climate impacts on the economic system, and is thus de facto an IAM. Similarly, the economic module of an IAM can be expanded into a full-fledged CGE model. The level of detail that can be captured in CGE models and IAMs is limited by computing power and, more importantly, the need to avoid the model becoming so complex that it is a black box.

The specification of climate change impacts in CGEs and IAMs is further discussed in Section 1.3.

This report builds on these recent studies and it uses the OECD's multi-region, multi-sector dynamic CGE model ENV-Linkages to analyse the economic consequences of a selection of climate change impacts until 2060. By using a detailed economic model, with explicit representation of the drivers of economic activity, the impacts of climate change can be linked to the economy in a much more realistic fashion. The analysis with the ENV-Linkages model is complemented with an assessment of consequences of climate change after 2060 and for a stylised analysis of the benefits of policy action with the integrated assessment model AD-DICE. While the sectoral and regional details of the CGE model are ideal for a detailed study of the consequences of climate change on the various parts of the global economy, and especially the wider economic consequences that trickle through the economy, the optimisation structure of the IAM model is better suited to study the policy trade-offs and longer term consequences. Both models use the same baseline scenario for socioeconomic developments (including population and GDP). For OECD countries and the main emerging economies, this is based on the OECD long-run aggregate growth scenario to 2060 (OECD, 2014a).

Chapter 2 of this report focuses on how a selected number of climate change impacts affect different parts of the economy. The impact categories that are investigated in Chapter 2 include some of the major impacts with respect to agriculture, coastal zones, extreme events, health, energy and tourism demand. For most impact categories, a number of the key economic impacts are included in the modelling exercise, while non-market impacts are discussed separately in Chapter 3. For other impacts, including those related to ecosystem services, water stress and tipping points, only anecdotal evidence is presented, as sufficiently robust data to study economic damages is not available.

In order to provide an indication of magnitude in a metric that is widely known to policymakers, the resulting impacts from both models are presented in terms of effects on gross domestic product (GDP). This is an imperfect measure of the total economic costs of climate change, since it does not consider wider consequences on well-being or costs to society (which can be considerable). Nevertheless, it provides insight in the macroeconomic consequences (i.e. economic feedbacks) of the selected climate change impacts; the sectoral decomposition of GDP can further illuminate the changes in economic structures associated with climate change damages. Moreover, expressing these costs of inaction in the same terms as the usual indicator for economic growth, i.e. in terms of GDP losses, helps to communicate the importance of climate change for mainstream economic policy making.

1.2. Main consequences of climate change

Climate change will have pervasive socio-economic consequences that will not only affect major economic sectors such as agriculture, energy or healthcare, but will also result in changes to the supply and demand for goods and services of all sectors of the economy, albeit with varying levels of intensity. Higher temperatures, sea level rise, and other climatic changes (changes in regional precipitation patterns, the water cycle, frequency and intensity of extreme weather events), will also impact aspects of life that are not primarily based on or related to economic activity, as for example human security, health and well-being, culture, people's capabilities, and environmental quality.

Table 1.1 provides an overview of the selection of climate impacts considered in this report. It is important to note that these are a subset of all impacts of climate change, even for the sectors covered. Not all of these impact categories are entirely discrete nor can they always be clearly separated from each other. Extreme events, for example, not only affect human health, land and capital damages, but might induce people to migrate to other places as a form of adaptation; extreme events can also cause long-lasting trauma for those directly or indirectly affected by their long-run consequences. Agriculture is highly dependent on

Table 1.1. **Categories of climate impacts considered in this study**

AGRICULTURE	Changes in crop yields (incl. cropland productivity and water stress)	Modelled
	Livestock mortality and morbidity from heat and cold exposure	Qualitatively
	Changes in pasture- and rangeland productivity	Stand-alone
	Changes in aquaculture productivity	Qualitatively
	Changes in fisheries catches	Modelled
COASTAL ZONES	Loss of land and capital from sea level rise	Modelled
	Non-market impacts in coastal zones	Qualitatively
EXTREME EVENTS	Mortality, land and capital damages from hurricanes	Modelled
	Mortality, land and capital damages from floods	Stand-alone
HEALTH	Mortality from heat exposure (incl. heatwaves)	Stand-alone
	Morbidity from heat and cold exposure (incl. heatwaves)	Modelled
	Mortality and morbidity from infectious diseases, cardiovascular and respiratory diseases	Modelled
ENERGY DEMAND	Changes in energy demand for cooling and heating	Modelled
TOURISM DEMAND	Changes in tourism flows and services	Modelled
ECOSYSTEMS	Loss of ecosystems and biodiversity	Stand-alone
	Changes in forest plantation yields	Qualitatively
WATER STRESS	Changes in energy supply	Qualitatively
	Changes in availability of drinking water to end users (incl. households)	Qualitatively
HUMAN SECURITY	Civil conflict	Qualitatively
	Human migration	Qualitatively
TIPPING POINTS	Large scale disruptive events	Stand-alone

Note: "Modelled" implies that the impact is captured (at least partially) in the main modelling framework; "stand-alone" refers to a quantitative assessment outside the main modelling framework, and "qualitatively" implies only a qualitative assessment was possible in this report.
Source: Own compilation.

functioning ecosystems and water availability, while damages in coastal zones affect, inter alia, ecosystems, livelihood, and agriculture. To avoid double-counting, all impacts considered in this study are allocated to only one impact category, along the lines of Table 1.1. Table 1.1 also indicates whether these impacts are included in the modelling exercise, are part of a stand-alone quantitative assessment, or are discussed qualitatively.

Working Group II of the IPCC (IPCC, 2014a) describes the most significant projected impacts of climate change to affect the economy, society, and the earth's environment in various scenarios (including greenhouse gas concentration pathways), where possible attaching information about the level of likelihood, evidence, and agreement on the findings or relationships between climate change and the impacted variables. It is not the aim of this report to summarise all possible impacts. Rather, without aiming to be complete, the following paragraphs give some selected examples of important impacts of climate change that may occur within the categories presented in Table 1.1. Many other impacts have been assessed by the IPCC, but could not be included in the assessment of this report.

In *agriculture*, climate change will have consequences for various subsectors, including crop production, livestock, pasture- and rangeland, and aquaculture. Of the various climatic drivers, the impacts of climate change (including changes in regional temperatures and precipitation patterns) on crop productivity have been studied most comprehensively, suggesting that at the global level the impacts will be largely negative for moderate to high levels of warming (Rosenzweig et al., 2013). At the regional level, however, there will be large differences among regions with positive impacts in some and negative impacts in others. Changes in rainfall, atmospheric carbon dioxide (CO_2) and ozone concentrations, changes in pest and disease prevalence, and extreme events spurred by climate change will likely also affect future agricultural activities, sometimes positively and sometimes negatively. According to the IPCC (2014a), there is high confidence that higher CO_2 concentration in the atmosphere will have a stimulatory effect on crop yields (but also on weeds), while higher levels of ozone are likely going to be damaging. In addition, climate change might have consequences for outcomes that depend on the way agriculture is conducted, including conservation of the countryside, food security and the maintenance of biodiversity. It might also affect negative externalities produced by agricultural activity, as for example soil and water pollution. The evidence on this relationship and its direction is not very clear, however (Ahlheim and Frör, 2003; OECD, 2001). OECD (2014b) discusses in detail the effects of climate change on the agricultural sector through the water system. With regards to fisheries, climate change is expected to negatively impact most developing countries – especially those located in tropical regions. Developed nations at more northern latitudes, in turn, may benefit (IPCC, 2014b).

Coastal zones or coastal systems include natural ecosystems (beaches, cliffs, lagoons, etc.) and human systems (settlements, cities, ports, food production, etc.). They comprise distinct coastal features and ecosystems, as well as built environment, human activities, and institutions that organize these human activities (IPCC, 2014a). Various climate change-related drivers can impact on these systems. Beyond likely changes in the frequency and intensity of storms (and storm surges), increases in precipitation, warmer ocean temperatures and ocean acidification, sea level rise is potentially the most significant contributing factor to coastal zone damage. There is high agreement among authors of the IPCC and other reports that rising sea levels can negatively impact the provision of market and non-market goods and services in coastal zones through events such as storm surge, submergence, salt-water intrusion and coastal erosion. Both natural and human systems will be affected by sea level rise.

Extreme weather events are very likely to be affected by climate change, although the regional changes vary. Tropical cyclone activity, including hurricanes, is more likely than not to become more intense by the end of the 21st century, as global mean surface temperature rise (IPCC, 2014a). The IPCC (2013) reports that with higher temperatures, extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century. Similarly, river floods are also projected to increase in number and severity in most river basins. Reduced rainfall and increased evaporation can both lead to droughts, which are projected to "become longer, or more frequent, or both, in some regions and seasons" (IPCC, 2014a). These trends and their related damages are projected to result in higher costs to the economy relative to a world without climate change. The main direct channels through which economies will experience these damages are impacts on physical capital (e.g. factories, houses, streets and bridges, machinery, computers, but also energy infrastructure), land (e.g. natural resources), and labour (i.e. the workforce). These events also lead to indirect economic effects, e.g. through the disruption to electricity supply or transport, or a temporary halt to almost all local economic activity. The increase in frequency and intensity of extreme events as a consequence of climate change also leads to premature deaths and injuries, and force people to leave their homes and temporarily or permanently move to other places, affecting well-bring and welfare. They also impact on ecosystems and the services these provide. Evidence is also emerging that economies do not fully recover from the macroeconomic costs of destruction but are permanently faced with lower levels of GDP and economic growth (Hsiang and Jina, 2014), although this may depend on the level of development and the stock of physical and human capital. Logically, this extends to climate-induced destruction.

Health impacts of climate change include both direct and indirect effects, including: heat and cold related mortality and morbidity, water, food and vector-borne disease; deaths and well-being; and changes in air pollution and allergens. There are also risks to health infrastructure and to occupational health (WHO, 2012; 2014). The economic costs of health impacts are not easy to assess as they include both market and non-market costs. For instance morbidity costs include market impacts, such as the effects of illnesses on labour productivity, and non-market impacts, such as the costs of pain and suffering.

The *demand for energy* will also be affected by climate change. The main channels for changes in energy demand are through reduced need for heating in winter, and increased need for cooling in summer. Energy supply may also disrupted, e.g. by water shortages, and this may in turn affect energy demand. The projected changes in the energy system are, however, dominated by the assumptions on mitigation policies. IEA (2013) investigates the links between climate change and the energy system in detail.

With regards to *tourism*, the effects of climate change arise from changes in local climate conditions, making certain tourist locations less attractive and others more. For instance, skiing in the Alps may become less snow-secure, and the high cost of providing artificial snow increases prices for Alpine skiing. This induces changes in both domestic and international tourist flows, plus changes in their expenditures.

Ecosystems on land and in water provide a multitude of precious services to humans and other species, including the supply of food, raw materials, climate and air quality, habitat for species, and opportunity for aesthetic appreciation and inspiration (TEEB, 2014). Climate change is expected to place ecosystem services under further stress – directly as well as indirectly by interacting with and intensifying other aggravating factors, such as human development. Warming, as a major direct climatic driver, and changes in extreme events, will likely reduce biodiversity and diminish abundance of species, or – if possible – force certain species (both animals and plants) to shift range to higher latitudes or higher elevations with more bearable temperatures to increase the chance of survival. Northward migration of fish and birds (and tree species in general) is one example for range shift as a response to warming in the Northern Hemisphere. Heavy precipitation, in turn, might act as an indirect impact on ecosystems, by accelerating the erosion of forest areas that have already been put under pressure, e.g. from recent logging (EPA, 2015). Changes in availability and quality of ecosystem services will also affect the functioning of economic sectors, not least the land-based agricultural sector, forestry and fisheries.

Climate change is projected to have both positive and negative impacts on *freshwater resources*, with the effect varying to a large extent by geographic latitude. While the global circulation climate system models vary significantly in their projections of regional climate changes, including precipitation patterns, it is expected that many humid mid-latitude and high latitude regions will most likely experience increased water availability with climate change. Groundwater is the biggest reservoir of available freshwater and is relatively better insulated from climate change. Nonetheless, groundwater recharge is projected to decline in many countries and sea level rise may increase salinity of groundwater reservoirs. Declining water availability and a larger number of extended dry periods are projected to affect drier many countries in the mid-latitudes and dry subtropical latitudes, although uncertainties on regional water availability are very large. Short-term or seasonal water reductions from more variable streamflow (mostly resulting from a greater variability in rainfall) and reduced storage of water in ice and snow might nonetheless also be felt in regions with projected larger water availability. In addition, negative impacts of climate change on water quality from toxins produced by algae, for example, can contribute to reduced availability of freshwater (OECD, 2012, 2013; IPCC, 2014a). These impacts are expected to affect, inter alia, end users through changes to the availability of drinking water as well as industry through impacts on water supply for irrigation and energy supply.

According to the IPCC (2014a), there is high confidence and robust evidence that climate change will intensify stressors that negatively impact *human security*, which can be defined as “a condition that exists when the vital core of human lives is protected, and when people have the freedom and capacity to live with dignity” (IPCC, 2014a). Forced migration and incidence of civil conflict are two key stressors to human security that have been widely discussed in the literature and that many expect to be magnified by climate change. However, evidence for direct causal linkage between climate change and these specific factors is still limited, and the linkage itself is contested by some.

Besides the changes occurring in the various sectors and regions as described above, there is a risk associated with large-scale disruptions caused by climate change (so-called large singular events). These large-scale events, or *tipping points* (tipping elements), can occur when small climate changes trigger a disproportionately large impact and thus pose a systemic risk. Models cannot easily assess the implications of major climate events, such as a collapse of North Atlantic thermohaline circulation (i.e. shut-down of the Gulf Stream) or abrupt solid ice discharge of the West Antarctic ice sheet. While most large-scale singular events are unlikely to occur in the 21st century (IPCC, 2013), with the exception of the partial loss of artic sea ice, the risks associated with the potential for a large and irreversible sea level rise from ice sheet loss "increase disproportionately as temperature increases between 1-2°C additional warming and become high above 3°C" (IPCC, 2014a). These risks potentially have very large consequences for the world economy, yet the changes in the climate system that trigger them – and the thresholds when these events may occur – are poorly understood, and the economic consequences de facto impossible to robustly project.

While there is mounting evidence that there are significant downside risks from large singular efents and other climate impacts, insofar these are related to different uncertainties and are thus largely independent, there is only a very small chance of all of them occurring. It is more likely that some of these risks may occur while other do not materialise. But when these risks are positively correlated (which is the case for those that are related to global temperature increases), then these risks may well combine and their probabilities move together.

These impact categories listed in Table 1.1 are used throughout the report to describe the methodology and the results of the analysis. As described in Section 1.4, several of these impacts are modelled in ENV-Linkages to estimate the costs of climate change inaction to 2060. That does not mean that the other impacts do not have economic consequences, but that there is not enough information to include them in the model, or that the impacts primarily have non-market consequences that cannot be readily included in an economic modelling framework. Such impacts are discussed in Chapter 3.

1.3. A framework to study climate change impacts on economic growth

1.3.1. A multi-model framework

A standard framework to assess climate damages begins by linking economic activities to emissions of greenhouse gases (GHG), and evaluating how human-induced increases in atmospheric GHG concentrations drive changes in climate, such as changes in regional and global temperature and precipitation patterns. These climatic changes in turn result in physical and biogeochemical impacts which influence the productivity of various sectors of the regional economies where the impacts occur, and ultimately give rise to economic losses.

This approach combines representations of some or all of the following components: the determinants of socioeconomic development, emissions caused by economic growth, the atmosphere-ocean-climate system, ecosystems, socioeconomic impacts, mitigation and adaptation policies and associated economic responses, with different types of models emphasizing different linkages (Parsons and Fisher-Vanden, 1997).

This report combines two models in one complementary framework in order to capture as many aspects as possible. A sectoral and regional computable general equilibrium model is used wherever possible, and the analysis is combined with that using a large scale integrated assessment model when needed. While the CGE model is ideal to study the market-based costs of inaction (or benefits of action) on the economy and the different regions and sectors for the coming decades (until 2060 in this report), the IAM model can be used to study long-term consequences of climate change as well as to explore optimal policy scenarios. Given their level of aggregation, this modelling framework cannot assess the consequences of climate change at the sub-national and local level, even though for some impacts (e.g. extreme events) local consequences far outstrip those at the national and global level. Furthermore, conventional representations of economic agents (households and firms), like in CGE models and IAMs, may not be appropriate if the shock is very large and discontinuous, not only on a local scale, but also in macroeconomic terms.

Large-scale IAMs, most notably those following Nordhaus' DICE and RICE models (Nordhaus and Boyer, 2000; Nordhaus, 2010, 2012; de Bruin et al., 2009a, b; Bosello et al., 2010), have often been used as tools to assess the interactions between economic activity and climate change. These models are constructed to include a stylised representation of as many components as possible of a standard framework to assess the economic costs of climate change. They are based on aggregate damage functions, which are calibrated to the assumed economic baseline and used to subtract the overall costs of climate change from an appropriate economic measure, such as GDP. IAMs are generally based on a forward-looking framework, which can be used to study the trade-off between the ability to adjust emissions and economic growth in anticipation of economic losses due to the impacts of future climate change as well as policy options to reduce climate change damages through adaptation.

However, climate change does not have a uniform effect on different economic activities, and more recently modelling efforts have attempted to reflect this. A key challenge is to adequately capture the heterogeneity of climate change impacts, their geographic occurrence, and response to shifts in climate variables. But, it is also necessary to capture how impacts on natural and human systems vary in character and magnitude across regions and how these translate into shocks to the economy through the channels of different economic variables, with some activities or sectors being more severely affected than others (Sue Wing and Lanzi, 2014).

To address this, a more recent literature has tried to combine economic models that have sectoral details with information obtained from climate models and the empirical literature on climate damages. The models mostly used for this type of assessment are CGE models, which have the characteristic of depicting economic sectors and regions through trade flows and productive activities. Compared to IAMs, these models have a more detailed regional and sectoral structure, which can be used to better link climate impacts to the various economic sectors. However, the inclusion of non-market impacts of climate change is by far not straightforward in a CGE model: they therefore tend to capture a smaller subset of impacts compared to some detailed IAMs – and an even smaller subset of the wider impacts literature. These models also have the disadvantage of being computationally more complicated, as they recalculate an economic equilibrium at each time step. While these models are often dynamic, they are in most cases not based on a forward looking structure. Thus, they do not permit the determination of an optimal level of mitigation. They are also generally used for shorter term analysis. While IAMs can generate projections to the end of the 21st century and beyond, CGE models generally have timeframes up to mid-century for relatively detailed models and out to the end of the century for aggregated models. The shorter timescale is partly due to the fact that it is difficult to obtain reliable information on projected changes in sectoral production and demands and other socioeconomic trends that are needed to calibrate the models.

Both modelling approaches have relative advantages and disadvantages. It is possible to overcome these shortcomings by creating an IAM with sectoral details, but this is computationally complicated and generally means that some of the details of the sectoral and regional characteristics are lost. Alternatively, as done in this report, the two approaches can be combined and used to complement each other. By calibrating the two types of models on the same economic baseline and aligning the climate impacts, they can be used as complementary assessments to study different aspects of the same storylines. Nevertheless, differences between the two models remain. Most importantly, the stylised representation of the economy and damages from climate change in AD-DICE cannot fully replicate the sectoral and regional behaviour underlying the more elaborate approach in ENV-Linkages.

This report combines the analysis of regional and sectoral damages of climate change in the ENV-Linkages model developed by the OECD Environment Directorate (Chateau et al., 2013) with an analysis of long-term consequences and policy action done with the AD-DICE model (de Bruin et al., 2009a, b; Agrawala et al., 2011). The damages from climate change are contrasted with a "no-damage 'baseline' projection", which reflects the trend development of the socioeconomic drivers of economic growth (see Section 2.1); these trends abstract from short-term disruptions and business cycles.

ENV-Linkages is a global dynamic computable general equilibrium (CGE) model that describes how economic activities are linked to each other between sectors and across regions. The version used for the current analysis contains 35 economic sectors (see Table A1.1 in the Annex) and 25 regions (reproduced in Table 1.2), bilateral trade flows and has a sophisticated description of capital accumulation using capital vintages, in which technological advances only trickle down slowly over time to affect existing capital stocks. It also links economic activity to environmental pressure, specifically to GHG emissions. In ENV-Linkages, sectoral and regional economic activities and GHG emissions are projected for the medium- and long-term future, up to 2060, based on socio-economic drivers such as demographic developments, economic growth and development in economic sectors (see Chapter 2).

Table 1.2. **Regions in ENV-Linkages**

Macro regions	ENV-Linkages countries and regions
OECD America	Canada Chile Mexico United States
OECD Europe	EU large 4 (France, Germany, Italy, United Kingdom) Other OECD EU (other OECD EU countries) Other OECD (Iceland, Norway, Switzerland, Turkey, Israel)
OECD Pacific	Australia and New Zealand Japan Korea
Rest of Europe and Asia	China Non-OECD EU (non-OECD EU countries) Russian Federation Caspian region Other Europe (non-OECD, non-EU European countries)
Latin America	Brazil Other Lat. Am. (other Latin-American countries)
Middle East and North Africa	Middle-East North Africa
South and South-East Asia	India Indonesia ASEAN9 (other ASEAN countries) Other Asia (other developing Asian countries)
Sub-Saharan Africa	South Africa Other Africa (other African countries)

Source: ENV-Linkages model.

AD-DICE is based on the well-known integrated assessment model DICE (Nordhaus, 1994, 2012) but it is extended to include an explicit representation of adaptation to climate change. In the model economic production leads to emissions of GHGs but industrial carbon dioxide (CO_2) is the only endogenous gas. Emissions increase the stock of CO_2 in the atmosphere, resulting in climate change, which is represented in the model with changes in atmospheric temperature compared to pre-industrial (1900) levels. The economic consequences of climate change (i.e. climate damages), as measured by the change in GDP, are calculated as a function of temperature changes. Climate damages can be reduced with investments in mitigation, that will reduce CO_2 emissions, or with adjustments to the economy (i.e. adaptation). The model is based on an inter-temporal optimisation framework which can be used to find the optimal balance of capital investments, mitigation investments, adaptation investments, adaptation costs. The model has global coverage. AD-DICE, and its sister model AD-RICE, were also used in previous OECD studies, e.g. Agrawala et al. (2011), to gain insights about longer-term dynamics of climate-economy interactions and the relation between mitigation and adaptation policies. Further details on both models are provided in the Annex.

In order to enhance the comparability of the two models, they have both been calibrated on the same economic baseline, which is briefly outlined in Section 2.1. For OECD countries and the main emerging economies, this based on the OECD long-run aggregate growth scenario to 2060 (OECD, 2014a); for other countries the OECD's ENV-Growth model is used. Beyond 2060, AD-DICE has been calibrated following the growth rates of the business-as-usual scenario of the DICE model. The emission pathways in the two models have also been harmonised in order to increase comparability of results on both climate change impacts and policy results.

Furthermore, the damage function of AD-DICE has been recalibrated to the ENV-Linkages damage projections until 2060. To be precise, the parameters for both climate damages and adaptation have been recalibrated using the sectoral damage information from ENV-Linkages. For longer-term developments, the damage function parameters evolve in line with the original DICE specification, i.e. in the very long run, the damage function replicates the original DICE model.

Notwithstanding the remaining differences between both models, combining them allows this report to present results on different aspects of the economic consequences of climate change. The stylised nature of the AD-DICE model makes it more suitable for explorative scenario analysis. The core of the analysis, however, focuses on the sectoral and regional results obtained with the ENV-Linkages model and derived from a production function approach, which links with as much detail as possible climate impact endpoints with the production function that underlies the structure of the model.

1.3.2. The production function approach

A key challenge in modelling the link between climate change impacts and economic activities is to adequately capture the heterogeneity of climate change impacts. These vary in character and magnitude across regions and translate into shocks to the economy with some activities and sectors being more severely affected than others, through the channels of different economic variables.

One way to study this complex system in an economic framework is to link each climate impact to different variables in the production function that represents the activity of a specific industry or group of industries in the basic structure of the model. For a general framework see Sue Wing and Fisher-Vanden (2013) and for an overview of modelling applications see Sue Wing and Lanzi (2014). In a production function, output is produced from distinct inputs (e.g. labour and capital), intermediate commodity inputs and primary resources.

By modelling climate change impacts with a production function approach, it is possible to obtain, as for integrated assessment models, the total economic costs of the selected impacts of climate change on GDP. The overall GDP costs are in turn an indicator of the extent to which climate change has an impact on future economic growth; as in this approach damages can also affect capital stocks, it includes a potential direct effect on the growth rate of the economy. Compared to integrated assessment models in which climate damages are subtracted as a total from GDP, the production function approach can also explain how the composition of GDP is affected over time by climate change: what sectors are most affected (for the impacts that have been assessed) and what changes in production factors mostly contribute to changes in GDP.

Climate impacts have the potential to directly affect sectors' use of labour, capital, intermediate inputs and resources.[1] But they will also affect the productivity of inputs to production. Adverse climate-related shocks to the economy therefore act in the same manner as technological retrogressions, necessitating the use of more inputs to generate a given level of output.

Explicitly linking climate impacts to the sectoral economic variable works well for those impacts that are directly affecting economic markets. For non-market impacts, such a direct link with a part of the production function does not exist, and the damages need to be evaluated separately. In principle, the utility function could be used to incorporate both market and non-market damages in one quantitative framework, but specifying such a utility function is far from obvious and left for future research (see Chapter 3 for more details). Thus, in this report some of the main non-market damages are discussed in a stand-alone fashion in Chapter 3.

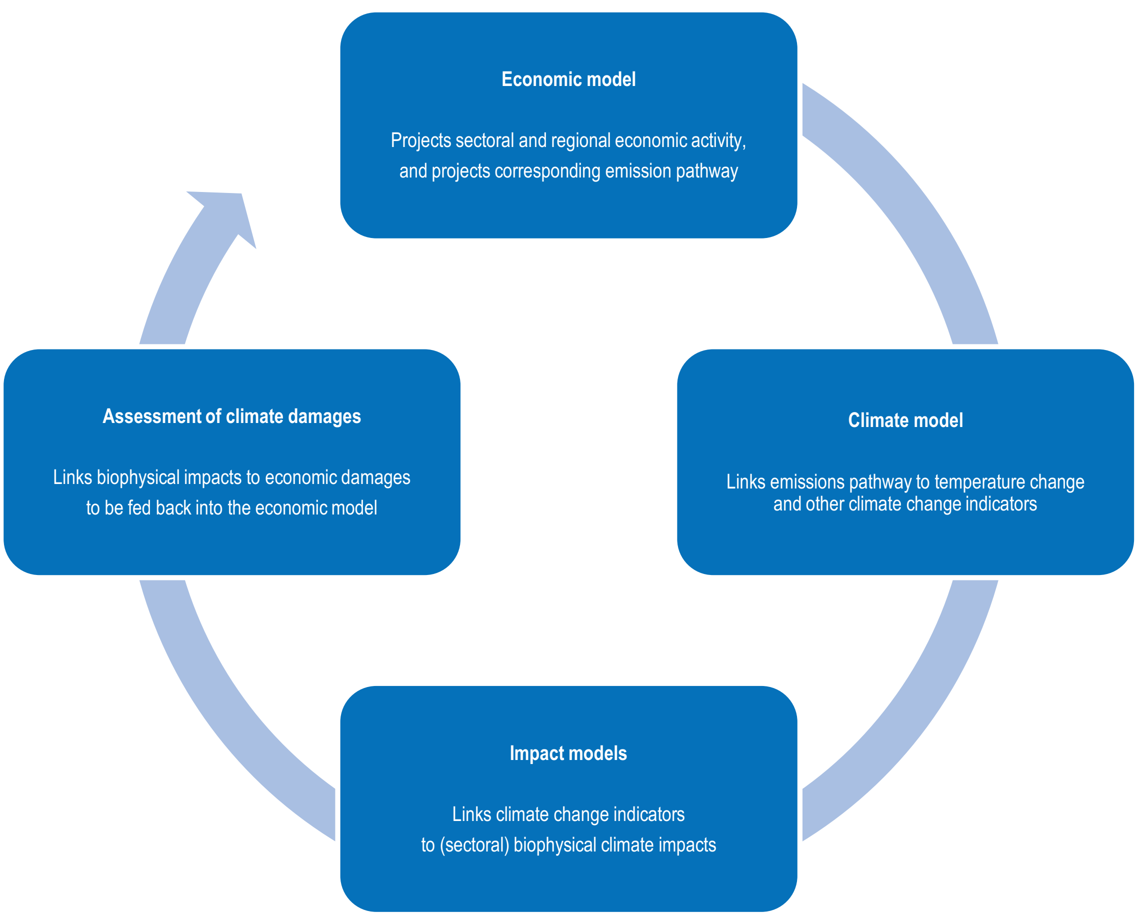
Modelling climate impacts with a production function approach relies heavily on the available empirical evidence, but also the opportunities to include this information with the modelling framework. Empirical studies that quantify the effect of climate change impact on the economy are numerous but their comprehensiveness varies in terms of geographical coverage and the impacts they consider (Agrawala and Fankhauser, 2008; OECD 2015). For instance, while there is a very large literature on agricultural damages from climate change, empirical studies on the dependence of energy supply on water availability and how this is affected by climate change are still scarce and limited to a few regions (cf. IEA, 2015).

The availability of empirical evidence also affects the decision on how to model each type of impact (Sue Wing and Lanzi, 2014) in the CGE environment. For example, changes in crop yields due to climate change can be modelled as a uniform shock to all crop sectors or, when more information is available, they can be differentiated between the crop sectors and regions. Similarly, impacts on coastal areas from sea level rise could be modelled in the CGE as a single productivity shock in all sectors or as a reduction in the supply of land together with an increase in non-productive defensive investments in exposed sectors.

Modelling climate damages in CGE models also means that a certain level of market-driven, reactive autonomous adaptation to the damages is inherently modelled. In models with sectoral details and a complex production and trade structure, a change in the productivity of a particular input will trigger substitution responses by producers that alter the use of the various inputs. Substitution is a powerful form of market adaptation once the level of the economy at which impacts manifest themselves is reached. The presence of market adaptation in the model also means that the final estimated costs of climate change impacts can be expected to be lower (or higher) than those estimated if adaptation is not considered (or considered to be optimal), as is often the case in IAMs. This feature also allows modellers to study both the direct effects of climate change and the indirect ones, such as the impacts that take place after trade effects.

The technical difficulty in implementing the detailed analysis of the sectoral and regional climate change feedbacks on economic growth is that the various steps that link the economy to climate change cannot be robustly summarised in a simple damage function, as is often used in IAMs. The economic model is used to create projections of economic growth with sectoral and regional details. The regional and sectoral structure of the models, as well as the energy details, can be exploited to produce projections of GHG emissions so as to obtain an emission pathway. Once the emissions are obtained, a climate module, such as MAGICC (Meinshausen et al., 2011), will translate the emission pathway into emission concentrations and temperature changes. This will then be the input or reference to obtain the needed information on climate damages for that specific scenario.

Figure 1.1. **Linking economic and climate change models**



Source: Own compilation.

The temperature pathway can be used as an input in two ways. In certain cases it can be used as input for specific sectoral models that will focus on a specific impact, such as a coastal system model for impacts of sea level rise, or an agricultural crop model to obtain crop yield changes. In other cases it can be used as a reference to seek for empirical or modelling studies that have already been done on existing temperature pathways. The existing reference pathways are usually the Representative Concentration Pathways (RCP) (Van Vuuren et al., 2012) or, for older studies, the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart, 2000). In this case the data used will be those relative to the pathway that is closed to the chosen reference scenario.

As a final step in the production function approach, the information obtained on climate damages is fed into the model by sector and region, choosing the most appropriate variables for each climate impact. The final output is a new level of sectoral, regional and global GDP that reflects the costs of climate change on economic growth. Figure 1.1 summarises this process.

1.4. Modelling of sectoral and regional climate impacts

The quantification of climate change impacts in ENV-Linkages relies on available information on how climate impacts affect different economic sectors. The information sources are mostly derived from bottom-up partial-equilibrium models, climate impact models and econometric studies.[2] Table 1.3 provides a summary of the impacts considered and their respective sources from the literature. They refer to the consequences of climate-related changes in agriculture and fisheries, coastal zones, health, and changes in the demand for tourism services and for energy for heating and cooling.

Table 1.3. **Climate impact categories included in ENV-Linkages**

Climate impacts	Impacts modelled	Source	Project	Time frame
Agriculture	Changes in crop yields	IMPACT model – Nelson et al. (2014)	AgMIP	2050
	Changes in fisheries catches	Cheung et al. (2010)	SESAME	2060
Coastal zones	Loss of land and capital from sea level rise	DIVA model – Vafeidis et al. (2008)	ClimateCost	2100
Extreme events	Capital damages from hurricanes	Mendelsohn et al. (2012)		2100
Health	Mortality and morbidity from infectious diseases, cardiovascular and respiratory diseases	Tol (2002)		2060
	Morbidity from heat and cold exposure	Roson and Van der Mensbrugghe (2012) and Ciscar et al. (2014) for Europe	World Bank ENVISAGE model and Peseta II (Europe)	2060
Energy demand	Changes in energy demand for cooling and heating	IEA (2013)	WEO	2050
Tourism demand	Changes in tourism flows and services	HTM – Bigano et al. (2007)	ClimateCost	2100
Ecosystems	No additional impacts covered in the modelling exercise			
Water stress	No additional impacts covered in the modelling exercise			
Tipping points	Not covered in the modelling exercise			

Source: Own compilation.

Most impacts used are assessed for the specific Representative Concentration Pathway (RCP) 8.5 scenario, which describes a pathway of climate change resulting from a fast increase in global emissions. The RCPs were developed by Van Vuuren et al. (2012) and adopted by the IPCC (2013; 2014a, b). Alternatively the impacts are related to the slightly older IPCC A1B SRES scenario (Nakicenovic and Swart, 2000), which describes a future world of very fast economic growth, global population that reaches its maximum number by 2050 and declines thereafter, and the rapid introduction of new and more efficient technologies for all energy sources (IPCC, 2000). The usage of different scenarios introduces only a minor approximation problem in specifying the RCP 8.5 reference, however, because until 2060 the temperature profiles of RCP 8.5 and A1B are reasonably close. Both scenarios are also similar to the ENV-Linkages model baseline with respect to GHG concentrations.

Wherever possible, the central projection uses results from the HadGEM3 model (Madec et al., 1996) from the Hadley Center of the UK Met Office, for the specification of the climate system variables. However, for certain climate impacts the data was only available from other climate models.

All source studies have a global coverage. As most studies come from grid-based data sets and models, they report data with a high spatial resolution, which permits the aggregation of data to match the regional aggregation of the ENV-linkages model. In some cases the source studies specified impact data with a regional aggregation tailored for other CGE models, including the ICES model[3] (Eboli et al., 2010; Bosello et al., 2012; Bosello and Parrado, 2014), which was used as a reference for several climate impacts. The ICES model presents a regional detail very close to that of ENV-Linkages. Simple averaging processes or other simplifying ad hoc assumptions have been used to determine impacts for those few regions not perfectly matching across the two models.

In cases where the data sources were only available until 2050, the trends between 2040 and 2050 have been extrapolated to 2060. In principle, the impacts are not provided for a specific year, but rather for a period of multiple years. Where applicable, the sectoral assessments of impacts for a future period, e.g. a period of 2045-55, have been translated into impacts for the middle year (in this case 2050) and then annual trends have been interpolated for earlier periods when no further information was available.

Two broad categories of climate change impacts can be distinguished. The first affects the supply-side of the economic system, namely the quantity or productivity of primary factors. Land and capital destruction from sea level rise, crop productivity impacts in agriculture, and labour productivity impacts on human health belong to this category. The second category of climate change impacts affects the demand side. Impacts on health expenditures[4] and on energy consumption are of this kind.

1.4.1. Agriculture

The climate change impacts on agriculture that are modelled in ENV-Linkages involve sector- and regional-specific changes in crop yields for each of the 8 crop sectors (see Annex I for the sectoral disaggregation of the ENV-Linkages model). The input data on crop yield changes (physical production per hectare) are those shared by the modelling teams involved in the Agricultural Model Intercomparison Project AgMIP (Rosenzweig et al., 2013; Nelson et al., 2014; Von Lampe et al., 2014). This project contains the most robust global assessment of agricultural impacts from climate change published to date. Although impacts on grasslands follow very similar patterns as impacts on crop land, the AgMIP project has not provided information on how grasslands are affected, so impacts on livestock are excluded from the modelling analysis. From the available scenarios shared in the AgMIP project, the central projection uses the HadGEM model, for the specification of the climate system variables, coupled with the DSSAT crop model (Hoogenboom et al., 2012; Jones et al., 2003). The specification of regional climate impacts coming from this model combination was then used as input for the International Food Policy Research Institute's IMPACT model (Rosegrant et al., 2012) to calculate the exogenous yield shocks from changes in crop growth and water stress by water basin. These shocks were then aggregated to the ENV-Linkages model regions. A pathway between 2010 and 2050 was produced by proportionally changing the effect of climate change on the yield growth rate such that in 2050, the yield shocks correspond to the AgMIP projection for the 2050s; this delivers a non-linear impact on yield levels. In line with AgMIP, the estimated yield shocks used in the central projection do not consider the carbon fertilization effects on vegetation as these are deemed too uncertain, although Rosenzweig et al. (2013) do identify it as "a crucial area of research".

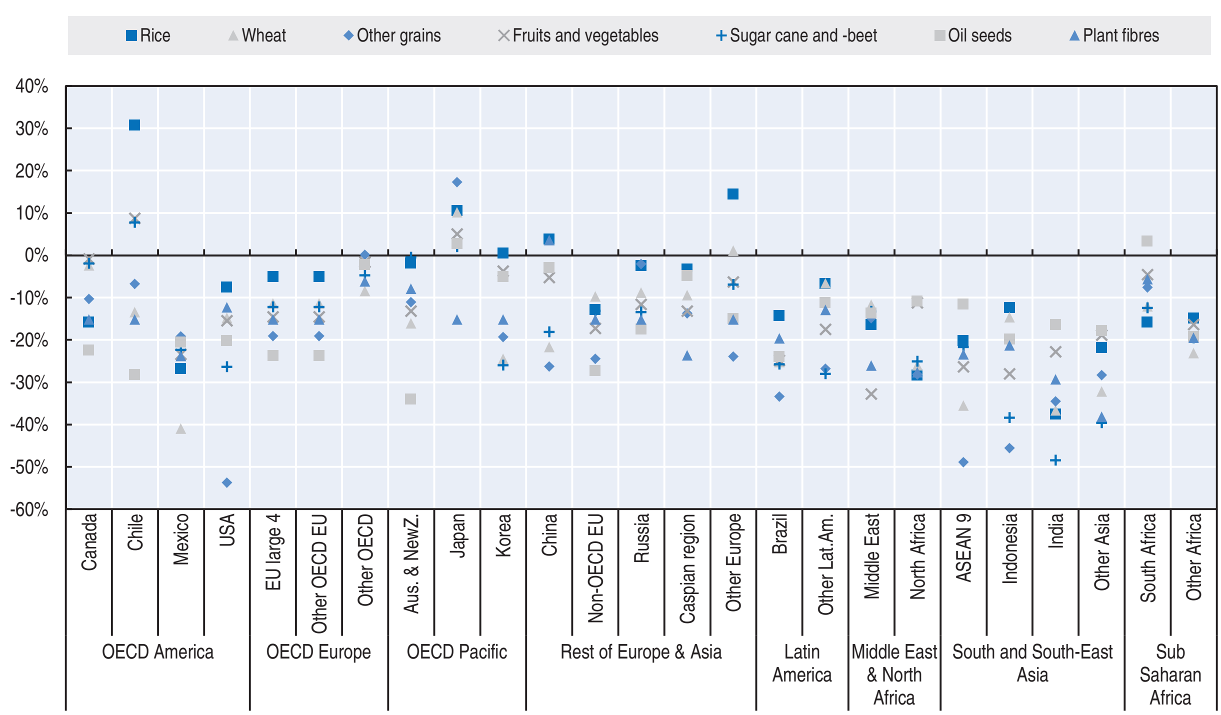
To further explore the uncertainty in the assessment of these agricultural impacts, Chapter 2 will also consider the implications of choosing other scenarios for specifying crop yield impacts, based on alternative choices for the underlying crop model, the underlying climate model and – not least – the assumption on CO_2 fertilisation.

Since the IMPACT model does not contain a full production function while ENV-Linkages does, the crop yield shocks have been translated into specific elements in the production functions of the ENV-Linkages agricultural sectors. The yield shocks are implemented in the model as a combination of the productivity of the land resource in agricultural production, and the total factor productivity of the agricultural sectors.[5] This specification mimics the idea that agricultural impacts affect not only purely biophysical crop growth rates but also other factors such as management practices.[6]

Climate change affects crop yields heterogeneously in different world regions. Further, the effects are also not the same for different crops. Figure 1.2 illustrates changes in crop yields at the regional level in 2050 for the central projection using the HadGEM climate model in combination with the DSSAT crop model. This excludes a CO_2 fertilisation effect; the uncertainty related to the choice of climate and crop model, and the effect of CO_2

Figure 1.2. **Impacts of climate change on crop yields in the central projection**

Percentage change in yields in 2050 relative to current climate



Source: IMPACT model, based on the AgMIP study (Von Lampe et al., 2014).

StatLink http://dx.doi.org/10.1787/888933275901

fertilisation, is further investigated in Chapter 2. While the maps illustrate impacts for 2050, the impacts are not constant over time. They follow a non-linear trend that is extended from 2050 to 2060 using the increase from the previous decade. Impacts for other crops can deviate substantially from the impacts for rice and wheat; they are not reproduced here, but are described in detail in Nelson et al. (2014). Note that these impacts refer to potential shocks: in the CGE model, farmers have options to change their production process and adapt to these shocks and will do so in order to minimise their costs, i.e. market-driven adaptation is endogenously handled inside the economic modelling framework. The modelling framework excludes the possibility to increase the size of irrigated agricultural land. In regions with low water stress levels, this adaptation option can be an important part of the response to climate change (Ignaciuk and Mason-D'Croz, 2014), but is excluded here as markets forces alone are usually insufficient to achieve large-scale expansion of irrigated areas (Ignaciuk, 2015).

Changes in yields of paddy rice by 2050 are strongest in tropical areas, including Central American and Mexico, Saharan African countries, some parts of the Middle East and a large part of South and South-East Asian countries. Some regions have large positive impacts on paddy rice yields. In particular, the highest gains will take place in the Southern parts of Latin America, and particularly in Chile, Japan, and in parts of Easter Europe and continental Asia. Such heterogeneity in impacts suggests that climate change will largely change trade patterns in widely traded commodities such as rice.

Changes in yields of wheat by 2050 are somehow less differentiated, as most regions are negatively affected. The most severe negative impacts take place in Mexico, Western and Eastern Africa, some Southern African countries, Middle East, South and South East Asia, and some Western European regions, such as Belgium, the Netherlands and Germany. While these are the most affected regions, negative impacts are widely spread and also affect most of Europe, continental Asia and North America. Some regions are positively affected by climate change. These include regions with cold climates such as Canada, Russia and Scandinavian countries, most of Central America, Argentina, some countries in Eastern Europe and continental Asia, and a few African countries.

For the *fisheries* sector, the damages reflect projected changes in global fish catch potential caused by climate change. This is modelled in ENV-Linkages as a change in the natural resource stock available to fishing sectors, which approximates the impacts of climate change for fish stocks and the resulting effects for the output of the fisheries sector. Acknowledging that the empirical basis for estimating the impacts on the fisheries sector is very small and uncertainties on projections are very large, the input data used for the modelling is based on one of the most comprehensive assessments, the EU's SESAME project, which in turn uses results from Cheung et al. (2010). This study applies an empirical model (Cheung et al., 2008) that predicts maximum catch potential as dependent upon primary production and distribution. It considers a range of 1066 species of exploited fish and invertebrates. Future projected changes in species distribution are simulated by using a model (Cheung et al., 2008, 2010) that starts with identifying species' preference for environmental conditions and then links them to the expected carrying capacity. The environmental conditions considered include seawater temperature, salinity, distance from sea-ice and habitat types, but the assessment excludes any effects related to ocean acidification. The model assumes that carrying capacity varies positively with habitat suitability of each spatial cell. Finally, the related change in total catch potential is determined aggregating spatially and across species.

The input data for the fisheries sector in the ENV-Linkages model is the percentage change in fish catch with respect to 2000 as described above. The most negatively affected regions by 2060 are North Africa (-27%) and Indonesia (-26%). Some European regions, the Middle East, Chile and several countries in South East Asia have impacts ranging from -10% to -15%. Smaller negative impacts also take place in China, Korea, Brazil and other Latin American countries, Mexico, and some European countries. In some countries fish catches actually increase. The highest increases will occur in Russia (+25%) and in the five major European economies (+23%). Small positive impacts are seen in the United States, Canada, Oceania and the Caspian region. Other world regions (India, other developing countries in Asia, South Africa and the rest of Africa) are basically unaffected.

1.4.2. Coastal zones

Coastal land losses due to sea level rise are included in the ENV-Linkages model as changes in the availability of land as well as damages to physical capital. Both modifications concern land and capital stock variables by region in the model. As information on capital losses are not readily available, in line with Bosello et al. (2012), land and capital stock changes are approximated by assuming that changes in capital supply match land losses as a percentage change from baseline.

Estimates of coastal land lost to sea level rise are based on the DIVA model outputs (Vafeidis et al., 2008) as used in the European Union's (EU) FP7 ClimateCost project (Brown et al., 2011) and generated with the HadGEM model. DIVA is a sector model designed to address the vulnerability of coastal areas to sea level rise and other ocean- and river-related events, such as storm surges, changes in river morphology and altered tidal regimes. The model is based on a world database of natural system and socioeconomic factors for world coastal areas reported with spatial details. Changes in natural and socio-economic conditions of possible future scenarios are implemented through a set of impact and adaptation algorithms. Impacts are then assessed both in terms of physical losses (i.e. sq. km of land lost) and economic costs (i.e. value of land lost and adaptation costs).

The regions that are most affected by sea level rise are those in South and South East Asia, with highest impacts in India, and other developing countries in the region. The projected land and capital losses expressed as percentage of total regional agricultural land area in 2060 with respect to the year 2000 are respectively -0.63% for India and -0.86% for the Other Developing Asia region of ENV-Linkages. Other countries in the region are also affected but to a smaller extent. Some impacts are also felt in North America, with Canada, Mexico and the United States being affected. Canada has the highest loss in land (and capital) in this region (-0.47% in 2060 with respect to 2000). Smaller impacts occur in Middle East (-0.35%) and in Europe, where the highest impacts are felt in the aggregate non-OECD Europe region (-0.37%), which includes, among other countries, Israel, Norway and Turkey. Other world regions, such as Africa, South America and continental European regions are on balance hardly affected by sea level rise.

1.4.3. Extreme events

There are many types of extreme events and they affect the economy in different ways. However, given the uncertainties involved in the frequency and damages caused by these events and the difficulties in attributing such events to climate change, the available data on how the economy will be affected is still scarce. Recently, the assessment by Mendelsohn et al. (2012) has provided some quantitative assessment and projections on damages from hurricanes that can be used as input in an economic framework. Mendelsohn et al. (2012) stress that the regional damages are quite sensitive to the climate model that is used to project future climate conditions, and projections based on the HadGEM model are not available. Hence, the analysis of the economic consequences was realised in ENV-Linkages on a multi-model average.[7] This may of course dampen some of the more severe consequences projected by individual models.

Mendelsohn et al. (2012) find that climate change is predicted to increase the frequency of high-intensity storms in selected ocean basins as the century progresses, although this depends on the climate model used. These climate-induced damages are included in ENV-Linkages as reductions in regional capital stocks from tropical cyclones. Due to lack of information, this is assumed to affect all sectors (which is in line with the normal CGE model assumption that new investments in capital are fully malleable across the economy).

Mendelsohn et al. (2012) also find that the current annual global damage from tropical cyclones is USD 26 billion, which is equivalent to 0.04% of global GDP, and roughly double (in absolute amount) by the end of the century under current climate conditions, i.e. due to changes in socioeconomic conditions.[8] However, these damages are projected to double again by the end of the century due to climate change. Most additional climate-induced damages are predicted to take place in North America, East Asia and the Caribbean-Central American region, where the United States, Japan and China will be most affected.

1.4.4. Health

Within the health impact category, the ENV-Linkages model covers both climate-related illnesses and effects related to heat stress. Impacts on human health linked with *climate-related diseases* are expressed by changes in mortality and morbidity, following Bosello et al. (2012) and Bosello and Parrado (2014).[9] The illnesses considered are vector-borne diseases (malaria, schistosomiasis and dengue), diarrhoea, cardiovascular and respiratory diseases. The assessment for cardiovascular diseases includes both cold and heat stress. Within the production function approach, the modelling technique for these health impacts is to translate the results of the empirical literature into changes in labour productivity and demand for health services (Bosello et al., 2006) – explicitly excluding the welfare (or "disutility") impacts of premature deaths from climate change. While there are other factors that are affected by these illnesses, labour productivity is the most suitable variable to capture the effects that climate-related diseases have on the economy.

Estimates of the change in mortality due to vector-borne diseases are taken from Tol (2002), which are based on modelling studies (Martens et al., 1995, 1997; Martin and Lefebvre, 1995; Morita et al., 1994) as well as on mortality and morbidity figures from the World Health Organization's Global Burden of Disease data (Murray and Lopez, 1996).[10] These studies suggest that the relationship between climate change and malaria is linear. This relationship is also applied to schistosomiasis and dengue fever. To account for changes in vulnerability possibly induced by improvement in living standards, Tol (2002) applies a relationship between per capita income and disease incidence (Tol and Dowlatabadi, 2001). This relationship is used to assess the impacts for the CIRCLE baseline by using the projected per capita regional income growth of the ENV-Linkages model (see Chapter 2).

For diarrhoea, an estimated equation describes how increased temperatures increase both mortality and morbidity, while negative income elasticities imply lower impacts with rising income, with mortality declining more rapidly than morbidity (Link and Tol, 2004). For premature deaths due to cardiovascular and respiratory diseases, data are based on a meta-analysis performed in 17 countries (Martens, 1998). Tol (2002) extrapolates these findings to all other countries, using the current climate as the main predictor. Cardiovascular (for both cold and heat stress) and respiratory mortality (for heat stress only) are assumed to only affect urban population.

The resulting changes in labour productivity from climate-induced diseases, which have been summarised in Bosello et al. (2012), are used as in input in ENV-Linkages. By 2060, the highest negative effects take place in Africa and the Middle East (-0.6% for South Africa, -0.5% for North Africa and the Middle East and -0.4% for other African countries). Smaller impacts take place in Brazil, Mexico and in developing countries in Asia (-0.3%), as well as in Indonesia, the United States, South-East Asia and most of Latin America (-0.2%). Some regions are projected to have positive impacts on labour productivity from climate-induced diseases, the highest being in Russia (+0.5%), Canada (+0.4%) and China (+0.2%). In other regions the impacts are either very small or inexistent.

Changes in *health care expenditures* for climate-related diseases are also taken from Bosello et al. (2012). The costs of vector borne diseases are based on Chima et al. (2003), who report the expenditure on prevention and treatment costs per person per month. Changes in health expenditure are small as percentage of GDP.[11] In 2060, they are projected to be highest in the developing countries in Asia (0.5%), in Brazil and in the Middle East and North Africa region (0.3%). Additional demands for health services are very small in other regions. Interestingly, they are negative in Canada and in large EU economies, such as Germany and France (-0.1%), where reduced cardiovascular disease expenditures dominate.

Occupational heat stress is modelled as having an impact on labour productivity. This builds on Kjellstrom et al. (2009), who identify a link between the global temperature, heat and humidity, and work ability for different types of activities (agriculture, industry and services). Ideally one would combine the sectoral reductions in work ability to the regional temperature increases to identify labour productivity losses. Unfortunately, there is insufficient data to do so. However, data derived from Roson and Van der Mensbrugghe (2012) translates the underlying regional climate profiles into labour productivity losses as a function of global average temperature increase. For the European regions, data from Ciscar et al. (2014) are adopted.

Until now, most assessments (Eboli et al., 2010, Ciscar et al., 2014) have first aggregated the various productivity losses across sectors and then apply these averages to all economic sectors. Recent research (e.g. Graff Zivin and Neidell, 2014; Somanathan et al., 2014) has highlighted that productivity of sectors where workers are mostly outdoor (i.e. heat-exposed industries) are on balance much more affected by increased heat. For indoor activities, in turn, the most severe consequences can be avoided by increased air conditioning, which is at least partially captured under the impacts of changed energy demand (see e.g. Somanathan et al., 2014). Hence, the impacts are assumed to be limited to heat-exposed sectors. In line with Ciscar et al. (2014), labour productivity losses are concentrated in the agricultural, forestry, fisheries, and construction sectors, and exclude most manufacturing and services sectors (see Annex I for a full list of sectors in ENV-Linkages).

The highest impacts on labour productivity caused by heat stress in 2060 take place in regions with relative large proportions of outdoor workers and warm climates. The most severely affected regions, with productivity losses between 3 and 5%for outdoor activities for a one degree temperature increase are in non-OECD, non-EU European countries, Latin America (incl. Brazil and Chile), Mexico, China, Other Developing Asia and South Africa. Most OECD countries, including USA, Japan and the OECD EU countries have much smaller effects, of less than 1%.[12]

The health impacts of climate change have economic consequences that go beyond market costs. These costs, such as the costs of premature deaths, cannot be accounted for in the ENV-Linkages model. However, they can be evaluated using WTP techniques and, for premature deaths, the Value of a Statistical Life. These impacts are further discussed in Chapter 3.

1.4.5. *Energy demand*

Residential *energy demand* has been projected to change due to climate change. As discussed in Chapter 4, the energy sector is heavily influenced by mitigation policies. But even in the absence of mitigation policies will there be impacts on energy demand and supply. Changes in households' *demand for oil, gas, coal and electricity* from less energy consumption for heating and more for cooling, have been captured directly in the model as a change in consumer demand for the output of these energy services. Changing residential energy demand in response to climate change is derived from the IEA, which provides data on space heating and cooling by carrier until 2050 under its Current Policies Scenario (IEA, 2013a). Data until 2060 was extrapolated using trends in demand from 2040 to 2050. The IEA derives its projections from its World Energy Model, which is a large-scale partial-equilibrium model designed to replicate the functioning of energy markets over the medium- to long-term. It determines future energy supply and demand for different energy carriers (supply: coal, oil, natural gas, biomass; demand: coal, oil, natural gas, nuclear, hydro, bioenergy, and other renewables) according to trends in energy prices, CO_2 prices, technologies, and socioeconomic drivers. The baseline trends without climate change are characterised by increased heating and cooling demand for most economies, driven to a large extent by higher incomes; the baseline also projects a strong trend of electrification, which affects especially heating energy demand. Demand for space heating and cooling under climate change is affected by factors including the anticipated change in heating and cooling degree days due to climate change (IEA, 2013; IEA, 2014).

Overall, global energy demand for space cooling is projected to grow by roughly 250% between 2010 and 2060 under no climate change and by 330% if climate change is taken into account. Increases in demand for heating are much lower, with a projected 42% rise until 2060 without climate change and a 16%-increase in the climate change scenario, but start from a much larger base level. Non-OECD countries drive most of the increase in demand both for heating and cooling, and particularly so in heating. By 2060, household demand for cooling is projected to be 27% of the total demand for space heating and cooling purposes as compared to 9% in 2010.

Climate change-induced shifts in the demand for electricity until 2060 can reflect both an increased demand for cooling purposes, i.e. air conditioning, as well as decreased demand for electric space heating as a response to higher average temperatures. Globally, total annual electricity demand is projected to remain largely unaffected by climate change by 2060, with increases in demand for cooling during summers balancing decreases in demand for heating during winters. Of the 25 regions in ENV-Linkages, about half are projected to increase their total demand for electricity due to greater need for cooling, including the EU7 (+11.4%), Chile (+8.4%) and non-OECD EU countries (+7.3%). Korea (-6.7%), non-EU OECD Europe (-3.7%), and the Caspian region (-3.1%) are part of the other half of the regions in which decreased consumption of electricity for heating will more than offset increases in demand for cooling (given the strong trend towards electrification of heating in the baseline without climate change). In the vast majority of the regions, positive or negative variations in demand for cooling and heating under climate change are projected to stay below 3% relative to the baseline total electricity demand of households.

As global temperatures increase with climate change, the IEA projections suggest that climate change will lead to reduced household demand for all major space heating fuels, i.e. gas, oil and coal, relative to the baseline. In total household demand for gas, change in gas-based space heating is projected to fall by about 7%; oil-based space heating by 1% (out of total household demand for oil); and coal-fired heating by 17% (out of total household demand for coal). If aggregated, the demand for gas, oil, and coal for heating purposes is projected to decline by approximately 3% of total household demand for these fuels (or decline by 2% out of total energy demand for heating and cooling if electricity is included). At the regional level, changes can be more pronounced: the demand of gas, oil and coal in total household demand for these fuels is going to decrease most by 2060 in other EU countries (-19.8%), OCE (-17.6%), EU7 (-13.5%), and Chile (-12.5%). The other regions will experience falling demand for these fuels by less than 10% of household fuel demand (with 12 regions reducing demand by less than 2.5%).

While the consequences of climate change on space cooling and heating demand are captured in the model, the impacts of climate change on *energy supply* (such as interruptions in the availability of cooling water for thermal electricity generation due to heat extremes or droughts, the change in water availability for hydro-electricity, etc.) are not included in the analysis. The direct impacts of climate change on energy supply are not included in the analysis, but the CGE model does capture the endogenous effects on energy markets induced by the impacts on demand, and cause changes in energy prices and supply. As with other demand impacts, any endogenous shifts in demand between carriers, as a result of changing prices and income levels, are also fully captured in the model.

1.4.6. Tourism demand

Changes in *tourism* flows reflect projected changes in tourist destinations due to changes in climate. For instance, projected decreases in snow cover in the Alps in the future might lead tourists to go skiing in other regions. These changes in the regional demand for tourism services are derived from simulations based on the Hamburg Tourism Model (Bigano et al., 2007); it thus contains only one projection and alternative models may provide different projections, especially at the regional scale. However, this approach has been amply used in EU research projects and in previous applications in CGE models (Berrittella et al., 2006 and Bigano et al., 2008). The Hamburg Tourism Model is an econometric simulation model that projects domestic and international tourism by country. The share of domestic tourists in total tourism depends on the climate in the home country and on per capita income. Climate change is represented in this simple approximation by annual mean temperature. A number of other variables, such as country size, are included in the estimation, but these factors are held constant in the simulation. International tourists are allocated to all other countries on the basis of a general attractiveness index, climate, per capita income in the destination countries, and the distance between origin and destination. Total tourism expenditure is then calculated multiplying the number of tourists times an estimated value of the average individual expenditure.

In the ENV-Linkages model, climate damages from tourism have been modelled by modifying the quality of tourism services in different regions. In contrast to Bosello et al. (2012), changes in demand for tourism are not forced changes in household expenditures, but they are rather induced by a change in the quality of the service provided. Such quality changes are represented in the model as a change in total factor productivity of the tourism services sector. Changes in tourism expenditures are largely a shift between countries, plus a shift from tourism to other commodities in domestic consumption, as changes in domestic tourism flows do not affect economy-wide expenditures. On balance, global expenditures on tourism are decreasing, implying a net negative impact on the global economy. The main reason for the reduction of global tourism expenditures is that the average quality of tourism services goes down, and to some extent consumers respond to the increase price of tourism to shift towards other consumption categories.

The regional effects are crucial for tourism, as some countries are negatively and others positively affected. The countries with the highest gains in tourism expenditure by 2060, expressed as percentage change with respect to the baseline scenario, are Canada (+92%), Russia (+66%) and the United States (+21%). Smaller positive impacts (of around +10%) also occur in Chile and Japan. The largest negative impacts instead take place in Latin America, excluding Chile and Brazil (-27%), Mexico (-25%), as well as Africa, excluding South Africa, China, South-East Asia and developing countries in Asia (with impacts around -20%). Smaller negative impacts take place in South Africa (-14%), Indonesia (-13%) the EU OECD regions (-9%) and the Caspian region (-7%). Other countries have much smaller impacts.

Notes

1. An example is loss of coastal land, buildings and infrastructure due to inundation as a result of sea level rise.
2. Much of the information used is an elaboration of data provided by recently concluded and ongoing research projects, including both EU Sixth and Seventh Framework Programs (FP6 and FP7) such as ClimateCost, SESAME and Global-IQ and model inter-comparison exercises such as AgMIP. These data have been kindly provided by the researchers involved in these projects.
3. The ICES model is operated by the Euro-Mediterranean Centre for Climate Change (CMCC), Italy. For detailed information about the model please refer to the ICES website: *www.cmcc.it/models/ices-intertemporal-computable-equilibrium-system*.
4. Health impacts are calculated with a cost of inaction approach, which does not account for other costs to society. A valuation of full economic impacts would imply higher costs.
5. Due to a lack of further information, the percentage change in yields is attributed equally to both parts.
6. Note that labour productivity changes in agriculture due to heat stress are captured in the health category.
7. The emission projection used by Mendelsohn et al. (2012) is the SRES A1B scenario, which leads to somewhat lower projected climate change than the CIRLE baseline; this difference implies that the hurricane damages presented here are slightly underestimated but this effect is ignored as the differences until 2060 are small.
8. Note that Hsiang and Jina (2014) find much larger impacts of tropical cyclones on the future global economy by focusing on the consequences for long-term economic growth.

9. Mortality effects have not been incorporated in the model for other climate damages. However, in the case of diseases, it was not possible to disentangle morbidity and mortality effects, so they have been included in the assessment.
10. It is acknowledged that this implies that the assessment cannot take recent developments in the literature, such as updates to the Global Burden of Disease study, into account. Unfortunately, a full updated assessment of the effects of climate change on disease-related health impacts is beyond the scope of the current study.
11. Using explained in Section 1.3, additional health care costs are not directly subtracted from GDP, but rather represented as a forced expenditure by households and the government. Indirectly, this affects GDP.
12. In some cases, there are large differences within the aggregated regions. For example, on the OECD EU countries, the productivity losses are largely concentrated in the Mediterranean countries.

References

Agrawala, S. and S. Fankhauser (2008), "Putting Climate Change Adaptation in an Economic Context", in *Economic Aspects of Adaptation to Climate Change: Costs, Benefits and Policy Instruments*, OECD Publishing, Paris, *http://dx.doi.org/10.1787/9789264046214-3-en*.

Agrawala, S. et al. (2011), "Plan or React? Analysis of adaptation costs and benefits using Integrated Assessment Models", *Climate Change Economics*, Vol. 2(3), pp. 175-208.

Berrittella, M. et al. (2006), "A general equilibrium analysis of climate change impacts on tourism", *Tourism Management*, Vol. 25, pp. 913-924.

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 Journal,* Vol. 7, pp. 25-49.

Bigano, A. et al. (2008), "Economy-wide impacts of climate change: a joint analysis for sea level rise and tourism", *Mitigation and Adaptation Strategies for Global Change,* Vol. 13(8), pp. 765-791.

Risky Business Project (2014), *The economic risks of climate change in the United States: A climate risk assessment for the United States*, *www.riskybusiness.org*.

Bosello, F. and R. Parrado (2014), "Climate Change Impacts and Market Driven Adaptation: the Costs of Inaction Including Market Rigidities", *FEEM Working Paper*, No. 64.2014.

Bosello, F., F. Eboli and R. Pierfederici (2012), "Assessing the Economic Impacts of Climate Change. An Updated CGE Point of View", *FEEM Working Paper,* No. 2.2012.

Bosello, F., C. Carraro and E. De Cian (2010), "Climate Policy and the Optimal Balance between Mitigation, Adaptation and Unavoided Damage", *Climate Change Economics,* 1: pp. 71-92.

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

Braconier, H., G. Nicoletti and B. Westmore (2014), "Policy Challenges for the Next 50 Years", *OECD Economic Policy Papers*, No. 9, OECD Publishing, Paris, *http://dx.doi.org/10.1787/5jz18gs5fckf-en*.

Brown S. et al. (2011), "The Impacts and Economic Costs of Sea-Level Rise in Europe and the Costs and Benefits of Adaptation. Summary of Results from the EC RTD ClimateCost Project", in: P. Watkiss, (ed.), *The ClimateCost Project. Final Report. Volume 1: Europe*, Stockholm Environment Institute, Sweden.

Chateau, J., R. Dellink and E. Lanzi (2014), "An Overview of the OECD ENV-Linkages Model: Version 3", *OECD Environment Working Papers*, No. 65, OECD Publishing, Paris, *http://dx.doi.org/10.1787/5jz2qck2b2vd-en*.

Cheung, W.W.L., V.W.Y. Lam, J.L. Sarmiento, K. Kearney, R. Watson, R., D. Zeller and D. Pauly (2010), "Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change", *Global Change Biology*, Vol. 16, pp. 24-35.

Cheung, W.W.L., V.W.Y. Lam and D. Pauly (2008), "Dynamic bioclimate envelope model to predict climate-induced changes in distribution of marine fishes and invertebrates", in: *Modelling Present and Climate-Shifted Distributions of Marine Fishes and Invertebrates,* Fisheries Centre Research Reports 16(3) (W.W.L. Cheung, V.W.Y. Lam and D. Pauly, eds.), pp. 5-50. University of British Columbia, Vancouver.

Chima, R.I., C.A. Goodman and A. Mills (2003), "The economic impact of malaria in Africa: A critical review of the evidence", *Health Policy*, Vol. 63, pp. 17-36.

Ciscar, J.C. et al. (2011), "Physical and economic consequences of climate change in Europe", *Proceedings of the National Academy of Science (PNAS)*, Vol. 108, pp. 2678-83.

Ciscar. J.C. et al. (2014), "Climate impacts in Europe. The JRC PESETA II project", *JRC Scientific and Policy Reports*, No. EUR 26586EN, Luxembourg: Publications Office of the European Union.

De Bruin, K.C., R.B. Dellink and R.S.J. Tol (2009a), "AD-DICE: An implementation of adaptation in the DICE model", *Climatic Change*, Vol. 95, pp. 63-81.

De Bruin, K., R. Dellink and S. Agrawala (2009b), "Economic Aspects of Adaptation to Climate Change: Integrated Assessment Modelling of Adaptation Costs and Benefits", *OECD Environment Working Papers*, No. 6, OECD Publishing, Paris, *http://dx.doi.org/10.1787/225282538105*.

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

Dell, M., B.F. Jones and B.A. Olken (2013), "What do we learn from the weather? The new climate-economy literature", *NBER (National Bureau of Economic Research) Working Paper Series*, No. 19578, NBER, Cambridge, Massachusetts.

Dellink, R. et al. (2014), "Consequences of Climate Change Damages for Economic Growth: A Dynamic Quantitative Assessment", *OECD Economics Department Working Papers*, No. 1135, OECD Publishing, Paris, *http://dx.doi.org/10.1787/5jz2bxb8kmf3-en*.

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*, Vol. 15, pp. 515-533.

EPA (2015), "Ecosystems: Climate impacts on ecosystems", website article, United States Environmental Protection Agency, *www.epa.gov/climatechange/impacts-adaptation/ecosystems.html* (accessed 24 March 2015).

Hsiang, S.M. and A.S. Jina (2014), "The causal effect of environmental catastrophe on long-run economic growth", *NBER Workshop Paper*, No. 20352.

Hoogenboom, G. et al. (2012), "Decision support system for agrotechnology transfer (DSSAT) version 4.5", CD-ROM. University of Hawaii, Honolulu, Hawaii.

Garnaut, R. (2008), *The Garnaut Climate Change Review: Final Report*, Cambridge University Press.

Garnaut, R. (2011), *The Garnaut review 2011: Australia in the global response to climate change*, Cambridge University Press.

Graff Zivin, J. and M. Neidell (2014), "Temperature and the Allocation of Time: Implications for Climate Change", *Journal of Labor Economics*, 32: 1-26.

IEA (2015), *World Energy Outlook Special Report on Energy and Climate Change*, IEA, Paris.

IEA (2014), *World Energy Outlook*, IEA, Paris, *http://dx.doi.org/10.1787/weo-2014-en*.

IEA (2013), *Redrawing the energy climate map*, IEA, Paris.

Ignaciuk, A. (2015), "Adapting Agriculture to Climate Change: A Role for Public Policies", *OECD Food, Agriculture and Fisheries Papers*, No. 85, OECD Publishing, Paris, *http://dx.doi.org/10.1787/5js08hwvfnr4-en*.

Ignaciuk, A. and D. Mason-D'Croz (2014), "Modelling Adaptation to Climate Change in Agriculture", *OECD Food, Agriculture and Fisheries Papers*, No. 70, OECD Publishing, Paris, *http://dx.doi.org/10.1787/5jxrclljnbxq-en*.

IPCC (2014a), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.

IPCC (2014b), *Climate Change 2014: Mitigation of Climate Change*, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2013), *Climate Change 2013: The Physical Science Basis*, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Jones, J.W. et al. (2003), DSSAT Cropping System Model, *European Journal of Agronomy,* Vol. 18, pp. 235-265.

Kjellstrom T. et al. (2009), "The direct impact of climate change on regional labor productivity", *Archives of Environmental Occupation and Health*, Winter; 64(4), pp. 217-27.

Link, P.M. and R.S.J. Tol (2004), "Possible economic impacts of a shutdown of the thermohaline circulation: An application of *FUND*", *Portuguese Economic Journal,* Vol. 3, pp. 99-114.

Madec, G. and M. Imbard (1996), "A global ocean mesh to overcome the north pole singularity", *Climate Dynamics*, Vol. 12, p381-388.

Martens, W.J.M., T.H. Jetten, J. Rotmans and L.W. Niessen (1995), "Climate change and vector-borne diseases: A global modelling perspective", *Global Environmental Change*, Vol. 5(3), pp. 195-209.

Martens, W.J.M., T.H. Jetten and D.A. Focks (1997), "Sensitivity of malaria, schistosomiasis and dengue to global warming", *Climatic Change*, Vol. 35, pp. 145-156.

Martens, W.J.M. (1998), "Health impacts of climate change and ozone depletion: An ecoepidemiologic modelling approach", *Environmental Health Perspectives*, Vol. 106(1), pp. 241-251.

Martin, P.H. and M.G. Lefebvre (1995), "Malaria and Climate: Sensitivity of Malaria Potential Transmission to Climate", *Ambio*, Vol. 24(4), pp. 200-207.

Meinshausen, M., S.C.B. Raper and T.M.L. Wigley (2011), "Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6: Part I – Model Description and Calibration", *Atmospheric Chemistry and Physics*, Vol. 11, pp. 1417-1456.

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.

Morita, T., M. Kainuma, H. Harasawa, K. Kai and Y. Matsuoka (1994), "An Estimation of Climatic Change Effects on Malaria", *Working Paper, National Institute for Environmental Studies*, Tsukuba.

Murray, C.J.L. and A.D. Lopez (1996), *Global Health Statistics*, Harvard School of Public Health, Cambridge.

Nakicenovic, N. and R. Swart (eds.) (2000), *Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change.* Cambridge University Press: Cambridge, UK and New York.

Nelson, G.C. et al. (2014), "Climate change effects on agriculture: Economic responses to biophysical shocks", *Proceedings of the National Academy of Sciences*, Vol. 111(9), pp. 3274-3279.

Nordhaus, W.D. (2012), "Integrated Economic and Climate Modeling,", in: P. Dixon and D. Jorgenson (eds.), *Handbook of Computable General Equilibrium Modeling,* Elsevier.

Nordhaus, W.D. (2010), "Economic aspects of global warming in a post-Copenhagen environment", *Proceedings of the National Academy of Sciences*, Vol. 107(26), pp. 11721-11726.

Nordhaus, W.D. (2007), *A question of balance*, Yale University Press, New Haven, United States.

Nordhaus, W.D. (1994), *Managing the Global Commons: The Economics of the Greenhouse Effect,* MIT Press, Cambridge, MA.

Nordhaus W.D. and J. Boyer (2000), *Warming the World*. Economic Models of Global Warming, The MIT Press, Cambridge, MA.

OECD (2015), *Climate Change Risks and Adaptation: Linking Policy and Economics*, OECD Publishing, Paris, *http://dx.doi.org/10.1787/9789264234611-en*.

OECD (2014a), *OECD Economic Outlook*, Vol. 2014/1, OECD Publishing, Paris, *http://dx.doi.org/10.1787/eco_outlook-v2014-1-en*.

OECD (2014b), *Climate Change, Water and Agriculture: Towards Resilient Systems*, *OECD Studies on Water*, OECD Publishing, Paris, *http://dx.doi.org/10.1787/9789264209138-en*.

OECD (2012), *OECD Environmental Outlook to 2050: The Consequences of Inaction*, OECD Publishing, Paris, *http://dx.doi.org/10.1787/9789264122246-en*.

Parson, E.A. and K. Fisher-Vanden (1997), "Integrated Assessment Models of Global Climate Change", *Annual Review of Energy and Environment*, 1997, 22, 589-628.

Rosegrant, M.W. and the IMPACT Development Team (2012), "International model for policy analysis of agricultural commodities and trade (IMPACT): Model Description", International Food Policy Research Institute (IFPRI), Washington, DC (2), *www.ifpri.org/sites/default/files/publications/impactwater2012.pdf*.

Rosenzweig, C. et al. (2013), "Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison", *Proceedings of the National Academy of Sciences (PNAS)*, Vol. 111(9), pp. 3268-73.

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

Somanathan, E., R. Smanathan, A. Sudarshan and M. Tewari (2014), "The impacts of temperature on productivity and labor supply: Evidence from Indian manufacturing", *Indian Statistical Institute Discussion Paper* 14-10, Delhi.

Steininger, K.W. et al. (2015), *Economic Evaluation of Climate Change Impacts: Development of a Cross-Sectoral Framework and Results for Austria*, Springer International Publishing, Switzerland.

Stern, N. (2007), *The Economics of Climate Change: The Stern Review*, Cambridge and New York: Cambridge University Press.

Sue Wing, I. and K. Fisher-Vanden (2013), "Confronting the Challenge of Integrated Assessment of Climate Adaptation: A Conceptual Framework", *Climatic Change*, Vol. 117(3), pp. 497-514.

Sue Wing, I. and E. Lanzi (2014), "Integrated assessment of climate change impacts: Conceptual frameworks, modelling approaches and research needs", *OECD Environment Working Papers*, No. 66, OECD Publishing, Paris, *http://dx.doi.org/10.1787/5jz2qcjsrvzx-en*.

Tol, R.S.J. and H. Dowlatabadi (2001), "Vector-borne diseases, climate change, and economic growth", *Integrated Assessment*, Vol. 2, pp. 173-181.

Tol, R.S.J. (2002), "New Estimates of the Damage Costs of Climate Change, Part I: Benchmark Estimates", *Environmental and Resource Economics*, Vol. 21 (1), pp. 47-73.

Tol, R.S.J. (2005), "Emission abatement versus development as strategies to reduce vulnerability to climate change: an application of FUND", *Environment and Development Economics*, Vol. 10(5), pp. 615-629.

US Interagency Working Group on Social Cost of Carbon (2010), "Social cost of carbon for regulatory impact analysis – under executive order 12866", *Technical Support Document*.

US Interagency Working Group on Social Cost of Carbon (2013), "Technical update of the social cost of carbon for regulatory impact analysis – under executive order 12866", *Technical Support Document*.

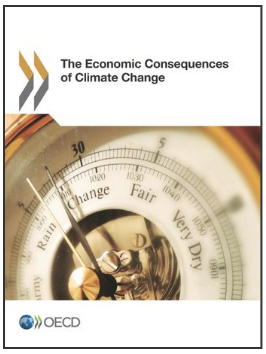
Vafeidis, A.T., R.J. Nicholls, L. McFadden, R.S.J. Tol, J. Hinkel, T. Spencer, P.S. Grashoff, G. Boot and R.J.T. Klein (2008), "A new global coastal database for impact and vulnerability analysis to sea level rise", *Journal of Coastal Research*, Vol. 24(4), pp. 917-924.

Van Vuuren, D.P., K. Riahi, R. Moss, J. Edmonds, A. Thomson, N. Nakicenovic, T. Kram, F. Berkhout, R. Swart, A. Janetos, S.K. Rose and N. Arnell (2012), "A proposal for a new scenario framework to support research and assessment in different climate research communities", *Global Environmental Change*, Vol. 22(1), pp. 21-35.

Von Lampe, M.D. et al. (2014), "Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison", *Agricultural Economics*, Vol. 45(1), pp. 3-20.

WHO (2012), *Atlas of Health and Climate*, World Health Organization and World Meteorological Organization, Geneva.

WHO (2014), *Quantitative Risk Assessment of the Effects of Climate Change on Selected causes of Death, 2030s and 2050s*, World Health Organization, Geneva.



From:

The Economic Consequences of Climate Change

Access the complete publication at:
https://doi.org/10.1787/9789264235410-en

Please cite this chapter as:

OECD (2015), “Modelling the economic consequences of climate change”, in *The Economic Consequences of Climate Change*, OECD Publishing, Paris.

DOI: https://doi.org/10.1787/9789264235410-4-en

OECD