OECD Economics Department Working Papers No. 1135

Consequences of Climate Change Damages for Economic Growth: A Dynamic Quantitative Assessment

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https://dx.doi.org/10.1787/5jz2bxb8kmf3-en

Unclassified **ECO/WKP(2014)31**

Organisation de Coopération et de Développement Économiques
Organisation for Economic Co-operation and Development **30-Jun-2014**

English - Or. English

ECONOMICS DEPARTMENT

CONSEQUENCES OF CLIMATE CHANGE DAMAGES FOR ECONOMIC GROWTH – A DYNAMIC QUANTITATIVE ASSESSMENT

ECONOMICS DEPARTMENT WORKING PAPERS No. 1135

By Rob Dellink, Elisa Lanzi, Jean Chateau, Francesco Bosello, Ramiro Parrado and Kelly de Bruin

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JT03359976

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ABSTRACT/RÉSUMÉ

Consequences of Climate Change Damages for Economic Growth – A Dynamic Quantitative Assessment

This report focuses on the effects of climate change impacts on economic growth. Simulations with the OECD's dynamic global general equilibrium model ENV-Linkages assess the consequences of a selected number of climate change impacts in the various world regions at the macroeconomic and sectoral level. This is complemented with an assessment of very long-run implications, using the AD-RICE model. The analysis finds that the effect of climate change impacts on annual global GDP is projected to increase over time, leading to a global GDP loss of 0.7% to 2.5% by 2060 for the most likely equilibrium climate sensitivity range. Underlying these annual global GDP losses are much larger sectoral and regional variations. Agricultural impacts dominate in most regions, while damages from sea level rise gradually become more important. Negative economic consequences are especially large in South and South-East Asia whereas other regions will be less affected and, in some cases, benefit thanks to adjustments from international trade. Emissions to 2060 will have important consequences in later decades and centuries. Simulations with the AD-RICE model suggest that if emissions continue to grow after 2060, annual damages of climate change could reach 1.5%-4.8% of GDP by the end of the century. Some impacts and risks from climate change have not been quantified in this study, including extreme weather events, water stress and large-scale disruptions. These will potentially have large economic consequences, and on balance the costs of inaction presented here likely underestimate the full costs of climate change impacts. More research is needed to assess them as well as the various uncertainties and risks involved. However, this should not delay policy action, but rather induce policy frameworks that are able to deal with new information and with the fact that by their nature some uncertainties and risks will never be resolved.

JEL classification codes: D58, O44, Q54
Keywords: climate change, computable general equilibrium modelling, economic growth

Conséquences des impacts du changement climatique sur la croissance économique – Une Évaluation quantitative en dynamique

Ce rapport approfondit les impacts du changement climatique sur la croissance économique. Sur la base de simulations dynamiques, effectuées avec le modèle d'équilibre général de l'OCDE ENV-Linkages, les conséquences sur la croissance de long terme d'un certain nombre d'impacts du changement climatique sont évaluées. Une appréciation des conséquences à très long terme avec le modèle AD-RICE complète cette analyse. L'analyse révèle que les effets des impacts du changement climatique sur le PIB annuel mondial devraient s'accroître à l'avenir, conduisant à une perte de PIB mondial de 0,7% à 2,5% en 2060, selon un éventail raisonnable de sensibilités climatiques. L'analyse souligne en outre de fortes disparités dans les impacts selon les secteurs et les régions concernées. Dans la plupart des régions, les impacts sur les rendements agricoles dominent, cependant la raréfaction des surfaces cultivables due à la montée des océans prend de plus en plus d'importance. Les conséquences économiques négatives devraient être particulièrement élevées dans le Sud et Sud-Est de l'Asie, tandis que les autres régions seraient moins affectées et, pourraient même, dans certains cas, bénéficier du changement climatique, grâce notamment aux ajustements du commerce international. Les émissions de gaz à effets de serre dégagées jusqu'en 2060 auront d'importantes conséquences dans les décennies et des siècles qui suivront. Des simulations effectuées avec le modèle AD-RICE suggèrent que si les émissions continuent à augmenter après 2060, les dommages annuels du changement climatique pourraient atteindre 1,5% -4,8% du PIB d'ici la fin du siècle. Certains impacts et risques du changement climatique ne sont pas quantifiés dans ce rapport, y compris des événements météorologiques extrêmes, le stress hydrique et des perturbations à grande échelle. Ceux-ci pourraient avoir de grandes conséquences économiques et, finalement, les coûts de l'inaction présentés dans ce rapport sous-estiment probablement les coûts totaux des impacts du changement climatique. Un progrès de la science dans ces domaines seraient nécessaire afin de mieux comprendre ces sujets ainsi que les divers incertitudes et risques associés. Toutefois, cela ne devrait pas retarder l'action politique, mais plutôt inciter à circonscrire des cadres politiques capables de faire face à de tenir compte de ces nouvelles informations.

Classification JEL: D58, O44, Q54
Mots clés: changement climatique, modèle d'équilibre général calculable, croissance économique

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CONSEQUENCES OF CLIMATE CHANGE DAMAGES FOR ECONOMIC GROWTH – A DYNAMIC QUANTITATIVE ASSESSMENT

By

Rob Dellink, Elisa Lanzi, Jean Chateau, Francesco Bosello,
Ramiro Parrado and Kelly de Bruin[1]

1. Introduction

1. Further degradation of the environment and natural capital can compromise prospects for future economic growth and human well-being. In line with a wider literature, the *OECD Environmental Outlook to 2050: Consequences of Inaction* (OECD, 2012) projected significant consequences of inaction on climate change, biodiversity loss, water scarcity and health impacts of pollution by 2050, unless more ambitious policies are implemented. Stringent policies are needed to reconcile economic growth with the conservation and sustainable use of the environment and natural resources. This report contributes to the quantitative assessment of the economic consequences of climate change (i.e. climate damages) and thus provides a scenario for the OECD@100 long-term scenario analysis (Braconier et al., 2014). This assessment will also feed into OECD's CIRCLE project, which aims at assessing the feedbacks from a range of environmental challenges on economic growth.

2. Evidence is growing that climate change is contributing to impacts that are already affecting the economy (e.g. IPCC, 2007; Dell et al., 2009, 2013). Future impacts are expected to be much larger (IPCC Working Group II, 2014a). This paper presents some preliminary findings of modelling the feedbacks of climate change damages on economic growth for the coming decades. The focus of this paper is on the **costs of inaction on climate change**; assessments of the associated benefits of policy action will be investigated in future work. Given the inter-temporal aspects of climate change, and the large uncertainties in projecting climatic changes and their impacts, these costs of inaction should not be taken out of context and comparison with the benefits of action needs to be based on an inter-temporal risk assessment.

3. There is extensive literature on the economic impacts of climate change (e.g. Nordhaus 1994, 2007; 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) and the JRC-Peseta project for the European Union (Ciscar et al., 2011, 2014). 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 also confirmed by the latest IPCC reports (2013, 2014a, 2014b).

4. 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

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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. A much smaller strand of literature uses computable general equilibrium (CGE) models to examine the *sectoral* economic implications of climate change impacts in specific sectors, often using a comparative static approach (e.g. Bosello et al. 2006; 2007). 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 Mensbrugghe, 2012).

5. This paper builds on these approaches, and focuses on how a selected number of climate change impacts affect different parts of the economy. The impacts considered include sea level rise, health, ecosystems, agriculture, tourism, energy demand and fisheries. These have been chosen as there is a literature available on their projected impact on the economy of major world regions at the macro and sectoral level. The assessment is preliminary and neither the impact of extreme weather events, flooding and water stress, nor the implications of catastrophic risk could be accounted for in this study.

6. The resulting impacts are presented in terms of effects on GDP. This is an imperfect measure of the total economic costs of climate change, since it does not consider wider impacts on well-being or costs to society. Nevertheless, it allows an understanding of the sectoral and macroeconomic consequences of climate change impacts. It can thus shed light on the economic feedbacks from climate change. 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 economic policy making. The main analysis for a selection of climate change impacts until 2060 is carried out combining the OECD long-run aggregate growth scenario to 2060 (OECD, 2014) with the multi-region, multi-sector dynamic CGE model ENV-Linkages. For a stylised assessment of consequences after 2060, the integrated assessment model AD-RICE is used.

7. The paper is structured as follows. Section 2 presents the methodology; it briefly outlines the economic modelling framework and how climate change impacts can be linked to specific economic activities. Section 3 presents the preliminary results, while Section 4 concludes. The Annexes contain more information on the modelling framework and the scientific basis for calibration of the climate change impacts.

2. Methodology

2.1 The economic modelling frameworks

8. The OECD's in-house dynamic CGE model - ENV-Linkages - is used as the basis for the assessment of the economic consequences of climate impacts until 2060. The advantage of using a CGE framework to model climate impacts is that the sectoral details of the model can be exploited. Contrary to aggregated IAMs, where monetised impacts are directly subtracted from GDP, in a CGE model the various types of climate damages can be modelled as directly linked to the relevant sectors and economic activities.

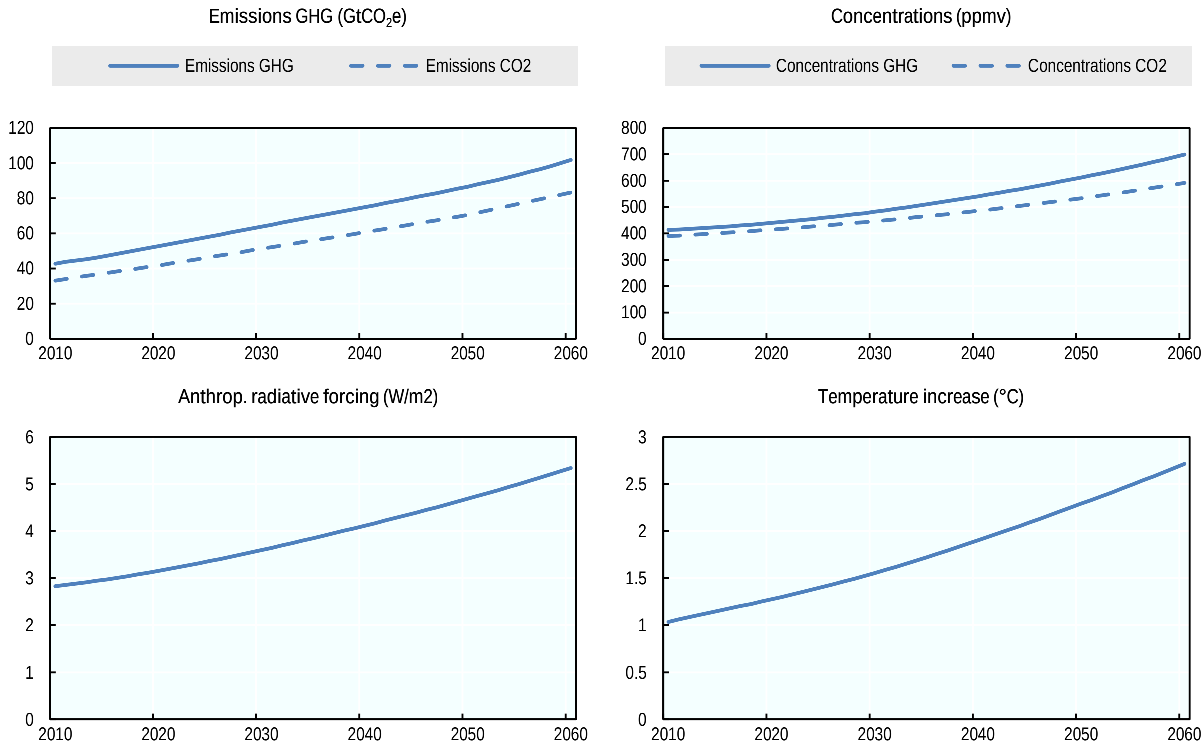
9. ENV-Linkages is a multi-sectoral, multi-regional model that links economic activities to energy and environmental issues; Chateau et al. (2014) provide a description of the model. The model is calibrated for the period 2013 - 2060 using the most recent macroeconomic trends of the baseline scenario of the OECD's Economic Outlook (2014). Annex I contains an overview of the ENV-Linkages model, as well as the sectoral and regional aggregation used in this paper.

10. The baseline calibration of ENV-Linkages in the absence of climate change damages has been carried out in consistency with the central scenario of the OECD@100 project (Braconier et al., 2014). The baseline is characterised by an absence of climate policies, continuation of current policies for other policy

domains (including energy) and plausible socio-economic developments; but it is not a prediction of what will happen. The average global growth rate of GDP is projected to be 2.9%. Economic growth in the OECD countries between now and 2060 is projected to be mediocre, with the highest growth rates shifting from the currently emerging economies, such as China and India, towards developing countries. Energy projections until 2035 are in line with the IEA's World Energy Outlook (IEA, 2013). Chateau et al. (2011) describe the baseline calibration procedure in more detail, although the numerical calibration of the model has since been updated to reflect more recent data.

11. Figure 1 shows how the baseline economic activities lead to a steady increase in global emissions. Global greenhouse gas (GHG) emissions (excl. emissions from land use, land-use change and forestry) are projected to rise from roughly 45 $GtCO_2e$ in 2010 to just over 100 $GtCO_2e$ in 2060. Concentrations of carbon in the atmosphere (CO_2 only) rise from 390 ppm to 590 ppm in the same time frame. Using a central estimate of the equilibrium climate sensitivity (ECS) of 3°C from a doubling of carbon concentrations, these emissions put the world on a pathway to temperature increases of more than 2.5°C by 2060, and well above 4°C by the end of the century.[2]

Figure 1. Evolution of key climate indicators in the no-damages baseline projection



Source: Own calculations using the ENV-Linkages model (for emissions) and MAGICC6.4 (Meinshausen et al., 2011).

12. The results of the ENV-Linkages framework are complemented with results from stylised simulations with the AD-RICE model to examine longer-term impacts of climate change on economic growth, i.e. beyond 2060, which is the OECD@100 horizon.[3] AD-RICE is a Ramsey-type growth model

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[2] The equilibrium climate sensitivity is often used to represent the major uncertainties in the climate system in a stylised way. See footnote 8 for more details.

[3] AD-RICE does not allow calibrating climate change damages using the production function approach detailed in Section 2.2. Rather, impacts are first valued and aggregated in a stylised damage function and then directly subtracted from GDP.

with explicit representation of adaptation to climate change (De Bruin et al., 2009a,b). It is described in more detail in Annex III. AD-RICE also features in previous studies, e.g. Agrawala et al. (2011), where it was used to gain insights about longer-term dynamics of climate-economy interactions and the relation between mitigation and adaptation policies.

2.2 Linking climate change impacts to economic activity

13. A key challenge in modelling climate impacts with a sectoral approach is to capture how different aspects of climate change, such as changes in temperature and precipitation patterns, affect natural and human systems at the regional level, and how these influences translate into shocks to the economy, with some activities or sectors being more severely affected than others, through the channels of different (and potentially multiple) economic variables.

14. In order to link climate damages to relevant sectors in the ENV-Linkages model, a production function approach has been adopted. As outlined in Sue Wing and Lanzi (2014), the production function approach specifies how climate damages affect key elements in the sectoral production functions. Parameters capturing the level of productivity, biased technical change and changes in use of primary factors can be modified to reflect climate damages. Similarly, changes in the households' demand system can be used to reflect consumption-related impacts. Finally, impacts on the supply of primary factors are important because they affect producers' inputs demands and output supplies and consumers' income and expenditures, which in turn lead to shifts in the equilibria in markets for factors and commodities.

15. The sectoral and international trade representation in computable general equilibrium (CGE) models is particularly suited to modelling the economic response to climate impacts, especially market-driven adaptation. Shifts in key variables used to represent the climate damages lead to changes in the equilibrium prices and supply of primary factors. The specification of international commodity markets in the CGE model allows projection of how demand, supply and trade patterns adjust to minimise economic damages and maximise opportunities. These adjustments that take place in the model can be considered as market-driven adaptation, which already diminishes the level of damages imposed. For instance, a change in labour productivity in a region will trigger substitution responses by producers that alter not only their use of labour but also uses of other inputs, and substitution responses by consumers that may shift away to foreign producers of the commodity and to other commodities. Without such adjustments, the costs of climate change would be substantially higher.

16. The level of sophistication with which climate damages can be included in a CGE model depends on data availability. In this study, as far as possible, impacts are modelled using data that come from sector-specific models or particularly detailed empirical studies. These data are used to link impacts to economic sectors, trying to differentiate between regions as appropriate and to the extent possible. Gathering data relative to a range of climate impacts for various world regions is a time-consuming and difficult effort. Following Bosello et al. (2012), damages have been implemented in ENV-Linkages building on the data and methodology of the ICES model; see Section 2.3 and Annex II.

17. 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. Impacts from sea level rise, impacts on agriculture, and impacts on human health belong to this category.

18. The second category of climate change impacts affects the demand side. Impacts on health expenditures[4] and on energy consumption are of this kind. The technicalities involved are more complex

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[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.

than in the case of exogenous variables and the following procedure is adopted. The variations in household and government expenditure are imposed as exogenous shifts in the respective demand equations. The implicit assumption is that the starting information refers to partial equilibrium assessments; thus with all prices and income levels constant. The model then determines the final demand adjustments. To ensure that the budget is balanced, the changed consumption of energy and health services is compensated by opposite changes in expenditure for all the other commodities, using the marginal propensities to consume. Effectively, the modelling approach assumes that consumers are forced to spend more on health and energy, at the expense of other goods and services.[5]

19. Climate change impacts have been calibrated in the ENV-Linkages model to a specific scenario of climate change using the OECD@100 ENV-Linkages baseline emission profile, exploiting the richness of the underlying sector-specific models and empirical studies. Consequently, the specification of damages in ENV-Linkages does not rely on stylised damages functions that depend only on global average temperature, and thus avoids the fallacy that all regional and sectoral damages are a linear function of global average temperature increase (as stylised damage functions assume). This approach is consistent with a more nuanced representation of climate change, through changes in regional temperature and precipitation patterns, as used in the underlying assessments of the impacts outlined in Annex II. A logical consequence of not relying on a stylised damage function is that the model results cannot be easily extrapolated beyond 2060 or for other emission pathways (as the relation between temperature changes and damages may be non-linear and no reduced-form function for this is derived).[6]

2.3 Overview of climate change feedbacks incorporated in ENV-Linkages

20. The ENV-Linkages model has been improved to include climate impacts related to sea level rise, health, ecosystems, agriculture, tourism, energy and fisheries. Table 1 summarises how these impacts have been included in the model. A detailed justification of the parameterisation of these impacts by sector, region and time period in ENV-Linkages is given in Annex II, based on the expertise of FEEM/CMCC. Although the full regional and sectoral disaggregation of the model is used to specify the climate impacts, more aggregated results are presented in the figures below (see Table AI.2 in Annex I).

21. Although this parameterisation represents the state of the art and is based on detailed underlying assessments of specific impacts, the robustness of the calibration is limited by the availability of reliable data and literature. These remain of variable quality and coverage, especially at the regional and sectoral level, with much better coverage of agricultural impacts and consequences of sea level rise than some of the other impact categories. Further research work is needed to gather data and expand the list of impacts. This can build on the work of the IPCC and the comprehensive reviews of climate impacts in Agrawala and Fankhauser (2008) and Sue Wing and Lanzi (2014).

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[5] The demand system in ENV-Linkages differs from the one used in ICES. ENV-Linkages has an extended linear expenditure system. Thus, in the ENV-Linkages model there are lower possibilities for adjustments in household expenditures following price changes. This is because in an extended linear expenditure system only part of household consumption can be adjusted since there is a minimum required consumption for each good.

[6] The longer-term implications are investigated in Section 3.2 using stylised simulations with an Integrated Assessment model.

Table 1. Selected climate impacts and modelling strategies

Sea level rise	•Coastal land losses and damages to capital
Health	•Changes in morbidity and demand for healthcare
Ecosystems	•Changes in productivity of production sectors
Crop yields	•Changes in agricultural productivity
Tourism flows	•Changes in productivity of tourism services
Energy demand	•Changes in the demand for energy from cooling and heating
Fisheries	•Changes in catchment
Extreme weather events	•Not included
Catastrophic risks	•Not included
Other impacts	•Not included

22. Land losses due to *sea level rise* have been modelled as percent decreases in the stock of productive land and capital by region. Both modifications concern land and capital stocks variables, which are exogenous to the model and therefore can be straightforwardly implemented. As information on capital losses are not readily available, in line with Bosello et al. (2012), it is crudely approximated by assuming that changes in capital services match land losses in terms of percentage change from baseline.

23. Changes in regional labour productivity are considered as the primary channel to account for *health impacts*. Lower mortality translates in an increased labour productivity which is one-on-one proportional to the change in the total population. The underlying assumption is that health impacts affect the active population, disregarding the age characteristic of cardiovascular and respiratory diseases. This information is complemented with changes in health expenditures, reflecting a need for households and governments to allocate increasing parts of their budget to health.

24. Impacts on *ecosystems* have been accounted for as a loss of total factor productivity (TFP).[7] The assumption made is that ecosystems offer a set of support services to production activities which are not captured by the existing inputs to production. The amount of the deterioration of TFP is calibrated to reflect a GDP impact that is suggested in the literature as the change in value of ecosystem services due to climate change, estimated for the baseline temperature increases (see Annex II for a description of the ecosystem losses assessment). This approach only partially accounts for the total costs of ecosystem losses as it does not include costs such as those deriving from extinction of certain animal species. In contrast to the other impact categories, the sectoral and regional differentiation of this impact is limited to a scaling by region based on GDP levels.

25. Changes in *agricultural crop yields* have been modelled through exogenous changes in regional land productivity and total factor productivity. Due to the aggregated representation of the agricultural sectors in ENV-Linkages, only an aggregate agricultural impact for all crop sectors together could be simulated for each region. The agricultural impacts do not include a *CO_2 fertilisation effect*, in line with the underlying study (the EU FP7 Global IQ project) on which the impacts are based. Including a CO_2 fertilisation effect, which has been highly debated, would lead to higher agricultural productivity, especially for wheat and soybeans, although less so for maize. Rosenzweig et al. (2013) find "approximately ±10% yield change" by the end of the 21st century from CO_2 effects across a range of models and climate scenarios, but also note that there is wide variation between models and that "crop model parameterization of CO_2 effects remains a crucial area of research". Further analysis is needed to expand the representation of agriculture in ENV-Linkages and allow for crop-specific impacts of climate change.

26. Changes in consumer expenditures on *tourism* have been modelled by modifying the quality of tourism services in different regions. Changes in demand for tourism are not forced changes in household expenditures, like for health care or energy, 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.[8] While changes in tourism expenditures are largely a shift between countries, global expenditures on tourism are decreasing, implying a net negative impact on the global economy.

27. Changes in households' *demand for oil, gas and electricity*, for instance less energy consumption for heating and more for cooling and the associated fuel switches, have been captured directly in the model as a change in each region's consumer demand for the output of the respective industries. While the consequences for energy supply are captured in the model, direct impacts of climate change on energy supply (such as interruptions of the availability of cooling water in electricity due to droughts) are not included in the analysis. As with other demand impacts, endogenous shifts in demand between commodities, as a result of changing prices and income levels, are fully captured in the model.

28. Changes in potential *fish catches* have been modelled as reductions in the natural resource stock available to fishing sectors in the various regions. This approximates the impacts of climate change for fish stocks and the resulting effects for the fisheries sector.

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7. In ICES, ecosystem service losses are associated with a reduction in the capital stock, but this is revised in ENV-Linkages, as there is no clear evidence that capital-intensive sectors are more dependent on ecosystems than other sectors.

8. ICES models this as increased demand for tourism, but given the differences in the demand systems used, this is more accurately reproduced in ENV-Linkages as a change in productivity of supply of tourism services.

29. Some relevant impacts and risks, such as extreme (weather) events, flooding and water stress, and international migration, cannot be accounted for. These may be significant (IPCC Working Group II, 2014a) and on balance are likely to have a negative effect on GDP, although gains for specific sectors in specific regions cannot be excluded.

30. Impacts due to events related to *extreme weather* conditions, such as floods, severer storms and forest fires are excluded from the analysis, not least because of their local character and short duration. Some literature exists that attempts to estimate the costs of specific natural disasters, especially hurricanes, but these estimates vary from virtually zero to several percent of GDP. Furthermore, e.g. Dunne et al. (2013) highlight the consequences of heatwaves on labour productivity. Evidence is also emerging that economies do not recover from the macroeconomic costs of destruction but are permanently faced with lower levels of GDP (Hsiang and Jina, 2014). There is, however, no robust literature on the macroeconomic costs of climate-induced extreme weather events, although Dell et al. (2013) provide some empirical evidence linking weather patterns to economic growth.

31. Finally, climate change also leads to increases in the risk of crossing irreversible tipping points for large-scale disruptive events (*catastrophic risks*); their macroeconomic costs cannot be robustly quantified either and are not included in the projections. This topic is further discussed in Section 3.3.2.

3. Results

3.1 Economic effects of selected climate change impacts using ENV-Linkages

3.1.1 Global results

32. Figure 2 illustrates how global economic impacts of the selected climate change impacts are projected to evolve over time through to 2060, with a range showing how this depends on the assumptions made with respect to the relationship between carbon concentrations and global average temperature increase.[9] While impacts become more severe over time, they are already measurable in the coming decades, indicating that the consequences of climate change are not just an issue for the distant future.[10] Perhaps more importantly, emissions between now and 2060 commit the world to a deteriorating risk profile: a high-emissions infrastructure is locked in, damages continue for a century or more, and the risk of large-scale disruptions (‘catastrophes’) increases.

33. The central projection, which leads to GDP losses that gradually increase to 1.5% in 2060, represents the central (“best guess”) estimate of damages as calculated with the available data for the subset of impacts studied. These projections are surrounded by a wide range of uncertainties in the

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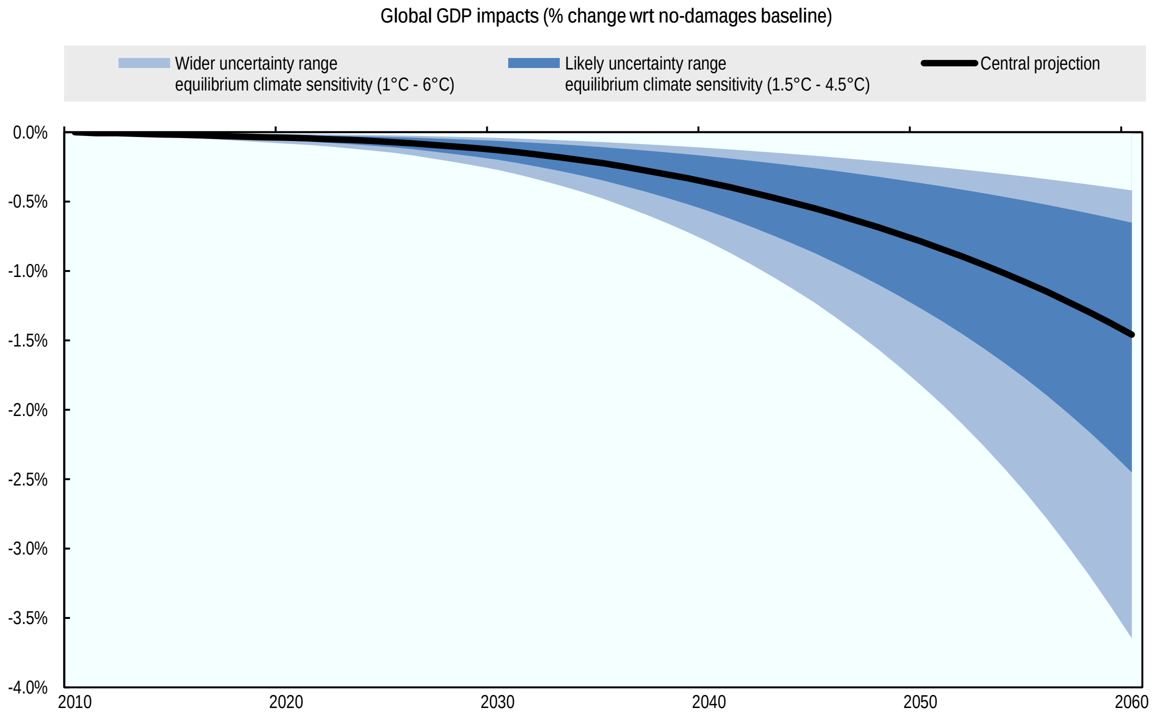
[9] The equilibrium climate sensitivity (ECS) parameter, which reflects the equilibrium climate response (i.e. the long-term global average temperature increase) to a doubling of carbon concentrations, equals 3°C in the central projection. It is varied between 1.5°C and 4.5°C in the likely uncertainty range, and between 1°C and 6°C in the wider uncertainty range, in line with the ranges indicated in the IPCC’s 5th Assessment Report (IPCC, 2013). Due to lack of reliable data, a number of ad hoc assumptions underlie these calculations, not least the assumption that climate impacts scale proportionately with the value of the equilibrium climate sensitivity parameter. If damages increase more than proportionately in this parameter, the potential GDP losses will be larger than shown in the figure. The uncertainty ranges given throughout this paper only reflect this particular – albeit important – uncertainty. A wider discussion of uncertainties is presented in Section 3.3.

[10] Note that an empirical literature is starting to emerge pointing to already occurring climate impacts (Dell et al., 2009; 2013). Although this literature cannot be properly reflected in the long-term projections presented here, the modelling simulations do show small feedback effects on economic growth in the current decade.

economic and climate system, in the evaluation of the climate impacts and in the way they feed back into the economy. Figure 2 illustrates a large uncertainty range corresponding to the equilibrium sensitivity of the climate system to accumulation of carbon (ECS): by 2060, the annual GDP losses for the likely ECS range are 0.7%-2.5%, whereas the possibility that global losses are as low as 0.4% or as high as 3.6% cannot be excluded. As this approximation of the impacts of uncertainty in the climate system is likely to be less robust at the regional and sectoral level, they are only presented for the global results. Other climate change impacts, such as extreme weather events, water stress and large-scale disruptive events that are not included in the analysis, potentially also have large economic consequences. These constitute further sources of uncertainty, and on balance the costs of inaction presented here are likely to underestimate the full costs of climate change impacts (IPCC, 2014a).

34. These caveats notwithstanding, the projections are well-aligned with the literature on quantified economic damages. The latest IPCC Working Group II report (2014a) surveyed the existing literature and found "global aggregate economic losses between 0.2 and 2.0% of income ("medium evidence, medium agreement", Ch. 10) for a temperature increase of 2.5°C. In the central projection of ENV-Linkages, this threshold is reached in 2055, and the associated global GDP loss amounts to 1.1%.

Figure 2. Change in global GDP from selected climate change impacts to 2060

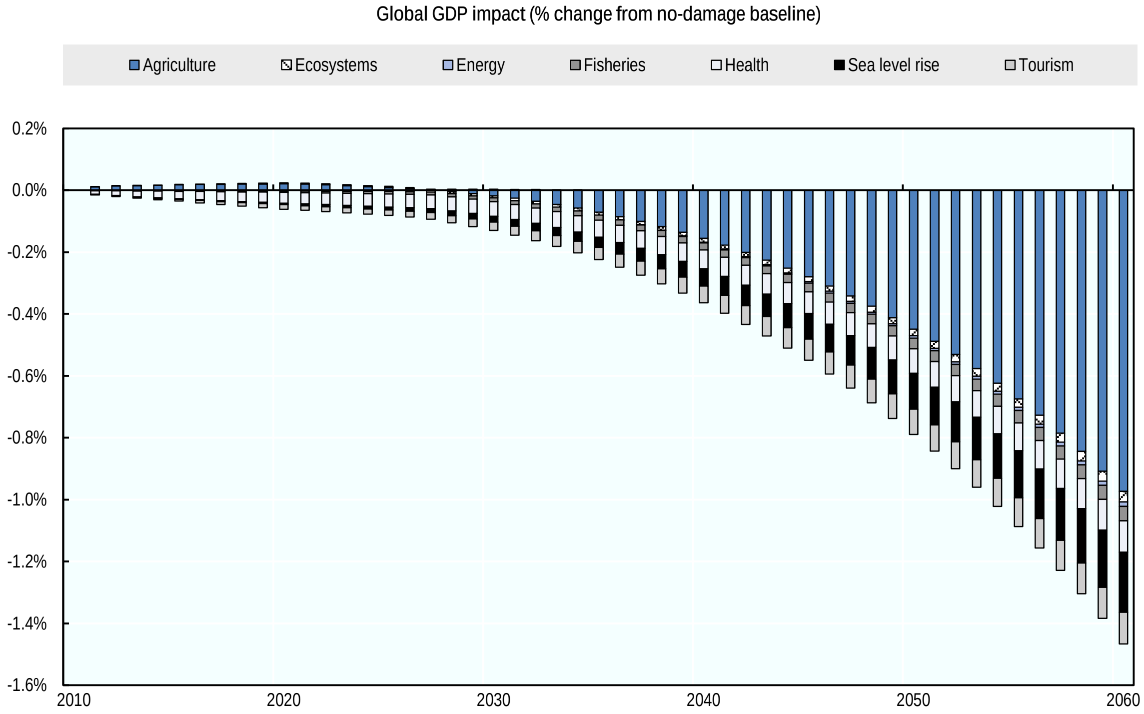


Source: Own calculations using the ENV-Linkages model

35. Figure 3 illustrates the relative contribution of the selected climate impact categories to their combined global effects of GDP. According to the model simulations, agricultural impacts are the most important of the categories included in the analysis, at least at the global level. Other impacts, such as changes in energy use, entail predominantly a shift between regions, hence their aggregate global effect is very small. The fact that the share of damages associated with agricultural impacts increases over time does not mean that the other impacts become smaller over time, but rather that agricultural impacts increase more. Obviously, adding more impact categories will affect these shares. For instance, Roson and Van der Mensbrugghe (2012) add a stylised representation of a wider set of labour productivity impacts, including for instance losses in labour productivity due to heat waves, and find that these dominate overall

impacts. As data on these labour productivity impacts are hard to robustly calibrate, even at the global level, they are not included in this analysis.

Figure 3. Attribution of changes in global GDP to selected climate change impacts for 2035 and 2060 (central projection)



Source: Own calculations using the ENV-Linkages model

3.1.2 Regional results

36. There are large regional differences in climate impacts on GDP, which cannot be analysed looking at the global totals shown above. All regions are negatively affected by at least some impacts, but the overall net effect is negative in 13 of the 25 regions distinguished in the model, representing more than half of global GDP and almost three quarters of global population.[11] Figure 4 illustrates the regional economic impacts of climate change for 8 main macro-economic regions. The countries that make up South & South-East Asia, which includes e.g. India and Indonesia, are expected to be most severely affected by the climate change impacts modelled here. One of the most striking conclusions is that climate impacts are, to a large extent, concentrated in vulnerable, highly-populated regions.

37. For some regions, the impacts are positive for low levels of climate change, but after the first decades, the negative impacts start to dominate. Regions where there are both positive and negative climate impacts, such as some of the OECD Pacific countries, can benefit from a *relative* improvement in their

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[11] This is just a crude approximation of the number of people affected by climate change, as many people in countries where overall impacts are positive are negatively affected, either directly by health impacts or indirectly through changes in the domestic economy. Similarly, there will be people in all regions that may benefit from the climate changes.

competitive position in agriculture.[12] However, impacts are expected to vary substantially between crops. The induced trade flows also largely differ at the crop level. Furthermore, incorporation of other climate impacts in the analysis can substantially alter the picture, as e.g. extreme droughts are likely to severely affect Australia and negatively alter the projection for the OECD Pacific region. The results presented here should therefore be seen as very preliminary, and a more thorough analysis is warranted.

38. The relative gain in competitive position for the OECD-Pacific region occurs especially when the main trading partners, not least the major economies in South and South-East Asia, observe substantial losses in agricultural productivity (this is explored in more detail in Box 1). This endogenous adaptation effect through adjustments in international trade patterns is a strong mechanism to limit costs of climate damages. Production moves away from regions that are negatively affected by climatic changes, such as regional temperature and precipitation changes. Box 1 explains more clearly how trade effects and adjustments in production patterns affect the economy-wide impacts of climate change.

39. Although there are significant differences between the modelling approach and calibration used here and earlier economic studies of climate damages (not least in the calibration of the impacts and the specification of the economic response through national and international substitution effects), similar patterns emerge in e.g. Eboli et al. (2010), Bosello et al. (2012), Roson and Van der Mensbrugghe (2012) and Nordhaus (2007; 2011). In these studies, global impacts are increasing more than proportionately with temperature increases (and hence over time) and amount to reductions of several percent of GDP by the end of the century. Highest impacts are foreseen in emerging and developing countries, especially in South and South-East Asia and Africa, whereas countries at a high latitude in the Northern hemisphere, especially Russia, may be able to reap some economic benefits from the climatic changes. Partial impact studies, which focus on a specific region or impact, tend to show larger negative impacts on the local economy, but by nature ignore the endogenous adjustment processes that take place within economies, and changes in international trade patterns.

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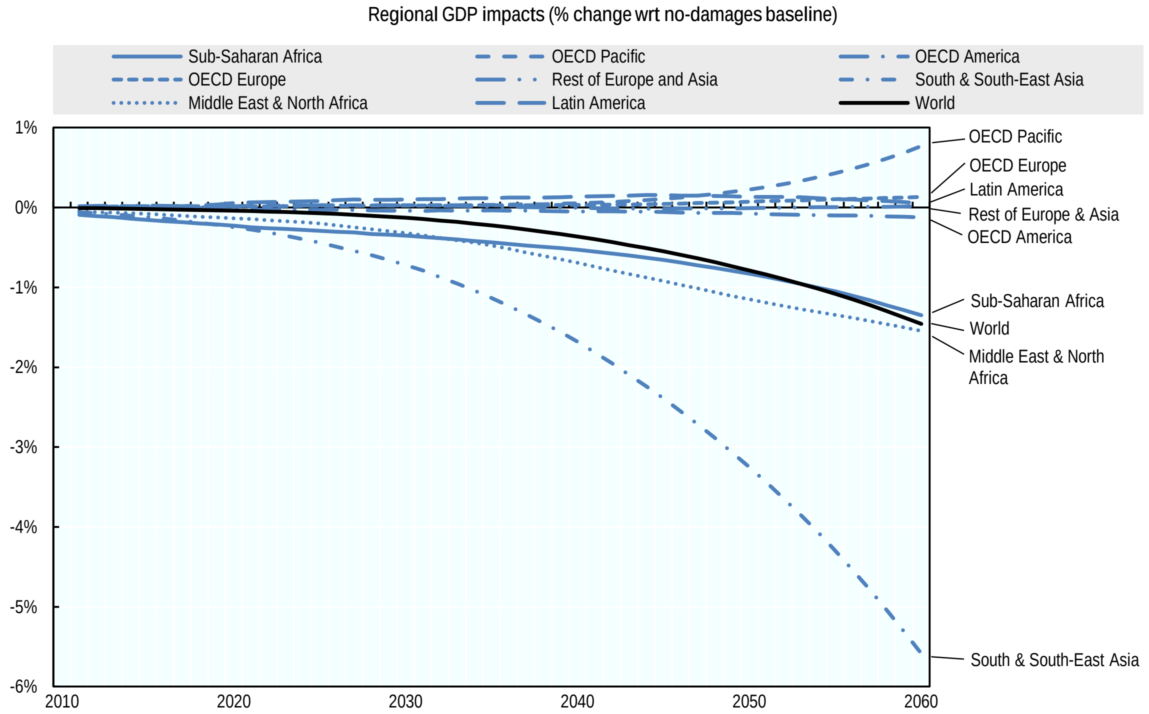
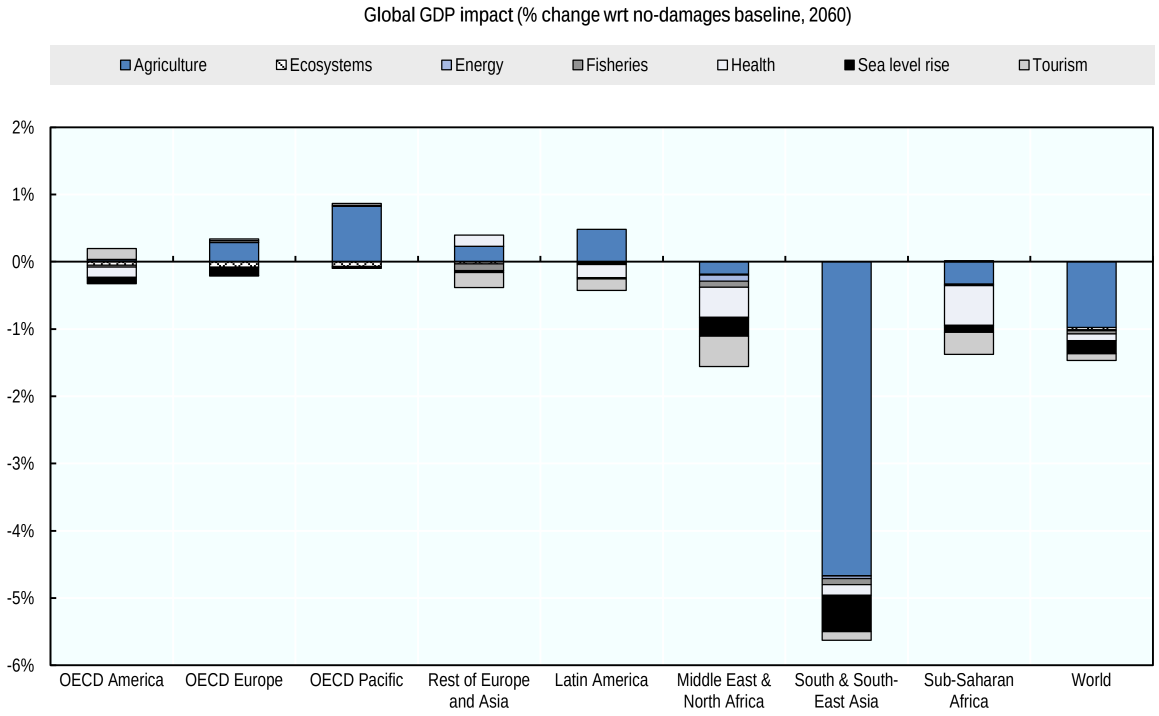
[12] Note that the no-damages baseline GDP growth is projected to be lower in the OECD Pacific region than in the other regions. Incorporating the selected climate feedbacks does not alter that. The results vary substantially within the group of OECD Pacific countries, with by far the largest productivity increases in New Zealand, much smaller effects in Japan and Australia, and negative impacts in Korea (cf. Rosenzweig et al., 2013; see Annex II).

Figure 4. Change in regional GDP for selected climate change impacts to 2060 (central projection)

Panel A. Evolution over time



Panel B. Attribution to specific impacts in 2060

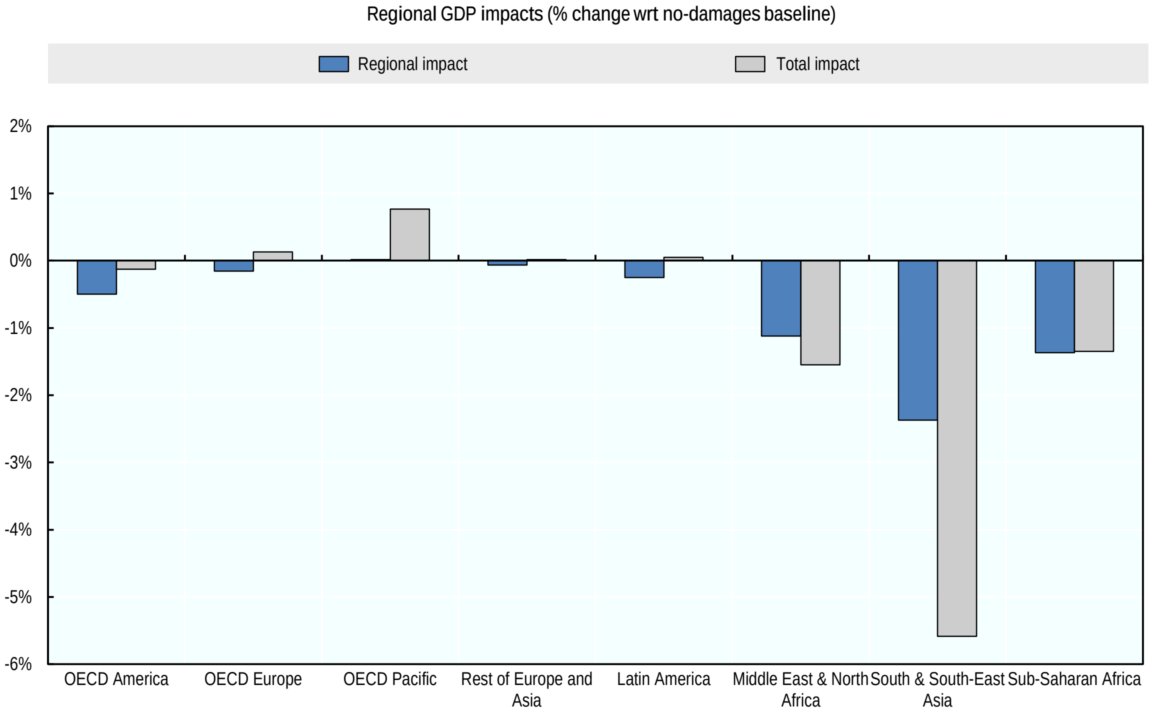


Source: Own calculations using the ENV-Linkages model

Box 1. More detailed analysis of regional effects: regional versus global impacts

Economies do not operate in isolation, and the climate impacts in one region affect the economy in other regions as well. The role of international links between regions can be analysed by comparing global climate impacts to the hypothetical case in which impacts occur only in each single region ("regional impacts" in Figure 5). In the "unilateral" case, world market prices are not or hardly affected and thus domestic impacts dominate indirect effects through adjusting international trade patterns. In contrast, in the multilateral case the climate impacts in all regions affect international trade patterns. If impacts were identical across countries, all regions would benefit from maintaining their international competitive position when the damages are global. Simultaneously, they would be negatively affected by the reduced demand for exports following the economic slowdown in the trading partners who are affected by climate change. However, heterogeneity in impacts means that relative competitive positions start to shift, and if climate change is beneficial for the main trading partners, whereas the domestic impacts are negative, the gap in competitive position may further widen in the global impacts case.

Figure 5. Change in regional GDP for 2060 under regional and global selected climate change impacts (central projection)



Source: Own calculations using the ENV-Linkages model

Figure 5 shows how different regions are affected differently by the adjustments in international links. In the OECD regions, the GDP losses from domestic impacts can be largely mitigated or even transformed into benefits when other countries are also affected by climate change. In other regions, and especially South and South-East Asia (SEA), the domestic effects are further aggravated by the loss in competitive position compared to their main trading partners, especially OECD-Pacific countries. In turn, this leads to a further slow-down of the economies of the SEA region, lowering investment and consequently GDP levels.

Box 1. More detailed analysis of regional effects: unilateral versus global impacts *(continued)*

These results clearly depend on the possibilities of adjustments of international trade patterns as assumed in the model.[13] The trade adjustments for agricultural commodities would in particular benefit from a more detailed representation of the agricultural sector, which is foreseen as a top priority for future analysis. For instance, disaggregating agricultural sectors would highlight domestic and international adjustments that take place across agricultural inputs, which are differently affected by climate change.

Although the "regional" cases are in most regions worse in terms of GDP impacts, in many countries consumers tend to be better off in terms of their utility levels, as reduced domestic supply of e.g. agricultural commodities can more easily be compensated by increased imports when other countries' production levels are not affected by climate damages.

3.1.3 Sectoral results

40. The different categories of climate impacts are linked to inputs in specific sectors. Thus, climate damages also affect the economic structure of the various regions, which is reflected by changes in the sectoral contributions to GDP. Figure 6 illustrates changes in value added in 2060 for the main aggregate sectors by region. As the effects of climate impacts on GDP are dominated by agricultural impacts and international trade flows of agricultural goods change substantially, the largest changes are in that sector, with gains in some regions and losses in others. Some sectors are directly impacted by certain climate impacts (e.g. services sectors are affected by health impacts, energy sectors by energy impacts, etc.). However, there are also substantial indirect impacts, such as changes in production in energy intensive sectors due to the full range of price changes that follow climate impacts or capital destruction from sea level rise which affects all sectors through changes in the marginal productivity of capital. OECD Europe and Latin America are typical cases where very small macroeconomic impacts hide a more pronounced effect in specific sectors: agriculture (and in the case of OECD Europe also trade-exposed industries) can benefit from improved international trade, whereas the more sheltered services sector is hurt by domestic tourism and health impacts, but also by reduced availability of capital from sea level rise. Agricultural gains also dominate in OECD Pacific.

41. While the contribution of agriculture to overall GDP loss is substantial, especially given the relatively small size of this sector in GDP terms (the drop in global agricultural value added of 3.5% translates into a reduction of global GDP by 0.3%), Figure 6 clearly shows how agriculture is interlinked with the other production sectors. Agricultural impacts cause a re-allocation of production factors (and especially capital) across all sectors. The endogenous economic response of the model ensures that the reduction in food consumption is limited by intensifying agricultural production and allocating more land to crop production. Further, the indirect impacts on other sectors show that there is a certain level of adaptation through trade and production adjustments which reduces the economy-wide costs of climate change.

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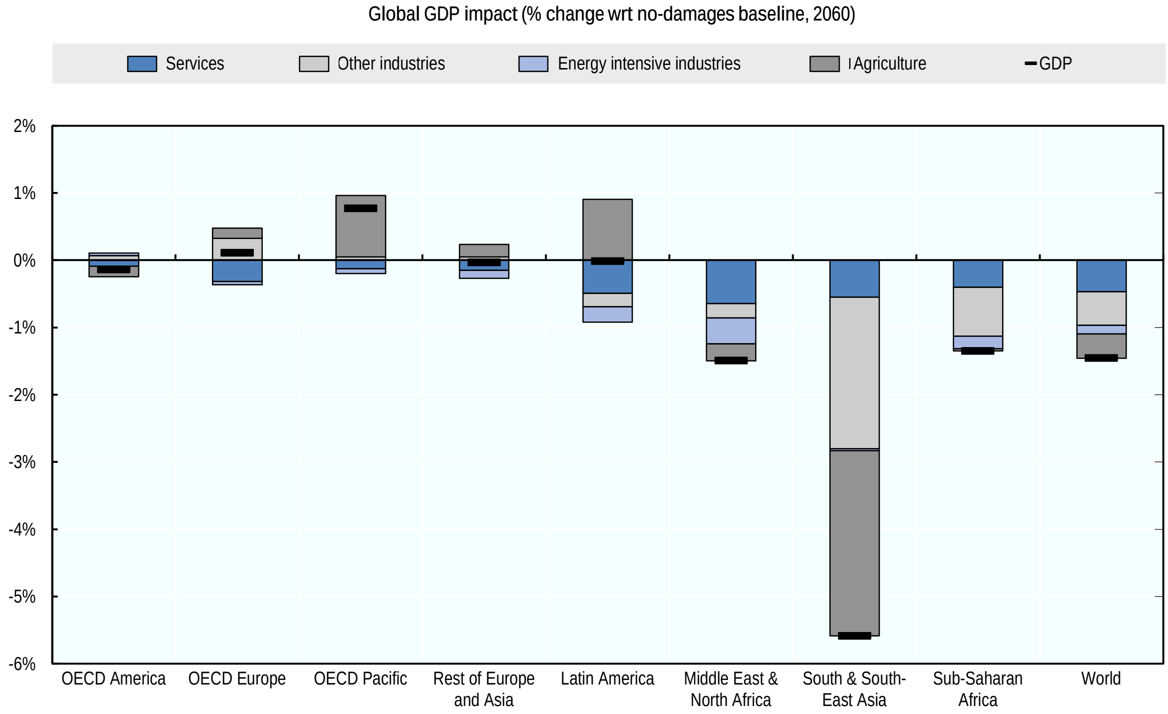
[13] The model assumes fixed trade balances and adjusting exchange rates. Furthermore, goods from different countries are imperfect substitutes. Different assumptions on the trade regimes may alter these results.

Figure 6. Composition of the change in regional GDP in 2060 (central projection)



Source: Own calculations using the ENV-Linkages model

3.2 Implications beyond 2060 – using the AD-RICE model

42. Greenhouse gases emitted by 2060 will affect the climate and the economy until 2060, but will also have important consequences in the decades and even centuries that will follow. Solely projecting the GDP impacts before 2060 will therefore underestimate the net present value of GDP impacts of climate change as the long run impacts (due to the inertia of the climate system) are ignored. The RICE model (or more precisely, the version with explicit adaptation, AD-RICE) is used to study the long-term consequences of climate change through stylised simulations.

43. AD-RICE has been calibrated to match the latest OECD Economic Outlook baseline scenario (OECD, 2014) and the more detailed socioeconomic developments in the ENV-Linkages baseline until 2060, and then follows the growth rates of the business as usual (BAU) scenario of the RICE model. This ensures comparability between the results of the two models. To assess economic consequences of climate change impacts, AD-RICE uses a stylised damage function rather than a more elaborate production function approach.[14] Nonetheless, these simulations shed some light on the order of magnitude of the potential climate feedbacks in the very long run.

44. In line with the damage assessment above, global annual GDP losses in the AD-RICE model also gradually increase to around 1.5% of GDP by 2060 (Figure 7), despite the independent calibration of damages in both models. If emissions continue to rise after 2060, the negative effect on GDP continues and central projections of GDP losses become more than 3% of GDP by the end of the 21st century. As in the

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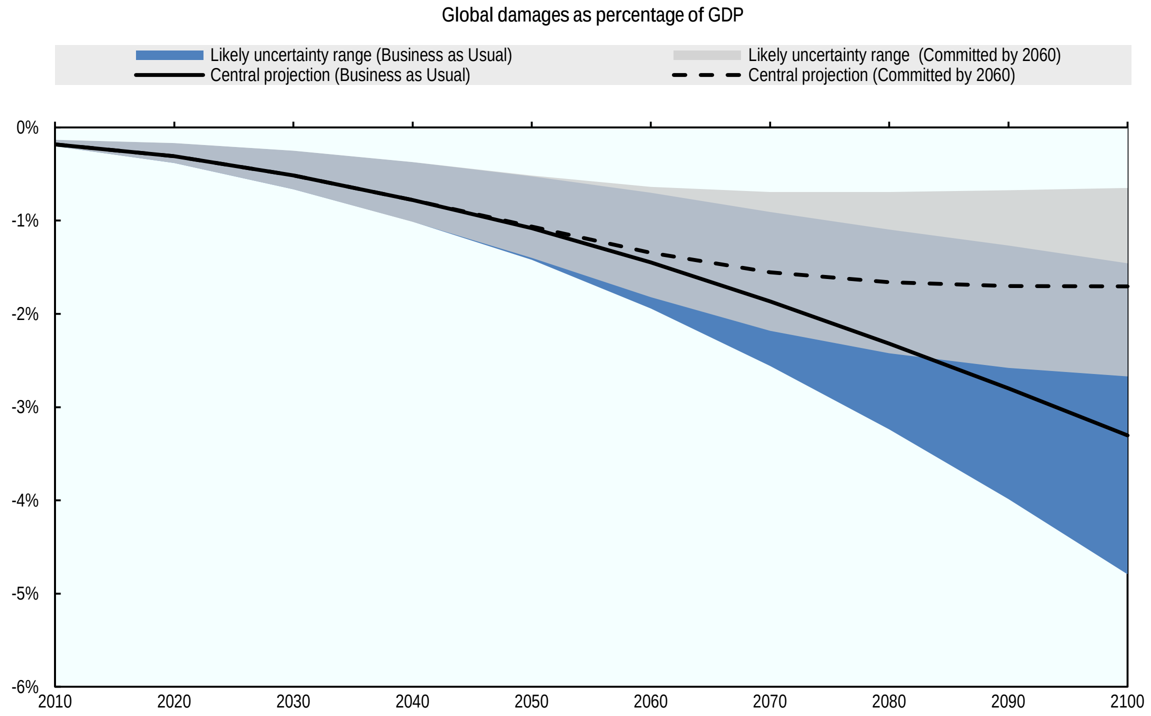
[14] Furthermore, AD-RICE is a forward-looking model, which implies that current GDP levels depend on future damage levels. Therefore, the GDP losses are calculated for each scenario separately as percentage of GDP.

ENV-Linkages calculations, these estimates are subject to uncertainty on the equilibrium climate sensitivity parameter. By the end of the 21st century, GDP losses for the likely ECS range are projected to be 1.5% to almost 5% (and the wider range 0.8% to 6%). The associated global average temperature increases by 2100 are 2.4-5.8°C.

Figure 7. Change in global GDP from climate change damages in the very long run (central projection)



Source: Own calculations using the AD-RICE model

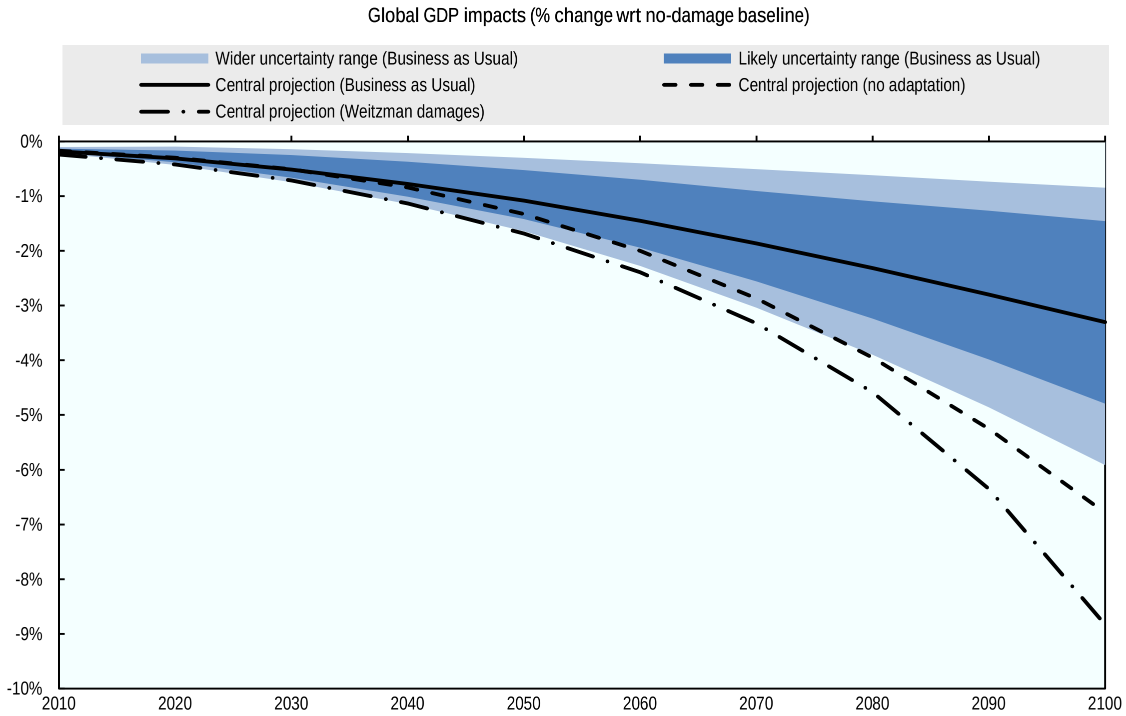
45. The *Committed by 2060* scenario projects how inaction until 2060 will affect the future estimated GDP impacts of climate change. This scenario sets emissions at their business as usual levels until 2060, after which emissions are set to zero. Figure 7 shows that a substantial part of these impacts are already locked-in by the emissions occurring until 2060. Even if net GHG emissions dropped to zero after 2060, climate damages and consequent effects on GDP (of around 1.7%) would continue for at least a century more due to the inertia in the climate system. This is in line with IPCC (2013), which stresses that "surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO_2 emissions" (IPCC, 2013, p. 26). Even if climate sensitivity in equilibrium is low (i.e. 1.5°C), annual GDP losses of at least 0.5% are committed to for over a century after 2060. In the case of a high climate sensitivity (equal to 4.5°C or 6°C), this annual loss rises to 2.7% and 3.7%, respectively. Logically, this insight also holds for climate impacts occurring before 2060: effectively any emission, whether now or in the future, triggers a series of chain events and inevitably leads to an increase in climate damages for at least a century. Thus, there are damages that are already committed due to historical emissions; in the AD-RICE model, these gradually increase to around 0.3% of GDP, although the model is not fine-grained enough (and not intended) to assess current damage levels accurately.

46. Long-term GDP impacts crucially depend on the shape of the damage function. However, as IPCC Working Group III (2014b) stresses, damage projections for higher temperature increases are much less robust. AD-RICE uses a typical quadratic damage function, but Weitzman (2009; 2012; 2013) has argued that these underestimate small-likelihood, high-impact possibilities (the so-called "fat tail").

Following Weitzman (2012), an alternative damage function is calibrated, where temperature increases up to 2°C lead to similar impact levels as in the specification of the RICE model, but where large temperature increases lead to much more dramatic reductions in GDP (by including a higher power term in the damage response to temperature increases, calibrated to match Weitzman's assumption that 6°C leads to 50% reduction in GDP). As shown in Figure 8, the long-term consequences of this alternative specification are dramatic in the *Business as usual* scenario, where GDP impacts go into the double digits in early 22nd century when temperature increases reach 5°C and continue to rise. Note that in the *Committed by 2060* scenario with the Weitzman damages function, the losses in the later decades of the 21st century are also markedly higher than in the base specification with the original damage function of the RICE model (not shown in Figure 8).

47. The damage assessments above, both for the ENV-Linkages and AD-RICE projections, assume that households and firms try to minimise their costs; in that sense, these projections include some *market-driven adaptation*, but no active government policy on adaptation. The AD-RICE model also calculates how high damages would be in the absence of implementation of adaptation measures. Using the same Business-as-Usual central projection, but excluding the possibility of adapting to climate change impacts, tends to roughly double the consequences for economic growth, cf. Figure 8. Note that combining the assumption of no adaptation with high climate sensitivity or a damage function based on Weitzman's approach leads to calculations of very high upper bounds on potential GDP impacts. Clearly, the probability of these circumstances all occurring simultaneously is very low. Moreover, smooth economic models that are based on the concept of marginal responses to shocks are incapable of adequately assessing the state of the economy that would reflect such extreme conditions.

Figure 8. Change in global GDP from climate change damages in the very long run (alternative specifications)



Source: Own calculations using the AD-RICE model

3.3 Major uncertainties

3.3.1 The need for uncertainty analysis

48. The projections presented above are surrounded by large uncertainties. The two alternative specifications presented in Figure 8 both fall outside the uncertainty range on the central projection stemming from different assumptions regarding the climate sensitivity parameter. This re-enforces the notion that the uncertainty ranges given throughout this paper only reflect one particular uncertainty – albeit an important one – concerning the equilibrium climate response to a doubling of carbon concentrations (climate sensitivity). Other uncertainties, such as impacts of catastrophic events, also surround these projections, but are not easily quantified.

49. A single central projection of global climate damages is insufficient to portray a robust message on the links between climate change and economic growth. Further exploration of the uncertainties can include: (i) the formulation of different scenarios for baseline projections, reflecting uncertainty on the socioeconomic megatrends with respect to demographics, economic growth and natural resources availability; (ii) investigating the role of adaptation as a means to limit negative impacts and boost positive ones; (iii) comparing different representations of the climate system, either through the use of different underlying climate models or – as a minimum – by varying the climate sensitivity (as done above in a stylised manner). Policies to address the costs of inaction need to be designed to address these uncertainties where possible, for example by increasing flexibility to take new information into account and identifying no-regret options that are good for economic growth regardless of the future state of the economy and environment.

3.3.2 Catastrophic risks

50. Besides the relatively gradual changes occurring in the various sectors and regions as described above, there is a more fundamental risk associated with large-scale disruptions caused by climate change. Large-scale discontinuities, or “tipping points”, 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 melting of the West Antarctic or Greenland ice sheets. As stated in the IPCC Working Group II report (2014a), the risks of large-scale singular events “increase disproportionately as temperature increases between 1-2°C additional warming and become high above 3°C”. Kriegler et al. (2009) use expert elicitation of climate experts to find some consensus that there is a non-negligible probability of at least one major disruption taking place, even at relatively low levels of carbon concentrations. The probability that such a disruption will take place before 2060 is uncertain and likely to be small, but the build-up of greenhouse gases in the atmosphere in the coming decades contributes to an increase of crossing irreversible tipping points for these risks.

51. The non-linear effects that are caused by these discontinuities or tipping points are highly uncertain, but such disruptive changes will induce a major shock to both the climate and the economic system, albeit often with large regional differences. In the quantitative assessments of the impacts of climate change, catastrophic risks are mostly ignored (Lenton and Ciscar, 2013). Nonetheless, many authors have claimed that catastrophic risks may be much more important than the more gradual changes that have been assessed in the analysis above (e.g. Pindyck, 2013; Stern, 2013, Weitzman, 2013). Some applied modelling studies adopt an *ad hoc* approach and make an assumption of a permanent fixed percentage loss of regional or global GDP (e.g. Hope, 2006, chooses 10% of GDP for the EU and varying rates for other countries, with China the lowest at 2% and India the highest at 25%; Nordhaus, 2007, chooses 25% of GDP), but there is little evidence on which to base such an assumption. A further complication is that the economic modelling tools, including CGE models such as ENV-Linkages, are

based on a marginal approach: large shocks change behaviour in ways that are not captured by the smooth elasticity-based functions in the modelling frameworks.

52. While future economic costs of catastrophic events are difficult to assess, the risks imposed by such catastrophes can be approximated through a hazard function (Gjerde et al., 1999); that is, the chance that no major catastrophe occurs in the current period, given that none has occurred in the past. There is insufficient information to robustly calibrate such a hazard function; the recalibration presented here matches the more recent information in Kriegler et al. (2009). This indicates that the chance of at least one of these catastrophic events happening could be as large as 16% by 2060 in the central projection, i.e. the hazard rate of not triggering any catastrophic event declines to 84% (Figure 9).[15] Given the large economic consequences of such events, this probability can be interpreted as a risk premium or option value that should be placed on current emissions, reflecting their long-term potential implications.[16] A robust quantification of such a risk premium, with regional differentiation, should be a high research priority for climate economists. Despite their uncertainty, ambitious mitigation action is warranted to reduce the risks of crossing the tipping points and avoid locking in irreversible climate change.

Figure 9. Hazard rate of catastrophic event

Source: Own calculations

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[15] And it follows from the inertia in the climate system that this risk would remain intact for more than a century, even if emissions were to drop to zero immediately after 2060.

[16] The damage function with a high power term on temperature as presented in Weitzman (2012) and discussed above in the context of the AD-RICE projections, can also be seen as a way to embody such catastrophic risks.

4. Concluding remarks

53. This report examined how a selection of impacts from climate change could affect the global economy and regional economies until 2060. Based on the long-run growth scenario embedded in the OECD Economic Outlook (OECD, 2014) and used in the OECD@100 project (Braconier *et al.*, 2014), detailed assessments of these specific impacts are fed into the dynamic global general equilibrium model ENV-Linkages (Chateau et al., 2014) to assess the implications for different economic activities. It used a production function approach to project how different economic activities are affected by climate change, and discussed how these should be seen in the context of the longer-term effects that are caused by emissions until 2060, as well as the large uncertainties surrounding these projections.

54. While necessarily stylised, the economic modelling framework used for this assessment is well-suited to investigate how climate impacts on different sectors and regions affect the rest of the economy. At the same time the assessment can only capture the economic implications of those impacts that could be quantified, and ignores e.g. the costs of extreme weather events and large-scale disruptions. It is also less well-suited to capture the total economic cost of impacts that are not directly related to markets, such as the non-use value of ecosystem services losses and pain and suffering from climate-induced diseases. Furthermore, the use of GDP as an indicator of economic costs also has drawbacks, and is an imperfect indicator of the true welfare costs of climate change. A cost-benefit analysis based on the results illustrated above could therefore lead to imprudent and potentially biased policy recommendations.

55. Despite these uncertainties and caveats, the analysis clearly shows that unabated emissions in the coming decades lock the world into a much worse risk profile. Production systems, not least in energy supply, get locked into high-carbon technologies (cf. OECD, 2012), and the inertia in the climate system implies that once climate impacts occur, they tend to remain for a century, if not longer. Risks of large-scale catastrophic events also increase steadily, and it is not clear whether and when thresholds are crossed.

56. These risks imply a call for action and an assessment of the benefits of policy action. Mitigation policies are needed to reduce climate change and thus avoid the most important damages, risks and tipping points. Given the long-term consequences of emissions, immediate action is needed to reduce emission levels. Such mitigation action cannot be based on the time profile of damages as they arise, and as presented above. Ideally, it should be based on the full stream of future avoided (market) damages stemming from current emission reductions, plus a risk premium to manage the risks of catastrophic events and crossing irreversible tipping points.

57. Adaptation policies are essential to deal with the impacts that will still occur. This includes government intervention where necessary, and facilitating market-driven adaptation by private actors, e.g. to overcome information barriers and moral hazard issues. The costs presented in this paper assume an optimal response by economic agents, implying that with less efficient adaptation policies, costs will be higher.

58. Finally, more research is needed to assess the economic consequences of major risks from climate change at the regional and sectoral level. The uncertainties and knowledge gaps are still large. That should not delay policy action, but rather induce policy frameworks that are able to deal with new information on the economic feedbacks of climate impacts, as well as with the fact that by their nature some uncertainties and risks will never be resolved.

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ANNEX I. OVERVIEW OF THE ENV-LINKAGES MODEL

1. The ENV-Linkages model is the successor to the OECD GREEN model for environmental studies (Burniaux, *et al.* 1992). A more comprehensive model description is given in Chateau *et al.* (2014).

2. Production in ENV-Linkages is assumed to operate under cost minimisation with perfect markets and constant return to scale technology. The production technology is specified as nested Constant Elasticity of Substitution (CES) production functions in a branching hierarchy (cf. Figure AI.1). This structure is replicated for each output, while the parameterisation of the CES functions may differ across sectors. The nesting of the production function for the agricultural sectors is further re-arranged to reflect substitution between intensification (e.g. more fertiliser use) and extensification (more land use) of crop production; or between intensive and extensive livestock production. The structure of electricity production assumes that a representative electricity producer maximizes its profit by using the different available technologies to generate electricity using a CES specification with a large degree of substitution. The structure of non-fossil electricity technologies is similar to that of other sectors, except for a top nest combining a sector-specific resource with a sub-nest of all other inputs. This specification acts as a capacity constraint on the supply of the electricity technologies.

3. The model adopts a putty/semi-putty technology specification, where substitution possibilities among factors are assumed to be higher with new vintage capital than with old vintage capital. In the short run this ensures inertia in the economic system, with limited possibilities to substitute away from more expensive inputs, but in the longer run this implies relatively smooth adjustment of quantities to price changes. Capital accumulation is modelled as in the traditional Solow/Swan neo-classical growth model.

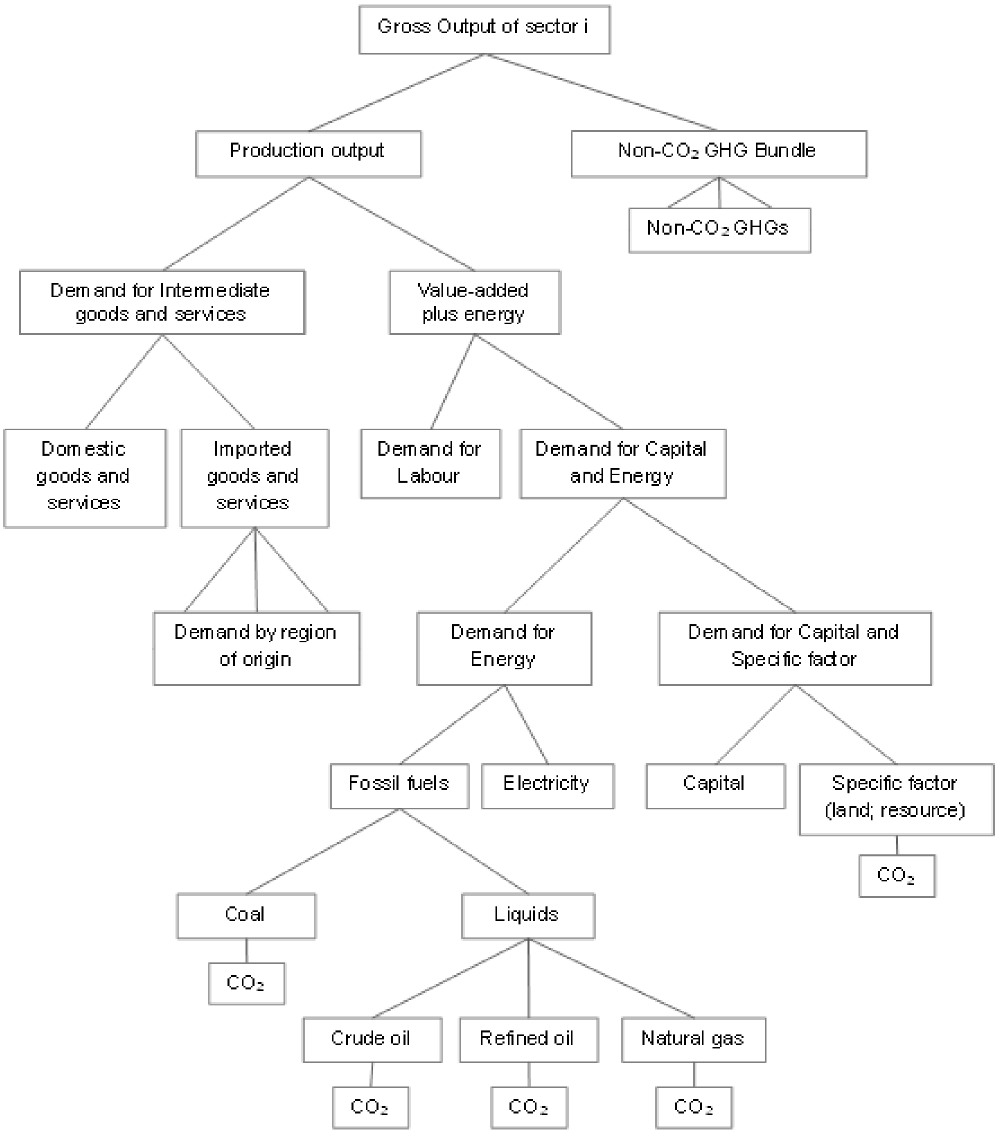
4. The energy bundle is of particular interest for analysis of climate change issues. Energy is a composite of fossil fuels and electricity. In turn, fossil fuel is a composite of coal and a bundle of the “other fossil fuels”. At the lowest nest, the composite “other fossil fuels” commodity consists of crude oil, refined oil products and natural gas. The value of the substitution elasticities are chosen as to imply a higher degree of substitution among the other fuels than with electricity and coal.

5. Household consumption demand is the result of static maximization behaviour which is formally implemented as an “Extended Linear Expenditure System”. A representative consumer in each region – who takes prices as given – optimally allocates disposal income among the full set of consumption commodities and savings. Saving is considered as a standard good in the utility function and does not rely on forward-looking behaviour by the consumer. The government in each region collects various kinds of taxes in order to finance government expenditures. Assuming fixed public savings (or deficits), the government budget is balanced through the adjustment of the income tax on consumer income. In each period, investment net-of-economic depreciation is equal to the sum of government savings, consumer savings and net capital flows from abroad.

6. International trade is based on a set of regional bilateral flows. The model adopts the Armington specification, assuming that domestic and imported products are not perfectly substitutable. Moreover, total imports are also imperfectly substitutable between regions of origin. Allocation of trade between partners then responds to relative prices at the equilibrium.

7. Market goods equilibria imply that, on the one side, the total production of any good or service is equal to the demand addressed to domestic producers plus exports; and, on the other side, the total demand is allocated between the demands (both final and intermediary) addressed to domestic producers and the import demand.

Figure AI.1. Production structure of a generic sector in ENV-Linkages[17]



Source: ENV-Linkages model

8. CO_2 emissions from combustion of energy are directly linked to the use of different fuels in production. Other GHG emissions are linked to output in a way similar to Hyman et al. (2002). The following non-CO_2 emission sources are considered: i) methane from rice cultivation, livestock production (enteric fermentation and manure management), fugitive methane emissions from coal mining, crude oil

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[17] This generic structure does not apply to energy and agricultural sectors.

extraction, natural gas and services (landfills and water sewage); ii) nitrous oxide from crops (nitrogenous fertilizers), livestock (manure management), chemicals (non-combustion industrial processes) and services (landfills); iii) industrial gases (SF6, PFCs and HFCs) from chemicals industry (foams, adipic acid, solvents), aluminium, magnesium and semi-conductors production. Over time, there is, however, some relative decoupling of emissions from the underlying economic activity through autonomous technical progress, implying that emissions grow less rapidly than economic activity.

9. Emissions can be abated through three channels: (i) reductions in emission intensity of economic activity; (ii) changes in structure of the associated sectors away from the 'dirty' input to cleaner inputs, and (iii) changes in economic structure away from relatively emission-intensive sectors to cleaner sectors. The first channel, which is not available for emissions from combustion of fossil fuels, entails end-of-pipe measures that reduce emissions per unit of the relevant input. The second channel includes for instance substitution from fossil fuels to renewable in electricity production, or investing in more energy-efficient machinery (which is represented through higher capital inputs but lower energy inputs in production). An example of the third channel is a substitution from consumption of energy-intensive industrial goods to services. In the model, the choice between these three channels is endogenous and driven by the price on emissions.

10. ENV-Linkages is fully homogeneous in prices and only relative prices matter. All prices are expressed relative to the *numéraire* of the price system that is arbitrarily chosen as the index of OECD manufacturing exports prices. Each region runs a current account balance, which is fixed in terms of the *numéraire*. One important implication from this assumption in the context of this report is that real exchange rates immediately adjust to restore current account balance when countries start exporting/importing emission permits.

11. As ENV-Linkages is recursive-dynamic and does not incorporate forward-looking behaviour, price-induced changes in innovation patterns are not represented in the model. The model does, however, entail technological progress through an annual adjustment of the various productivity parameters in the model, including e.g. autonomous energy efficiency and labour productivity improvements. Furthermore, as production with new capital has a relatively large degree of flexibility in choice of inputs, existing technologies can diffuse to other firms. Thus, within the CGE framework, firms choose the least-cost combination of inputs, given the existing state of technology. The capital vintage structure also ensures that such flexibilities are large in the long run than in the short run.

12. The sectoral and regional aggregation of the model, as used in the analysis for this paper, are given in Tables AI.1 and AI.2, respectively.

Table AI.1. Sectoral aggregation of ENV-Linkages

Agriculture

Paddy Rice
Wheat and meslin
Other Grains
Vegetables and fruits
Sugar cane and sugar beet
Oil Seeds
Plant Fibres
Other Crops
Livestock
Forestry
Fisheries

Natural Resources and Energy

Coal
Crude Oil
Gas extraction and distribution
Other mining
Petroleum and coal products
Electricity (7 technologies#)

Manufacturing

Paper and paper products
Chemicals
Non-metallic minerals
Iron and Steel
Metals n.e.s.
Fabricated metal products
Food Products
Other manufacturing
Motor vehicles
Electronic Equipment
Textiles

Services

Land Transport
Air and Water Transport
Construction
Trade Other Services and Dwellings
Other Services (Government)

Fossil-Fuel based Electricity ; Combustibe renewable and waste based Electricity ;
Nuclear Electricity; Hydro and Geothermal ; Solar and Wind ;
Coal Electricity with CCS ; Gas Electricity with CCS

Table AI.2. Regional aggregation of ENV-Linkages

Macro region	ENV-Linkages countries and regions
OECD America	United States; Canada; Mexico; Chile
OECD Europe	EG4 (France, Germany, Italy, United Kingdom); E17 (other OECD EU countries), OE5 (Iceland, Norway, Switzerland, Turkey, Israel)
OECD Pacific	Japan; Korea; Oceania (Australia, New Zealand)
Rest of Europe and Asia	EU7 (non-OECD EU countries); Russia; OEU (non-EU European countries); Caspian countries; China
Latin America	Brazil; OLA (other Latin-American countries)
Middle East & North Africa	Middle-East; North Africa
South and South-East Asia	India; Indonesia; ASEAN9 (other ASEAN countries), ODA (other developing Asian countries)
Sub-Saharan Africa	South Africa; OAF (other African countries)

ANNEX II. TECHNICAL DOCUMENTATION OF THE CLIMATE CHANGE IMPACT DATA FOR THE CALIBRATION OF PROJECTED CLIMATE CHANGE DAMAGES IN ENV-LINKAGES

1. This Annex describes the data used, and, when appropriate, the elaboration process applied by the Euro-Mediterranean Centre for Climate Change (CMCC) to determine a set of relevant climate change impacts expected by mid-21st century. Impacts have been specified to fit the regional and sectoral breakdown as well as the baseline of the OECD's ENV-Linkages model. The impact data has been elaborated by CMCC from existing studies based on sectoral or bottom-up models used to investigate specific impact categories.[18] Impacts are specified by sector, region and time period to account for the wide variation in impacts for different actors in different periods.

2. The climate change scenario on which the crop yield impacts are calibrated is the Representative Concentration Pathway (RCP) 8.5 (Van Vuuren et al., 2012). The source studies for the other impact categories quantify impacts using the A1B IPCC SRES scenario (Nakicenovic and Swart, 2000). For the relevant time frame for the calibration, i.e. until 2060, the temperature profiles of the RCP8.5 and A1B scenarios are reasonably close. Both scenarios are also close to the temperature profile of the ENV-Linkages model baseline. Hence, the approximation to harmonise the baseline climate change profile for the various impacts is relatively minor.

3. In some cases the source studies specified impact data with a regional aggregation tailored to that of the CMCC ICES CGE model[19] which was used jointly to sectoral/bottom up models in specific research projects to perform the economic assessment. ICES 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.

Climate change impacts by category

4. The quantifications of climate change impacts is largely derived from a set of bottom-up partial-equilibrium exercises performed within the framework of recently concluded and ongoing EU Sixth and Seventh Framework Program (FP6 and FP7) research projects: ClimateCost, SESAME and Global-IQ. The impact literature and the methodology applied by dynamic optimization hard linked Integrated Assessment Models supported the computations of impacts on health and ecosystem services. Table 1 provides a summary of the impacts considered and sources. They refer to the consequences of climate-related changes in sea level, fish stock productivity, land productivity, tourism flows, energy demand, health status, and

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[18] The data used in this project has been kindly provided by researchers who took part to several EU projects. In particular, the authors would like to thank Sally Brown, Robert Nicholls, Athanasios Vafeidis and Jochen Hinkel, who generated sea-level rise impacts as part of the EU Seventh Framework Programme project ClimateCost, researchers at the Met Office who elaborated climate change scenarios for sea-level rise within the same project; Silvana Mima who provided data on climate change impacts on energy demand elaborated during the EU Seventh Framework Programme project ClimateCost; Fraziska Piontek who provided data on climate change impacts on crop yields elaborated during the EU Seventh Framework Programme project Global IQ; and Richard Tol who provided data on climate change impacts on tourism elaborated during the EU Seventh Framework Programme project ClimateCost as an elaborations of climate change impacts on mortality and morbidity. The values reported in this document are an elaboration of these data. Accordingly, errors are solely the authors' responsibility.

[19] For detailed information about the model please refer to the ICES website:

http://www.cmcc.it/models/ices-intertemporal-computable-equilibrium-system.

ecosystem services. All source studies have a global coverage and, since they mostly come from grid-based data sets and models, they report data with a high spatial resolution. When necessary, results have been aggregated to match the geographical resolution of the ENV-linkages CGE model.

Table AII.1. Summary of climate change impacts

CC Impact	Source	Project	Time frame	Scenarios / Reduced form	
				AR5	SRES
Sea level Rise	DIVA model - Vafeidis et al. (2008)	ClimateCost	2001-2100		A1B
Fisheries	Cheung et. al (2010)	SESAME	2000-2060		A1
Agriculture	PIK – LPJmL model ISI-MIP runs	GLOBAL-IQ	2007-2100	RCP8.5	
Ecosystem	Warren et al (2006), Manne et al. (1995)		2000-2060	Reduced form	
Tourism	HTM - Bigano et. al (2007)	ClimateCost	2005-2100		A1
Energy demand	POLES - Criqui (2001) Criqui et al. (2009)	ClimateCost	2000-2050		A1
Health	Tol (2002)	-	2008-2060	Reduced form	

Sea level rise

5. Estimates of coastal land lost to sea level rise are based upon the Dynamic Integrated Vulnerability Assessment (DIVA) model outputs (Vafeidis et al., 2008) applied in the FP7 ClimateCost project (Brown et al. 2011) and generated by the Met Office Hadley Centre. DIVA is an engineering model designed to address the vulnerability of coastal areas to sea level rise. The model is based on a world database of natural system and socioeconomic factors for world coastal areas reported with a spatial resolution of 5°. The temporal resolution is 5-year time steps until 2100 and 100-year time steps from 2100 to 2500. Changes in natural as well as socio-economic conditions of possible future scenarios are implemented through a set of impact-adaptation algorithms. Impacts are then assessed both in physical (i.e. sq. Km of land lost) and economic (i.e. value of land lost and adaptation costs) terms.

Fisheries

6. Climate-change induced changes in global catch potential derive from the FP6 SESAME project and are based on Cheung et al. (2010). They applied an empirical model (Cheung et al. 2008a) that predicts maximum catch potential depending upon primary production and distribution range of 1066 species of exploited fish and invertebrates. Distribution of each species on a 30' latitude 30' longitude grid is derived from an algorithm (Close et al. 2006) including the species' maximum and minimum depth limits, northern and southern latitudinal range limits, an index of association with major habitat types and known occurrence boundaries as input parameters. Future changes in species distribution are simulated by using a dynamic bioclimate envelope model (Cheung et al., 2008b, 2010). First, the model identified species' preference profiles with environmental conditions. Then, these are linked to the expected carrying capacity in a population dynamic model. The model assumes that carrying capacity varies positively with habitat suitability of each spatial cell. Finally, aggregating spatially and across species, the related change in total catch potential can be determined.

Agriculture

7. Climate change impacts on crop yield (physical production per hectare) are derived from the output of the LPJmL Dynamic Global Vegetation Model (Bondeau et al., 2007) developed at PIK and

applied within the ISI-MIP project (Rosenzweig et al., 2013). The LPJ model endogenously determines spatially explicit transient vegetation composition and the associated carbon and water budgets for different land-uses. It can estimate potential yield and its changes for many crops with a global resolution of 0.5 degree grid cells. Using a detailed systems model such as LPJ ensures that underlying physical constraints are properly accounted for; these include the competition for scarce land and water resources. In the EU-FP7 project Global-IQ on which the results presented here are based, the ISI-MIP yield data for the different crops have been aggregated into just one weighted average value for the agricultural sector as a whole. The data estimated does not consider the carbon fertilization effects on vegetation. Impacts of climate change on the livestock and dairy sectors are not included in the analysis.

Ecosystems

8. To estimate losses in ecosystem services, a modified Willingness To Pay (WTP) approach has been used. The starting assumption is that these services are largely non-marketed and not directly marketable. Accordingly, their value can be only extracted through elicitation of preferences. In particular the WTP to avoid a given loss in ecosystems is used to approximate the lost value in case they are not protected. This is for instance the methodology applied in the MERGE model (Manne et al., 1995) where the monetized ecosystem losses related to a 2.5°C temperature increase above pre-industrial levels is set equal to the 2% of GDP when per capita income is above $ 40,000. The 2% figure is the US EPA expenditure on environmental protection in 1995. The implicit assumptions are that what actually paid is reasonably close to the WTP, and roughly sufficient to preserve ecosystems and their services in a world with moderately increasing temperatures.

9. This approach has been applied while also rescaling the impacts to the more recent data of the EU 2007 expenditure on environmental protection by the public sector (0.62% of GDP, EUROSTAT, 2013), and assuming, more conservatively than Manne et al. (1995), that the observed expenditure allows protection against 2°C warming. Then, to derive WTP in non EU countries the logistic function proposed by Manne et al., (1995) is used (see also Warren et al., 2006):

$$WTP_{n,t|t=2.°C} = \gamma \Delta T^{\varepsilon}{}_{n,t|t=2°C} \frac{1}{1+100e^{(-0.23 * GDPn,t|t=2°C / POPn,t|t=2°C)}}$$

10. The parameter calibration derives from EU data thus γ is set to give exactly 0.62% of GDP when per capita income is the 2007 EU average ($34,262), and ΔT=2°C. Finally, the WTP is used to measure the direct cost of losses in ecosystem and their services.

Tourism

11. Changes in tourism flows induced by climate change are derived from simulations based on the Hamburg Tourism (HTM) Model (Bigano et al., 2007) amply used in EU research projects (FP6 CIRCE, ClimChalp, and more recently the FP7 ClimateCost project). HTM is an econometric simulation model, estimating the number of domestic and international tourists by country, the share of international tourists in total tourists, and tourism flows between countries. The model runs in 5-year time steps. First, it estimates the total tourists in each country, depending on the size of the population and of average income per capita. Then, it divides tourists between those that travel abroad and those that stay within the country of origin. In this way, the model provides the total number of holidays as well as the trade-off between holidays at home and abroad. The share of domestic tourists in total tourism depends on the climate in the home country and on per capita income. International tourists are finally allocated to all other countries based on a general attractiveness index, climate, per capita income in the destination countries, and the distance between origin and destination.

12. As in Berrittella et al., (2006) and Bigano et al. (2008) estimations of tourism flows by region are obtained from version 1.2 of the Hamburg Tourism Model (HTM). Three econometrically estimated equations, for arrivals (Equation 2) and departures (Equations 3 and 4) define the core of the model. In these equations the variables are:

A	Total arrivals per year
G	Land area (km2)
T	Annual average temperature (C°)
C	Length of coastline (km)
Y	Per capita income
D	Total departures per year
P	Population (in thousands)
B	The number of countries with shared land borders
H	Total domestic tourist trips per year
D	The destination country
O	The origin country

13. Arrivals are defined by:

$$\ln A_d = \underset{0.97}{5.97} + \underset{0.96}{2.05} \cdot 10^{-7} G_d + \underset{0.07}{0.22} T_d - \underset{2.21}{7.91} \cdot 10^{-3} T_d^2 + \underset{3.03}{7.15} \cdot 10^{-5} C_d + \underset{0.09}{0.80} \ln Y_d$$
$$N = 139; R_{adj}^2 = 0.54$$

14. Departures are determined following a two-step procedure. First the number of tourists “generated” by a country is defined, then it is subdivided between domestic tourists and those who travel abroad. The number of tourists that a country generates depends on the size of the population and on average income. The share of domestic tourists in total tourism depends on the climate in the home country and on per capita income. Missing observations are completed using two regressions. Total tourist numbers, D+H, where H is the number of domestic tourists are interpolated using:

$$\ln \frac{D_o + H_o}{P_o} = -\underset{0.83}{1.67} + \underset{0.10}{0.93} \ln Y_o$$
$$N = 63; R_{adj}^2 = 0.60$$

15. The ratio of domestic to total holidays was interpolated using

$$\ln \frac{H_o}{D_o + H_o} = -\underset{1.19}{3.75} + \underset{0.42}{0.83} \cdot 10^{-1} \ln G_o + \underset{0.30}{0.93} \cdot 10^{-1} \ln C_o + \underset{0.32}{0.16} \cdot 10^{-1} T_o - \underset{1.11}{0.29} \cdot 10^{-3} T_o^2$$
$$+ \left(\underset{0.12}{0.16} - \underset{1.24}{4.43} \cdot 10^{-7} Y_o \right) \ln Y_o$$
$$N = 63; R_{adj}^2 = 0.36$$

16. The model is calibrated to 1995 data. Climate is proxied by the 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. Other explanatory variables are included in the regression for estimation efficiency, but these are held constant in the simulation. The number of international tourists to a country is the sum of international tourists from the other 206 countries. Total tourism expenditure is then calculated multiplying the number of tourists times an estimated value of the average individual expenditure.

Residential energy demand

17. Responses of residential energy demand to increasing temperatures derive from the POLES model (Criqui, 2001; Criqui et al., 2009), which was also used in FP7 ClimateCost project. POLES is a bottom-up partial-equilibrium model of the world energy system. It determines future energy demand and supply for different energy vectors (coal, oil, natural gas, electricity) according to trends in energy prices, technological innovation and climate impacts through their effects on heating and cooling degree-days.

Health

18. Impacts on human health are expressed by changes in mortality and morbidity associated to malaria, schistosomiasis, dengue, diarrhoea, cardiovascular and respiratory diseases applying the methodology of Bosello et al. (2006). Estimates of the change in mortality due to vector-borne diseases (malaria, schistosomiasis, dengue fever) as the result of a one degree increase in the global mean temperature are taken from Tol (2002). The estimates result from overlaying the model-studies of Martens et al. (1995, 1997), Martin and Lefebvre (1995), and Morita et al. (1994) with mortality and morbidity figures of the WHO (Murray and Lopez, 1996). These studies suggest that the relationship between global warming and malaria is linear. This relationship is assumed to apply to schistosomiasis and dengue fever as well.

19. To account for changes in vulnerability possibly induced by improved access to health care facilities associated to improvement in living standards (read GDP growth) Tol (2002a) applies the relationship between per capita income and disease incidence developed by Tol and Dowlatabadi (2001).[20] This relationship is used applied to the projected per capita regional income growth of the ENV-Linkages model.

20. For diarrhoea, impacts are calculated following Link and Tol (2004), who report the estimated relationship between mortality and morbidity on the one hand and temperature and per capita income on the other hand. Their study is based on the WHO Global Burden of Disease data (Murray and Lopez, 1996). Martens (1998) reports the results of a meta-analysis of the change in cardiovascular and respiratory mortality for 17 countries. Tol (2002) extrapolates these findings to all other countries, using the current climate as the main predictor. Cold-related cardiovascular, heat-related cardiovascular, and (heat-related) respiratory mortality are specified separately, as are the cardiovascular impacts on the population below 65 and above. Heat-related mortality is assumed to only affect the urban population. This model is used directly on a country basis, before aggregating to the ENV-Linkages regions.

21. Changes in health care expenditures are also estimated. The literature on the costs of diseases is thin and few papers can be used as reference. The costs of vector borne diseases are taken from Chima et al. (2003), who report the expenditure on prevention and treatment costs per person per month.

22. Their data suggest the following relationships

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[20] Vulnerability to vector-borne diseases strongly depends on basic health care and the ability to purchase medicine. Tol and Dowlatabadi (2001) suggest a linear relationship between per capita income and health. In this analysis, vector-borne diseases have an income elasticity of –2.7.

$$P = \underset{(0.3103)}{0.1406} + \underset{(0.0008)}{0.0026}Y$$

$$T = -\underset{(0.8217)}{0.4646} + \underset{(0.0018)}{0.0053}Y$$

where P is monthly prevention costs ($/capita), T is monthly treatment costs ($/cap) and Y is income per capita ($/cap). This is scaled up with the increase in mortality.

ANNEX III. OVERVIEW OF THE AD-RICE2012 MODEL

1. In this annex a short description of the AD-RICE2012 model and its calibration are given. AD-RICE is a Ramsey-type growth model with explicit representation of adaptation to climate change (De Bruin et al., 2009a,b). The AD-RICE2012 model (De Bruin 2014) has been developed based on the RICE2010 (Nordhaus 2011) model. The AD-RICE model extends the RICE model to include adaptation policy variables.

2. The AD-RICE2012 model is an Integrated Assessment Model (IAM), where economic production leads to GHG emissions. In this model, industrial CO_2 is the only endogenous GHG. The amount of industrial CO_2 emissions per unit of output is assumed to decrease over time due to technological development. In turn CO_2 emissions increase the stock of CO_2 in the atmosphere, resulting in climate change. Though climate change includes a multitude of phenomena (such as changes in precipitation, changes in weather variability, increased extreme weather), it is represented by changes in atmospheric temperature in this model. Overall climate change negatively affects society and the economy through various different impacts. GDP impacts due to climate change are modeled as a percentage decrease in production as a function of mean atmospheric temperature change compared to 1900. Investments in mitigation will reduce CO_2 emissions per unit of output at a cost, which decreases over time due to technological change. By adjustments to the economy (i.e. adaptation) initial climate change damages (gross damages) can be reduced to residual damages at a cost.

3. The model comprises 12 regions, which together represent the globe. The regions included in the model are as follows: USA, EU, Japan, Other High Income regions (OHI), India, China, Africa, Russia, European Asia (EUASIA), Asia, Latin America (LATAM) and the Middle East (ME).

4. AD-RICE2012 is a forward-looking Ramsey growth model, where regional utility is maximized (given regional endowments) over the model horizon. The model has time periods of 10 years and has a time horizon of 300 years. Utility is a function of consumption per capita discounted over time and over income per capita (richer generation's consumption creates less utility than poorer generation). The model finds the optimal balance of capital investments, mitigation investments, adaptation investments, adaptation costs and consumption to maximize utility.

5. The climate change damage estimates in the AD-RICE2012 model replicate the net damages of the RICE2010 model. The damages of the RICE2010 model have been calibrated based on Nordhaus (2007), Tol (2009) and IPCC(2007). The impacts generally considered in IAM and here as well are: health impacts, agricultural impacts, effects on leisure activities, water resources, energy and sea level rise. Given the obvious data restrictions, this list is not comprehensive and many impacts of climate change remain unquantified. The AD-RICE model uses a stylized damage function where temperature increases lead to direct decreases in production. A more detailed description of damages would include a production function approach, which includes the effects on production inputs and direct utility effects. There remains a large degree of uncertainty regarding the damages associated with climate change, where particularly many impacts have not yet been identified or quantified. The quantified damages in this model could be seen as a lower bound to expected climate change damages, but damages could be significantly higher than projected. Table A1 shows the climate change damages for the different regions in percentage of GDP for

2010, 2050 and 2100 in the BAU scenario. As can be seen in the table damages estimates vary considerable between regions in the model.

Table AIII.1. Climate change damages as percentage of GDP for regions of the AD-RICE2012 model for 2010, 2050 and 2100 for the BAU scenario.

Region	Japan	USA	EU	OHI	ME	LATAM	Russia	Asia	EuAsia	China	India	Africa
2010	0.1	0.1	0.1	0.1	0.4	0.1	0.1	0.2	0.1	0.1	0.4	0.5
2050	0.8	0.6	0.7	0.7	1.3	0.7	0.5	1.22	0.5	0.7	1.6	1.5
2100	2.3	2.0	1.8	1.9	3.0	2.0	1.3	2.8	1.9	1.9	4.6	4.3

6. The AD-RICE2012 model includes 2 forms of adaptation namely proactive adaptation, reactive adaptation. This distinction has been made to enable a more accurate description of the costs and benefits of different forms of adaptation and hence the total adaptation costs. Reactive adaptation describes adaptation measures that can be taken in reaction to climate change or climate change stimuli. This form of adaptation comes at a relatively low cost and is generally undertaken by individuals. Examples of this form of adaptation are the use of air-conditioning or the changing of crop planting times. Proactive adaptation on the other hand refers to adaptation measures that require investments long before the effects of climate change are felt. This form of adaptation usely requires large scale investments made by governments. Examples of this form of adaptation are research and development into new crop types or the construction of a dam for irrigation purposes.

7. The net damages of the RICE2010 models are separated into adaptation costs and residual damages. Firstly the gross damages (damages before/without adaptation) are defined as follows:

$$GD_{j,t} = \alpha_{1,j} \cdot T_t + \alpha_{2,j} \cdot T_t^{\alpha_{3,j}} .$$

where $\alpha_{1,j}$ and $\alpha_{2,j}$ are positive damage parameters and $\alpha_{3,j}$ ranges between 1-4 and T the level of atmospheric temperature increase compared to 1900.

8. These are the damages that occur if no adaptation takes place, and are thus higher than the net damages. These damages can be reduced through the use of adaptation, assuming the following relationship:

$$RD_{j,t} = \frac{GD_{j,t}}{1 + P_{j,t}} ,$$

where $P_{j,t}$ is the total level of protection (stock and flow) and $RD_{j,t}$ are the residual damages. This functional form is chosen because it limits the fraction by which the gross damages can be reduced to the interval of 0 to 1. When total protection reaches infinity, all gross damages are reduced (the residual damages are zero) and when no protection is undertaken no gross damages are reduced (residual damages equal gross damages). This functional form also ensures decreasing marginal damage reduction of protection, that is the more protection is used the less effective additional protection will be. This is assumed as more effective, efficient measures of adaptation will first be applied whereas less effective measures after that.

9. Two forms of adaptation (stock and flow) together create total adaptation. The two forms of adaptation are aggregated together using a Constant Elasticity of Substitution (CES) function. Here the elasticity of substitution can be calibrated to reflect the observed relationship between the two forms. This function is given as follows:

$$P_{j,t} = \gamma_j \cdot (\nu_{1,j} SAD_{j,t}{}^{\rho A} + \nu_{2,j} FAD_{j,t}^{\rho_A})^{\nu_{3,j}/\rho_A} ,$$

where $SAD_{j,t}$ is the total amount of adaptation capital stock. $FAD_{j,t}$ is the amount spent on reactive adaptation in that period. Furthermore, $\rho_A = \frac{\sigma - 1}{\sigma}$, where σ is the elasticity of substitution.

Adaptation capital stock is built up as follows:

$$SAD_{j,t+1} = (1 - \delta_k) SAD_{j,t} + IAD_{j,t} ,$$

where δ_k is the depreciation rate and $IAD_{j,t}$ are the investments in stock adaptation (SAD_t).

10. The adaptation module of AD-RICE2012 is calibrated based on estimates of adaptation costs and benefits from the impact literature. More precisely for each climate impact sector the adaptation costs and benefits for each region were estimated based on available impact studies and expert judgment. For a full description of this process, please refer to de Bruin (2014).

11. Climate change is global environmental problem, affecting all regions of the world both now and in centuries to come. Both the causes of climate change (different sources of GHG emissions) and the effects of climate change are innumerable, diverse, and vary is scope and scale. Attempting to include all causes and effects of climate change in a single model is a difficult task. Especially estimating the effects of climate change in the long run is a complex process, which involves many uncertainties. IAMs are tools created to assess the effects of the economy on climate change and vice versa in the long run. Due to the many mechanisms involved and the long time frame, these models need to make (simplifying) assumptions. IAMs are hence highly aggregated top-down models, which do not include all sectoral and regional impacts in detail. Though these assumptions and simplifications are necessary due to both lack of data (it is hard to predict future effects) and computational limitations, they do form a significant drawback of IAMs. Given these drawbacks applying a model such as AD-RICE can still give important insights into the magnitude and development of both the economy and the climate. Given that climate change is both a global problem and will have the greatest affects in the long term, an analysis of climate change is incomplete without a global long term perspective. The strength of IAMs such as AD-RICE is that they can shed some light on the long term climate consequences of our actions now.

Scenarios

12. The *Business as usual* scenario assumes that regions do not consider the effects of climate change when determining their optimal consumption and mitigation levels. The feedback from emissions to climate change back to the economy (i.e. climate change damages) is ignored. This implies that mitigation will only include (relatively low level of) mitigation undertaken solely due to fossil fuel resource scarcity. This is modelled by fixing mitigation at its optimal level given that no climage change damages occur. Adaptation is still applied at its optimal level given the expected gross damages.

13. The *Committed by 2060* scenario estimates how 50 years of inaction will affect the future estimated GDP impacts of climate change. Mitigation inaction until 2060 will increase GDP impacts due

to climate change in the period before 2060. GDP impacts, however, will also increase after 2060. Solely estimating the GDP impacts before 2060 will underestimate the GDP impacts of climate change as the long run impacts (due to the inertia of the climate system) are ignored. This is modelled by setting emissions at the business as usual levels until 2060, after which economic production is decoupled from emissions.

14. The *Weitzman damage* scenario is used as a sensitivity analysis for the damages assumed in the model. As mentioned before damages can be expected to be higher than replicated in the AD-RICE original damage function. Weitzman (2012) proposes a damage function which increases much more steeply over temperature change than the RICE/AD-RICE damage function. The Weitzman function is similar to the original RICE/AD-RICE damage function for low temperatures but is significantly higher for higher temperature change levels. The RICE damage function assumes that net damages as a fraction of GDP consist of a linear component and a quadratic component, as follows:

$$NHD_{j,t} = \alpha_{NH1,j} \cdot T_t + \alpha_{2NH,j} \cdot T_t^2$$

where t is the time period, j,the region , T the level of atmospheric temperature increase compared to 1900 and $\alpha_{NH1,j}, \alpha_{NH2,j}$ are damage parameters.

15. The Weitzman damage function has the following form:

$$WD_t = \left(\frac{T_t}{20.46}\right)^2 + \left(\frac{T_t}{6.08}\right)^{6.76}$$

16. The Weitzman damage function is a global damage function. To calibrate the regional Weitzman damages, global damages are divided amongst the regions based on their share (in each time period, in each scenario) in the original total global damages.

17. The *no adaptation* scenario assumed that regions do not or are unable to implement any form of adaptation. The regions now determine their optimal mitigation and consumption levels given the gross damages of climate change without the possibility of reducing gross damages through adaptation.

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