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The JRC PESETA II Project

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Preface

The main objective of the JRC PESETA II project (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis) has been to analyse in an integrated way the possible impacts of climate change in Europe. The project has involved the coordination of twelve different teams within the Joint Research Centre (JRC) of the European Commission (both from the Institute for Prospective Technological Studies –IPTS– and the Institute for Environment and Sustainability –IES–), with more than forty scientists involved from a wide range of disciplines, from river flood modelling to economics.

The JRC PESETA II project responds to a need to provide quantitative modelling support to the European Commission services regarding the impacts of climate change in Europe. The project preliminary results provided background information on climate adaptation and impacts to the 2013 EU Strategy on Adaptation to Climate Change.

High resolution biophysical impact assessment models have run high time-space resolution climate data (from DG Research projects) to derive a broad set of climate impacts covering, in particular, agriculture, energy, river floods, droughts, forest fires, transport infrastructure, coasts, tourism, habitat suitability of forest tree species and human health. Most of the biophysical impacts have been integrated into a general equilibrium economic model in order to assess the implications of climate change in terms of household welfare and economic activity (GDP).

Further research is needed in complex and relevant areas such as climate migration, effects on ecosystems services, and the possible consequences of abrupt climate change. How adaptation measures can reduce climate impacts should be better understood and assessed.

This publication documents the project methodology and analyses the main biophysical and economic results. Further information regarding each sectoral impact assessment can be found in the respective technical reports (please visit http://peseta.jrc.ec.europa.eu/).

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Policy context

The EU Strategy on Adaptation to Climate Change, adopted by the European Commission in April 2013, aims at contributing to a more climate resilient Europe by enhancing preparedness and capacity to respond to the impacts of climate change at different geographical scales, as well as developing a coherent approach and improved coordination.

Adaptation to climate change implies addressing the consequences of climate change, taking appropriate actions to prevent or minimise damages, and taking advantage of opportunities that may arise. However, in order to understand the potential benefits of adaptation it is necessary to estimate the impacts of climate change without it. The JRC PESETA II project (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis) has contributed to the EU Strategy on Adaptation to Climate Change by providing background information on how climate change could affect a broad set of impact areas across the EU, ranging from agriculture to human health and habitat suitability of tree species.

Purpose of the JRC PESETA II project

The fundamental purpose of the JRC PESETA II project is to gain insights into the sectoral and regional patterns of climate change impacts in Europe that may occur by the end of this century. The assessment concerns both the biophysical and economic impacts of climate change.

Scope of the project

Regarding the time horizon, the project covers the climate impacts over the period 2071-2100 (also referred to as 2080s), compared to 1961-1990. The study considers climate impacts in five large EU regions: Northern Europe (Sweden, Finland, Estonia, Lithuania, Latvia, and Denmark), UK & Ireland (UK and Ireland), Central Europe North (Belgium, Netherlands, Germany, and Poland), Central Europe

South (France, Austria, Czech Republic, Slovakia, Hungary, Slovenia, and Romania), and Southern Europe (Portugal, Spain, Italy, Greece, and Bulgaria).

The study analyses a total of ten biophysical impact categories (agriculture, energy, river floods, droughts, forest fires, transport infrastructure, coasts, tourism, habitat suitability of forest tree species and human health) and considers a broad set of climate model simulations (a maximum of fifteen for some impact sectors). Eight of those impacts (agriculture, energy, river floods, forest fires, transport infrastructure, coasts, tourism and human health) are integrated into an economic model to assess the impact on the overall economy and welfare at regional and EU level.

However, even if the coverage of impacts is relatively broad, it should be stressed that the study underestimates the climate damages in Europe because of a number of reasons. Firstly, the coverage of the effects due to climate extremes is limited in the sectoral models used in the project. Secondly, key impacts without market prices, such as losses of ecosystem services or damages to biodiversity, are not considered. Thirdly, abrupt climate change or the effects of passing climate tipping points are not integrated in the analysis. Finally, the study does not consider how Europe would be affected indirectly through the impacts of climate change in the rest of the world. Therefore the project cannot fully capture the overall scale of the risks due to climate change in Europe in a long-term context. Moreover, for these reasons the difference between the Reference and the 2°C simulations should not be interpreted as the benefits of mitigation policy.

Methodology

The project methodology has two distinctive features. Firstly, it is based on bottom-up biophysical impact models. Bottom-up models take into account the relationship between climate change and biophysical impacts in a structural way, modelling all the relevant interactions and mechanisms. Secondly, the assessment is made in a consistent way, where all biophysical impact models use the same climate scenarios.

Most of the biophysical impact models are operated within the JRC. The project has benefitted considerably from DG Research and Innovation projects, in particular ENSEMBLES and ClimateCost.

The economic analysis of climate impacts (in the eight categories mentioned above) has been carried out with an economic general equilibrium model. This enables comparison of the different impacts based on common metrics (household welfare and economic activity or GDP), and also the computation of the indirect effects (in addition to the biophysical direct effects). The economic analysis considers a hypothetical, counterfactual situation where the climate of the future is assumed to occur in the economy of today.

Adaptation is considered for some of the impacts identified in this report, depending on the tools and data available. For instance public adaptation can be analysed explicitly in the coastal impact assessment (through measures such as dike building), whereas market adaptation (which occurs via changes in market prices) is included in the eight sectors evaluated with the economic model.

Climate simulations

All sectoral models have considered four core climate simulations. Three of them are derived from a medium-high emission scenario without mitigation, namely the SRES A1B scenario, which lead to a global temperature increase of 3.5°C, compared to the pre-industrial level. The first one, called 'Reference simulation' is considered to be a business-as-usual scenario. Two other are driven by the same SRES A1B emission scenario but capture the boundaries of a wider range of simulations (warmer and drier than the reference, and colder and wetter than the reference). A fourth simulation is consistent with the EU 2°C climate goal, the so-called ENSEMBLES E1 scenario, which has lower emissions than the SRES A1B scenario.

For some impact categories a greater number of climate simulations has been considered (e.g. a total of twelve for the A1B scenario and three for the 2°C scenario for river floods). Some sectoral models have also used an emission scenario higher than the SRES A1B, the RCP8.5. That set partly covers the possible range of climate simulations due to emission scenarios (A1B, E1 and RCP8.5), climate modelling and climate variability (different global and regional climate models).

Biophysical impact results

The ten biophysical models cover very different types of climate impacts and provide a broad range of results.

Agriculture

Regarding agriculture in the 2080s, it is projected that under the Reference simulation crop yields overall will fall by around 10% in the EU, mainly driven by a fall of 20% in Southern Europe. In the 2°C simulation agriculture yields are not much affected at the EU level.

The specific analysis of agriculture impacts in the 2020s period (conducted with a different agriculture model) shows that technical adaptation can improve the yields to a large extent, with a general improvement all over Europe, except for the Iberian Peninsula. Under the warm variant of the Reference simulation, crop yields are projected to rise in Southern Europe thanks to the additional rainfall.

Energy

Energy demand patterns can also be affected by climate change. Under the Reference simulation overall EU energy demand could fall by 13%, due mainly to reduced heating requirements. All regions would expect to see reductions in energy demand except Southern Europe, where the need for additional cooling would lead to a demand increase of close to 8%. In the 2°C simulation, EU energy consumption would fall to a lesser extent, by 7%.

River floods

Climate change is projected to largely change the frequency and magnitude of river floods. Flood damages could more than double with the 2080s climate under the Reference simulation, reaching around €11 billion/year. The largest increase would occur in the UK & Ireland and Central Europe South regions. The number of people affected by floods per year could almost double to 290,000. Under the 2°C simulation the effects would be smaller, with an annual economic damage of around €10 billion, and 240,000 people/year affected by floods. If the 2080s economy is simulated (i.e. allowing for economic and population growth, instead of shocking the current economy as of today), then the damages would be much greater, reaching €98 billion/year and €68 billion/year under the A1B and E1 scenario, respectively. This difference is due to the much higher value of assets at risk because of economic and demographic developments.

The river flood analysis has also studied the costs and benefits of adaptation, with the objective to maintain a 1 in 100-year level of flood protection across Europe in future time periods. The reduction in damage costs is estimated at €53 billion/year by the 2080s, at a cost of €7.9 billion/year.

It is important to note that flood damage simulations are subject to a high degree of uncertainty, partly because of the uncertainty in the extreme precipitation projections.

Droughts

Streamflow droughts may become more severe and persistent in many parts of Europe due to climate change, except for northern and northeastern parts of Europe. In particular, southern regions will face strong reductions in low flows. As a consequence, EU cropland affected by droughts is projected to increase 7-fold in the Reference simulation, reaching 700,000 km^2/year, almost twice the area of Germany. The largest increase in exposed area would be in Southern Europe (reaching nearly 60% of the total EU affected area, compared to 30% today). People affected by droughts would also largely increase from today's levels by a factor of seven, reaching 153 million/year in the Reference simulation. Again half of the overall population affected would be in the Southern Europe region. The multi-model ensemble projections of more cropland and people affected by drought in the south and the opposite signal in the north are statistically highly significant and robust amongst the Reference simulation members, while the projected changes are more dissonant in a transition zone in between.

Forest fires

Burned area due to forest fires could more than double in the Southern European region in the Reference simulation, reaching almost 800,000 ha. The increase would be smaller (by 50%) under the 2°C simulation.

Transport infrastructure

The transport study did only consider a limited range of future impacts and adaptation measures for the land transport infrastructures and did not cover other transport modes. Damages to transport infrastructure due to extreme precipitation induced by climate change could increase by 50% in the Reference simulation to reach around €930 million/year. Under the 2°C simulation the damage would amount to €770 million/year. Higher temperatures would also require greater spending on asphalt binder, though milder winters would also result in reduced maintenance costs. In addition, greater expenditure would be needed to prevent bridge scour (damage to bridges from increased river flow) and speed restrictions would be needed to prevent buckling of railways. Altogether it is estimated that this would require around €590 million of additional annual spending in the 2080s, compared to a counterfactual without climate. In addition, it is estimated that 1 metre of sea level rise would place transport assets worth around €18.5 billion at risk of permanent or temporary inundation. Furthermore, these estimates do not account for potential expansion of the transport network between now and the 2080s.

Coasts

Regarding the effects due to sea level rise, damages associated with sea floods (without public adaptation) could more than triple in the Reference simulation, to attain €17 billion/year. The highest increase in damages could occur in the Central Europe North region (almost a four-fold rise, with a damage of €9 billion/year). The damages in the 2°C simulation would reach almost €14 billion/year.

Tourism

Concerning the effects on tourism expenditure the results for the Reference and 2°C simulations are quite similar, with a drop of €15 billion/year. The Southern Europe region would have a €7 billion/year fall in the Reference and €5 billion/year loss in the 2°C simulation.

Habitat suitability

The potential effects of anthropogenic climate change on the distribution of forest tree species are illustrated in a pilot study assessing changes in the suitable habitat of the Silver Fir (*Abies alba)*, a common and widely distributed European species. There could be a shift towards Northern and higher elevation areas of potential future habitat of *Abies alba* under the Reference simulation. Changes in suitable habitat of this species are less evident in the 2°C scenario. Nevertheless, new suitable areas are evident in the Scandinavian Peninsula and Northern British

Islands and Ireland. In addition to the shift to Northern regions of suitable areas it is also remarkable a shirking of suitable habitat in mountain regions such as the Pyrenees, Alps and Carpathian. This is consistent with an upslope shift towards higher elevation.

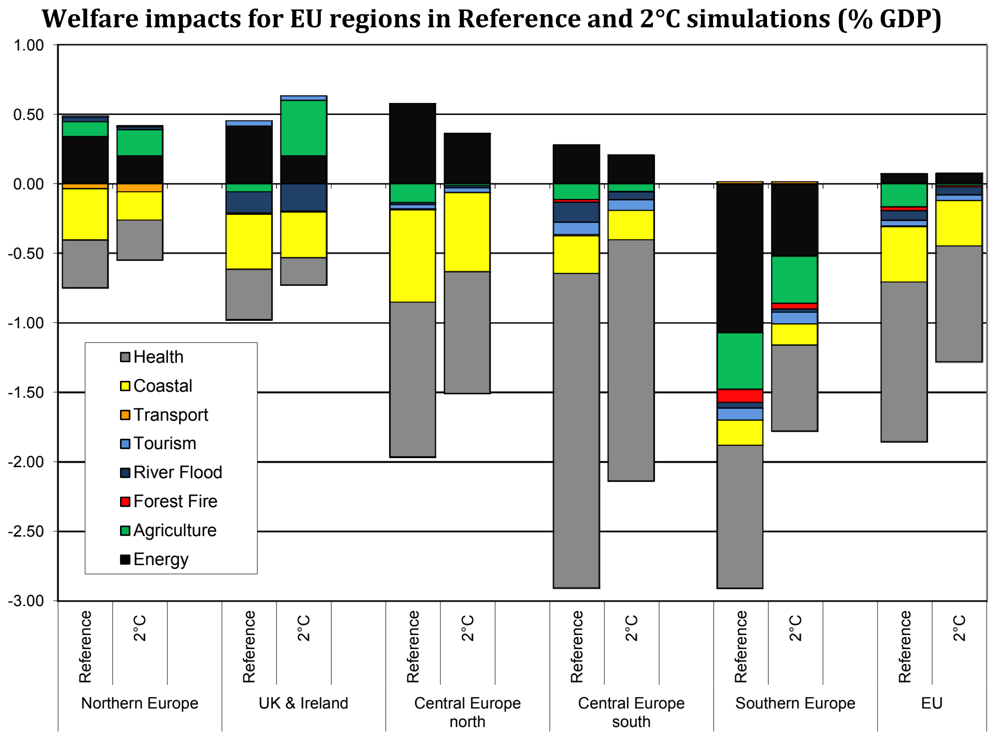
Human health

Climate change-attributable impacts on human health are assessed in those cases where the association is well-defined. Heat-related (including heat wave additional stress), direct impacts on mortality and morbidity (respiratory, cardiovascular, renal failure) and indirect impacts via food and water-borne diseases (salmonellosis and campylobacteriosis) have been considered. Under the Reference simulation EU annual mortality could more than double (with 100,000 additional deaths/year), with most of the increase occurring in the Central Europe regions and Southern Europe. Under the 2°C climate simulation the additional deaths/year would fall to less than 80,000.

Economic impact results

Most of the previous biophysical impacts (barring droughts and habitat suitability) have been integrated into an economic model to assess the effects in terms of household welfare losses. The economic effects consider the direct climate effects (as measured by the biophysical models) and the indirect effects in the economy (as calculated with the general equilibrium economic model). Under the Reference simulation the annual total damages would be around €190 billion, almost 2% of EU GDP today.

The geographical distribution of the climate damages is very asymmetric with a clear bias towards the southern European regions. Relative to GDP (see next Figure), the welfare losses range from 0.2% in Northern Europe to 3% in both the Central Europe South and Southern Europe regions, i.e. fifteen times higher than the damage in Northern Europe. The highest welfare losses would occur in Southern Europe (€74 billion), Central Europe South (€58 billion) and Central Europe North (€45 billion). The damage in the two regions in the south accounts for 70% of the overall EU damages in monetary terms.



More than half of the overall annual EU damages are due to the additional premature mortality (€130 billion). Damages because of impacts in the coasts (€42 billion) and the agriculture sector (€18 billion) are also quite significant.

Moving to a 2°C world would reduce annual climate damages by €60 billion to €120 billion (1.2% of GDP). There would be a reduction of €34 billion in human health damages, €16 billion in agriculture and €8 billion in coastal areas.

It is also found that climate impacts occurring in one EU region could cross the borders and affect the rest of the EU to a significant extent (around an extra 25-30% impact compared to the original climate impact). As impacts in one region would affect production and welfare elsewhere through trade effects, there seems to be a need for coordination at EU level to ensure an effective level of preparedness across the whole EU territory.

Climate tipping points

An exploratory study was launched within the JRC PESETA II project in order to assess through expert opinion the potential impacts of selected events where the response of the earth system components (e.g. Greenland ice sheet, West Antarctic ice sheet, thermohaline circulation) to climate change may be non-linear. Yet the agreement reached by the experts was not sufficient for a further economic assessment of the consequences of climate tipping points in Europe, due to the difficulty in characterising their biophysical consequences.

Future research efforts could concentrate on the impacts from West Antarctic ice sheet collapse and Greenland ice sheet meltdown as priority areas with a focus on the consequences on the sea level rise.

Further research

Additional research is required on a number of important areas. The inclusion of climate change variability (e.g. the effects of extreme weather events) into the various biophysical impact analyses is not comprehensive. Fundamental climate impacts that are difficult to model might play a key role in the overall estimate of climate damage. They include climate-related migration, the effects on ecosystems services and biodiversity, the possibility of abrupt climate change or climate tipping points, with potentially daunting consequences in Europe's economies and citizens. How all those effects could influence economic growth in the long term is an area that also deserves priority attention. In addition, future research could take a global perspective, as climate impacts in the rest of the world will affect Europe, e.g. via global (agriculture) markets or via migration flows. Generally speaking, uncertainties in climate change and impact modelling remain very large. The depth of uncertainly analysis largely varies across sectors. These uncertainties need to be reduced in order to allow for robust statements regarding overall climate costs and the importance of costs in one sector relative to another.

1 Introduction

Understanding the possible consequences of climate change in Europe matters for designing adaptation policies, intending to minimise negative consequences and maximise positive effects. This report presents the methodology and results of the climate impact assessment of the JRC PESETA II project (Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis). The project economic results have been published in the Impact Assessment accompanying the EU Strategy on Adaptation to Climate Change, 16 April 2013 (European Commission, 2013a).

The objective of the JRC PESETA II project has been to make a multi-sectoral assessment of the impacts of climate change in Europe. This report focuses on the very long term impacts, namely for the 2071-2100 time horizon, referred here to as the 2080s. The project methodology is based on bottom-up biophysical impact models that consider the relationship between climate change and biophysical impacts in a structural way[1]. All biophysical impact models use input data from the same climate scenarios. Indeed, with the proposed disaggregated PESETA methodology high time-space resolution climate data feed highly detailed sector-specific impact models to estimate the biophysical impacts.

A distinctive feature of the assessment relates to the consistent integration of various sectoral impacts within an economic modelling framework, that of multi-sectoral general equilibrium. The comparison of impacts with different metrics can be made within a sound and well-established economic methodological setting.

The project is largely based on the knowledge and experience derived from the previous PESETA project (Ciscar et al., 2011). The JRC PESETA II project goes beyond PESETA as it considers more impact categories and more climate simulations. While PESETA studied the impacts in five areas (agriculture, coastal systems, river floods, tourism and human health), JRC PESETA II extends the coverage to ten areas, adding droughts, energy, transport infrastructure, forest fires, and habitat suitability of forest tree species. Furthermore, in JRC PESETA II up to 15

[1] Ciscar et al. (2012a).

climate simulations have been modelled by some of the sectoral teams (while only 4 climate simulations were studied in PESETA).

The main motivation of launching this series of impact assessments has been to better understand the potential consequences of climate change in Europe in order to derive useful insights for climate change adaptation. A methodological effort has been made to integrate knowledge from the relevant scientific disciplines including physics, engineering, biology and economics.

Most of the impacts and economy modelling work of JRC PESETA II has been made within the Joint Research Centre (JRC) of the European Commission, with the involvement of both the Institute for Prospective Technological Studies (IPTS) and the Institute for Environment and Sustainability (IES).

The report is organized in eight sections, including this introduction. Section 2 presents the main features of the integrated methodology. Section 3 explains the climate simulations used in the project. Section 4 presents the main results in terms of biophysical or direct impacts, that is, from the biophysical models themselves, before their economic integration. Section 5 discusses the main economic impact results. Section 6 deals with the possible non-linear effects of climate change. Section 7 notes a series of caveats and, finally, section 8 presents the main conclusions of this study.

2 Methodology

This section presents the main elements of the methodological backbone of the project. The first subsection explains the integration of the main three components, i.e. climate data, biophysical and economic models. The second subsection deals with the time horizon of the assessment. The third subsection details the specific regions in which the EU member states have been aggregated to present the results. The fourth subsection explains the way adaptation has been treated in the project.

2.1 Overview of modelling integration

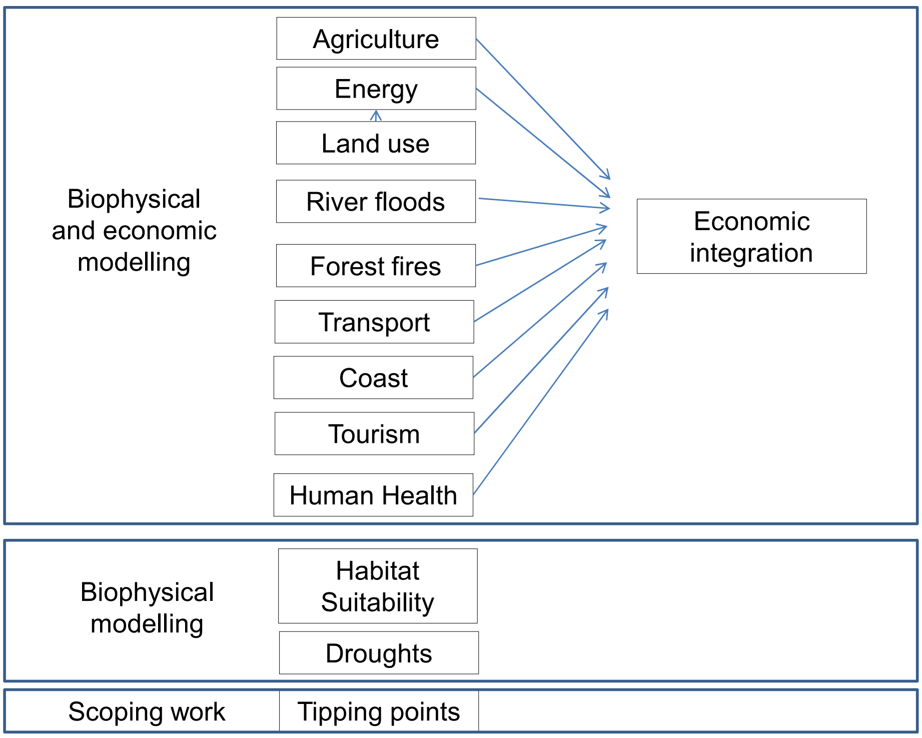
The methodology integrates various disciplines in a series of three steps, following the approach of the PESETA study[2]. In the first step the climate simulations are selected, which provide the primary climate data to all biophysical models. The properties of the selected climate simulations are documented in section 1. In the second stage, the biophysical impact models are run to compute the biophysical or direct impacts generated by each specific climate change simulation. Some of the models also compute impacts in monetary or economic terms, such as the cases of the river floods assessment and of transport infrastructures, which compute the expected economic damage on an annual basis. Methodological details and results of the biophysical assessments for each respective category (e.g. river floods, forest fires) and/or sector (e.g. energy, transport) are provided in section 4. In the third step, the direct impacts are consistently valued in macro-economic terms through their integration into a multi-sector computable general equilibrium model. The results in economic terms are presented in section 5.

Note that there is a conceptual difference between on the one hand the term direct or biophysical impact (which refers to the impacts as computed with the biophysical or bottom-up models) and, on the other hand, economic impact (which relate to the economic effects once the direct effects are integrated into the general equilibrium model).

[2] Ciscar et al. (2011); see also Christensen et al. (2012).

Figure 1 offers an overview of the methodological approach of the project, with two main components or tracks: a modelling track and a scoping track. In the modelling track, the project has made an explicit quantitative modelling of impacts at two levels. For eight impact categories (agriculture, energy, river floods, forest fires, transport, coast, tourism and human health) the biophysical impacts have been estimated and later integrated into an economic framework. The rest of the impact categories (droughts and habitat suitability) have only been analysed in biophysical terms, therefore without integrating the impacts into an economic setup. In the scoping track the potential impacts associated with passing climate tipping points have been studied in a qualitative way (section 6).

Figure 1. Overview of the project



Note that only one biophysical model has been taken into account in each of the impact areas, with the exception of agriculture. Therefore this is not a model inter-comparison project[3]. In the agriculture sector, two models have been considered: one model deals with the very long-term effects (2071-2100) and another one with the short time effects (2020-2030).

[3] There has been a large effort of model inter-comparison in the recently finished ISI-MIP project (see Schellnhuber et al., 2013).

2.2 Time dimension: comparative static framework

Most of the modelling of the project[4] has made an assessment of how future climate could affect the economy as of today (comparative static approach). The time horizon of the climate assessment is the 2080s (2071-2100 period), and also the 2020s (2020-2030 period) in the case of agriculture. The river flood analysis has computed the effects under that comparative static setup and also in a dynamic context, i.e. accounting for the dynamics in the economy and population as defined by the underlying socio-economic scenarios.

Therefore, the project looks at what would be the effects of climate change if the climate of a future period would occur today, under the current socioeconomic conditions. The estimated economic impacts represent a level shift or one-off change in welfare or GDP, and not a change in the growth rates. In other words, in this assessment the possible effects on economic growth due to the impacts on savings and investment decisions are not considered.

The advantage of this counterfactual situation perspective is that the modelling effort can be focused on the impacts of climate change rather than the wider question of how Europe's economy might develop to the period 2070-2100 (2080s). The disadvantage is that by definition the interactions between climate change and economic and population growth are not considered, since climate change is the only shock imposed on the EU economy.

From that perspective, the comparative static approach could be said to underestimate the absolute value of climate impacts because economic growth would notably increase the assets exposed to climate change. Indeed, the approach may also understate or overstate the resilience of the economy. On the one hand, climate-induced technological change (e.g. changes in building standards) may increase the economy's ability to tolerate climate impacts over time. On the other hand, developments that do not take account of climate-related risks (e.g. ill-considered development in areas affected by floods or forest fires) could increase the extent to which physical impacts create economic damage.

[4] The river flood assessment has considered also the influence of population dynamics and economic growth on impacts.

As a test of a dynamic assessment, where the impact of future climate is analysed allowing the economy and land use to change in time, a land use model has been used to study the effects on energy. The dynamic coupling of models has been tested in the linkage land-water-energy, proofing the feasibility of the approach and the potentialities for further multi-sectoral analysis This exploratory work is documented in subsection 4.12.

2.3 Space dimension: European regions

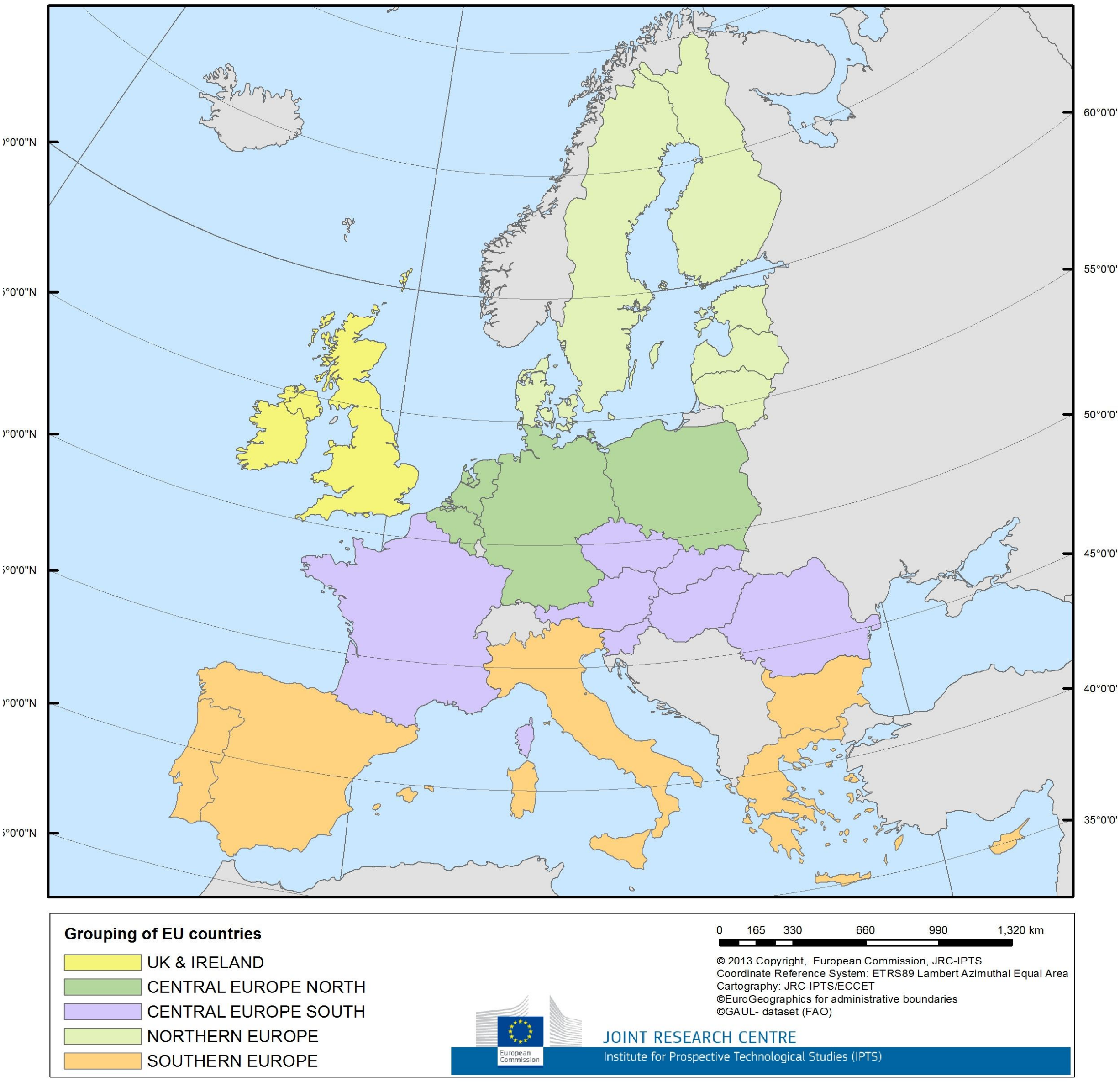
The biophysical impact analysis has been made in most of the EU countries, with the 27 member states at the time the analysis was made. The economic analysis has been made for 24 EU countries, because Luxemburg, Malta and Cyprus could not be modelled in the economic model due to their small economic size.

Following Ciscar et al. (2011), the results are presented dividing the EU into the following regions, according to their latitude and the relative economic size (Figure 2)[5]:

- Northern Europe: Sweden, Finland, Estonia, Lithuania, Latvia and Denmark.
- UK & Ireland: UK and Ireland.
- Central Europe North: Belgium, Netherlands, Germany and Poland.
- Central Europe South: France, Austria, Czech Republic, Slovakia, Hungary, Slovenia and Romania.
- Southern Europe: Portugal, Spain, Italy, Greece and Bulgaria.

[5] Luxemburg, Malta, Cyprus and Croatia are not included in the analysis mainly because they are not single regions in the economic GEM-E3 model.

Figure 2. Grouping of EU countries



2.4 Adaptation dimension

All reported impacts assume that there is no public adaptation, unless otherwise stated. Therefore, the methodology can be useful to understand where to prioritise adaptation policy options. But while promoted by public action is not modelled, except in some specific cases, autonomous adaptation is considered in more sectors.

Adaptation is usually described as action taken in order to moderate harm and exploit beneficial opportunities arising due to climate change (Levina and Tirpak (2006). Iglesias *et al.* (2007) specify several opposing types of adaptation (anticipatory and reactive, private and public, autonomous and policy-driven).

Autonomous adaptation is defined as action "taken naturally" by private actors and therefore includes any response by producers and consumers to climate-induced changes in market prices. This definition is particularly relevant for the current analysis since the response of actors to changing prices is the General Equilibrium effect that is central to CGE analysis[6]. For instance, the changes in energy demand for heating and cooling could be interpreted as autonomous adaptation[7] and, as a consequence, the damage to the energy sector could be understood as the cost of adaptation.

In this context several of the impact categories analysed in this study could themselves be considered forms of adaptation. This is shown in Table 1 where we distinguish between damages that are 'pure' (the immediate effect of climate change, without considering any reaction either by the private or public sectors) and those where some degree of (costed) adaptation is implied within the definition of the damage itself from a private perspective. This analysis does not therefore attempt to model the cost of certain damages in the case of absolutely no adaptation (*e.g.* refusal of people to migrate in response to flood danger, or refusal of authorities to repair the incremental damages to infrastructure that are attributable to climate change). It may be more important to consider this question further in future analysis (especially in poorer regions of the world).

In addition to the approach shown in Table 1 this study considers the effect of additional, explicit adaptation measures in the case of sea level rise and agriculture (in the 2020s and 2030s). Without modelling specific adaptation options, the flood analysis also assessed cost and benefits of adjusting protection levels to potential increases in flood hazard.

[6] The relationship between adaptation and the economic logic of CGE is discussed further in Aaheim et al. (2012).

[7] The increase use of air conditioning in order to avoid the negative consequences of heat on human health could be interpreted as a form of autonomous adaptation.

Table 1. Classification of damages

Impact category	'Pure' Damage	Autonomous Adaptation
Agriculture	Yield change modelled as productivity shock	
Energy	Effect of climate change on power plant efficiency (thermal, wind, hydro)	Temperature change induces demand change
River floods	Capital destruction	
Forest fires	Capital destruction	Cost of restoration
Tourism		Change in holiday destination, duration and frequency
Transport infrastructure	Capital destruction (extreme precipitation) Cost of maintenance and repair	Bridge scour protection, asphalt binder change, rail buckling risk mitigation, SLR
Sea level rise	Capital destruction	Cost of migration

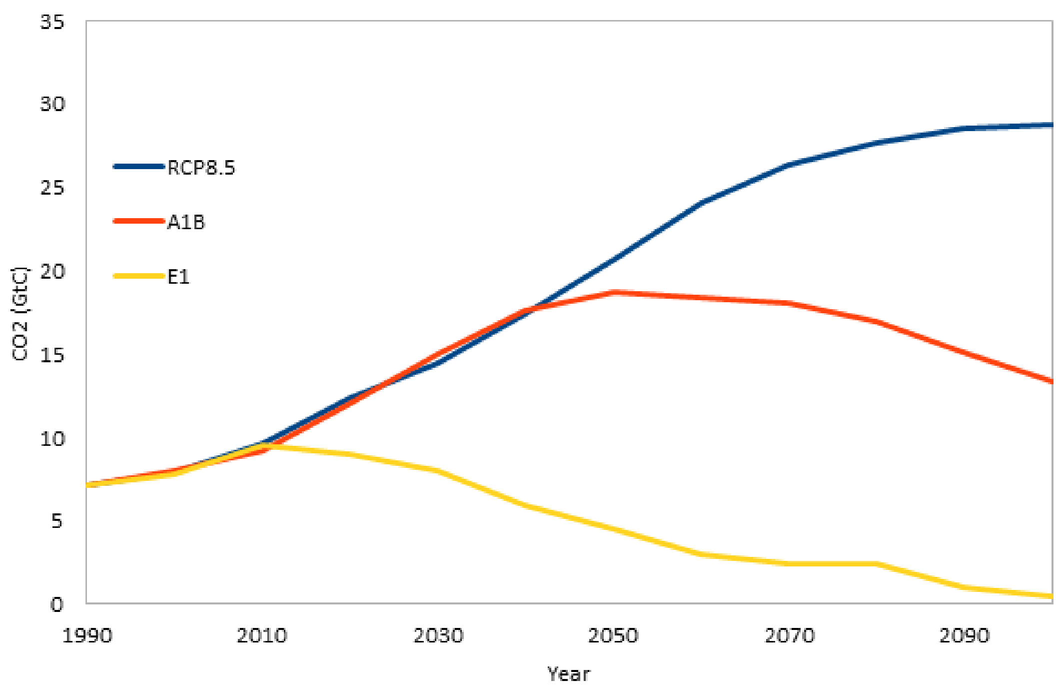
3 Climate change simulations

3.1 Emission scenarios

In this report the term scenario refers to the combination of socioeconomic drivers and GHG emissions projections. The term simulation (or run) refers to a specific combination of a Global Circulation Model (GCM) and Regional Climate Model (RCM) model forced by a given GHG emission scenario.

The JRC PESETA II project used high resolution (~ 25 Km) climate simulations forced by three emission scenarios, namely A1B, E1 and RCP8.5 (see Figure 3). This report focuses on impacts associated with the A1B and E1 scenarios. A1B has been considered as the reference emission scenario and E1 scenario as a scenario in which GHG emissions mitigation action is implemented.

Figure 3. Total CO_2 emission per year (GtC) from the JRC PESETA II scenarios



Source: IPCC SRES (A1B), ENSEMBLES project (E1) and IIASA (RCP8.5).

The IPCC SRES scenarios are based on a set of socio-economic driving forces such as economy, population, technology, energy and agriculture, which drive the change in global greenhouse gases (GHG) emissions. The A1B scenario depicts a future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality (Nakicenovic and Swart, 2000). The global temperature increase (compared to preindustrial levels) of the A1B scenario is roughly 3.5°C[8].

The A1B simulations were obtained from the FP6 ENSEMBLES project (van der Linden and Mitchell, 2009). The core A1B simulations considered in PESETA II (simulations common run by all sectoral models, see subsection 3.3) were selected amongst the 12 simulations listed in Table 2. The simulations used a combination of several global and regional climate models[9] (GCMs, and RCMs, respectively).

In this report the term scenario refers to the combination of socioeconomic drivers and emissions created by the IPCC or RCP classification (either A1B or E1 and RCP8.5 respectively). The term simulation (or run) refers to a specific combination of a GCM and RCM models within a given scenario.

[8] According to the technical summary of WG I of the IPCC AR4, the average of A1B global temperature increase is 2.8°C (2090-2099 over 1980-1999); adding 0.7°C from preindustrial to the 1980s results in 3.5°C temperature increase from pre-industrial to end of the XXI century.

[9] There are three versions of the HadCM3 model with perturbed parameterization impacting the simulated climate response with different sensitivities: Q0 (reference, ETHZ-CLM-HadCM3 and METO-HadRM3-HadCM3), Q3 (low-sensitivity, SMHI-RCA-HadCM3) and Q16 (high-sensitivity, C4I-RCA-HadCM3) (see Collins et al., 2006).

Table 2. Climate change simulations from the A1B scenario (25 km resolution)

Acronym	RCM	GCM
C4I-RCA-HadCM3	RCA	HadCM3
CNRM-ALADIN-ARPEGE	ALADIN	ARPEGE
DMI-HIRHAM5-ARPEGE	HIRHAM5	ARPEGE
DMI-HIRHAM5-BCM	HIRHAM5	BCM
DMI-HIRHAM5_ECHAM5	HIRHAM5	ECHAM5
ETHZ-CLM-HadCM3Q0	CLM	HadCM3Q0
KNMI-RACMO2-ECHAM5	RACMO2	ECHAM5
METO-HadRM3Q0-HadCM3Q0	HadRM3Q0	HadCM3Q0
MPI-REMO-ECHAM5	REMO	ECHAM5
SMHI-RCA-BCM	RCA	BCM
SMHI-RCA-ECHAM5	RCA	ECHAM5
SMHI-RCA-HADCM3Q3	RCA	HADCM3Q3

The E1 scenario was specifically developed within the ENSEMBLES project as an attempt to match the European Union target of keeping global anthropogenic warming below 2°C above pre-industrial levels, following a methodology used earlier to develop low stabilization scenarios from B2 baseline (Van Vuuren et al, 2007).

Three simulations of E1 scenario (listed in Table 3) were performed by MPI (Max-Planck-Institute for Meteorology, Germany). While the A1B simulations were produced by a combination of different GCMs and RCMs, the E1 simulations were obtained by downscaling, with a single RCM, one simulation of the ECHAM5 model, using three different sets of initial conditions defined as "-r1", "-r2", and "-r3" (see Kendon et al., 2010). Thus the range of considered E1 simulations may capture much less uncertainty in future climate than in the case of the A1B simulation.

Table 3. Climate change simulations from the E1 scenario (50 km resolution)

Acronym	RCM	GCM
MPI-REMO-ECHAM5-r1	REMO	ECHAM5 (BC r1)
MPI-REMO-ECHAM5-r2	REMO	ECHAM5 (BC r2)
MPI-REMO-ECHAM5-r3	REMO	ECHAM5 (BC r3)

The Representative Concentration Pathways (RCP's) represent a new set of scenarios developed for the IPCC 5th assessment report, with a range of radiative forcing values in the year 2100 (+2.6, +4.5, +6.0, and +8.5 W/m^2). The RCP8.5 scenario (with a radiative forcing value of +8.5 W/m^2) combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long term to high energy demand and GHG emissions in absence of climate change policies. RCP8.5 thus corresponds to the pathway with the highest greenhouse gas emissions, without any specific climate mitigation target. The RCP8.5 simulation was performed at DMI (Danish Meteorological Institute) as part of the ClimateCost FP7 project.

3.2 Bias correction

By using the outputs of CGMs as boundary and initial conditions, limited-area, high-resolution regional climate models (RCMs) are usually applied in order to obtain fine-resolution information that is essential to assess the impact of climate change, especially in regions of complex topography, or with highly heterogeneous land-cover. This technique is usually referred to as dynamical downscaling

The main 'added value' in the use of RCMs is in their ability to resolve small-scale features especially when the surface is the main forcing in generating atmospheric variability. However, as RCMs are not able to improve the simulation skills of large-scale fields over those simulated by the GCMs, the dynamically downscaled climate may still present large errors, when compared to observations. In fact, the errors inherited from the driving GCM, add up to those introduced by the RCM by means, for instance, of model errors and parameterizations (e.g. Fowler et al., 2007).

For instance, several studies show that modelled summer temperatures in Southern Europe are usually overestimated (e.g. Christensen et al., 2008), while large biases exist for precipitation, particularly in Northern Europe (Kjellström et al., 2010).

The existence of these biases needs to be taken into account when using the outputs of climate models in the assessment of weather driven impacts. The influence of such biases on hydrological modelling has been thoroughly investigated by e.g. Teutschbein and Seibert (2010), who claimed that unless models' outputs are corrected, their application to impact models may be unrealistic.

Consequently, all the climate simulations used in the JRC PESETA II study were corrected for biases in maximum, average and minimum temperatures and precipitation following the procedure discussed by Dosio and Paruolo (2011) and Dosio et al. (2012).

Here, a brief description of the technique is reported. More details can be found in the original description of the bias correction by Piani et al (2010).

Let x_t denote the time series of an observed climate variable, where t is time (i.e. days), and $x_{mod,t}$ the prediction of a climate model for the same variable. The bias correction is based on the calculation of a transfer function G (henceforth referred to as TF) which, when applied to model predictions $x_{mod,t}$ delivers the corrected prediction $x_{cor,t}$

$x_{cor,t} = G(x_{mod,t})$,

such that the marginal probability density function (PDF) of $x_{cor,t}$ matches that of the observed measurement x_t. The TF is estimated parametrically as a function of up to 4 parameters, using the following functional forms:

$$x_{cor,t} = a + bx_{mod,t} \quad (1)$$

$$x_{cor,t} = (a + bx_{mod,t})\,(1-\exp(-(bx_{mod,t} - x_0)/\tau)) \quad (2)$$

where, a, b, x_0 and τ are parameters. The functional form (1) is used for temperature, while (2) is used for precipitation. The parameters of the TF (1)–(2) are estimated by ordinary least squares on sorted values of x_t and $x_{mod,t}$ in a given month m, so that monthly TFs are produced, which are in turn interpolated into daily values.

Bias correction parameters are calculated for the period 1961-1990 by employing the E-OBS dataset (Haylock et al., 2008). A 30-year period was chosen in order to take longer climate variability (e.g. decadal) into account. As pointed out by Piani et al. (2010), since the bias is defined as the portion of error that is constant in time, if the bias correction is constructed over shorter periods of time (e.g. a single decade) the component of the error linked to decadal variability may not be removed.

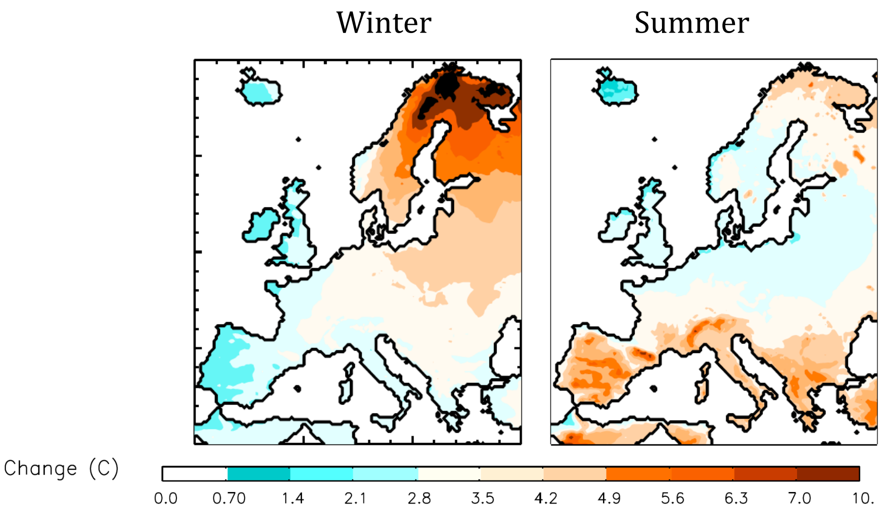
A thorough evaluation of the technique is reported in Dosio and Paruolo (2011) and Dosio et al. (2012), who show that the bias correction technique performs successfully for all variables over large part of the European continent, for all seasons. In particular, PDFs of both temperature and precipitation are greatly improved by the bias correction, especially at the ends of the distributions, i.e. increasing the capability of reproducing extreme events. In addition, the bias correction technique is also able to improve statistics that depend strongly on the temporal sequence of the original field, such as the number of consecutive dry days and the total amount of precipitation in consecutive heavy precipitation episodes, which are quantities that may have a large influence on, e.g., hydrological or crop impact models. For instance, Rojas et al., (2011) showed that by using the bias correction technique, the simulation of extreme hydrological events with LISFLOOD, (which are the basis for the flood assessment in PESETA II), were considerably improved.

Figure 4 and Figure 5 show the geographical distribution of mean summer and winter temperature and precipitation climate change signal (i.e. the difference between the period 2071-2100 and the control period 1961-1990) as simulated by the ensemble of the 12 A1B (bias corrected) simulations. These results are in accordance with those from the ENSEMBLES final report (van der Linden and Mitchell, 2009) and show a general warming up by more than 4°C in Northern Europe in winter and in Southern Europe in summer.

Daily precipitation change at the end of the century shows a general positive trend in winter (with the exception of parts of the Iberian Peninsula, Southern Italy and Greece), with the increase over Northern Europe and Scandinavia ranging between

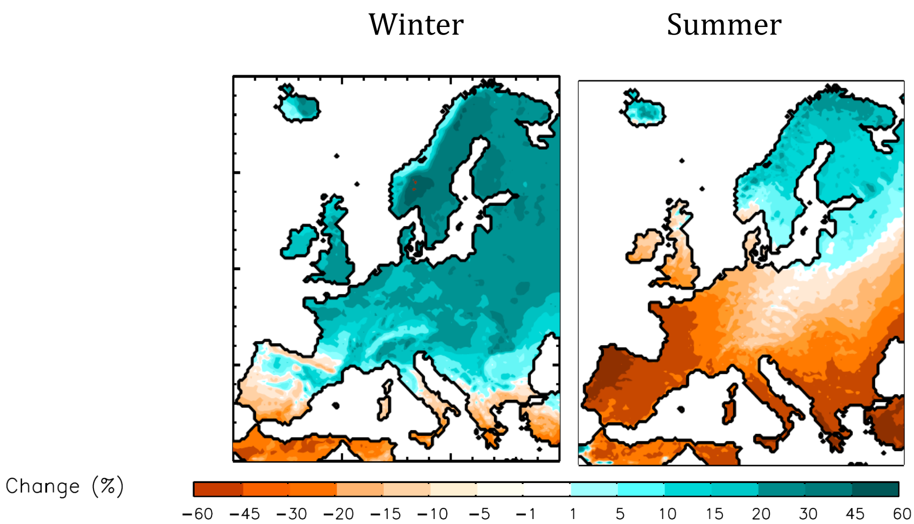
20% and 45%. However, over Middle, Southern, and Eastern Europe, the value (and in some cases also the sign) of the change depends strongly on the model. In summer, Southern Europe will face a reduction in precipitation up to more than 40%. Over great part of Central and Eastern Europe, however, the value of the change is small (less than 15%) and comparable to the value of the inter model variability (Dosio et al., 2012).

Figure 4. Mean seasonal climate change signal (°C) for bias corrected temperature under the A1B scenario



Source: Dosio et al. (2012)

Figure 5. Mean seasonal climate change signal (%) for bias corrected daily precipitation under the A1B scenario



Source: Dosio et al. (2012)

3.3 Core and additional climate simulations

All the models' simulations driven by the same emission scenario represent an equally probable projection of the future evolution of the climate. However, due to differences in the models' formulation and physical parameterization, the climate change signal projected by different climate models may present significant differences.

Although the use of the entire ensemble would obviously be preferable, many impact models are too expensive to be run by using as an input the entire set of climate simulations.

By selecting a subset of models that represent both the mean climate change signal and the most extreme deviations from it, one assumes that the main statistical properties of the whole ensemble of simulations are conserved[10].

Therefore, the JRC PESETA II study considered four core climate simulations:

- **Reference Simulation**. This simulation represents the main characteristics of the entire ensemble of 12 A1B simulations. This simulation can be interpreted as business-as-usual scenario, as it does not entail significant mitigation efforts.

Two additional A1B simulations were selected that show significant deviations from the ensemble averaged climate change signal:

- **Reference Variant 1**. It shows a climate change signal that is warmer and drier than the average;

- **Reference Variant 2**. It shows a climate change signal that is colder and wetter than the average;

- The **2°C Simulation**. This simulation is driven by the E1 scenario and is used to illustrate the future impacts in case of global mitigation efforts.

The combination of climate models chosen for each core simulation[11] is shown in Table 4.

[10] It must be acknowledged that if even this is a pragmatic approach, it will under-sample potential model candidates and as such uncertainty will be underestimated.

[11] The agriculture simulations refer to the 2080s assessment, and the climate data come from the ClimateCost project (Christensen et al., 2011).

Table 4. Climate models chosen for the JRC PESETA II core simulations

Core simulation	Climate Models Employed	
	All other impacts	Agriculture 2080s
Reference simulation	A1B KNMI-RACMO2-ECHAM5	A1B ECHAM5 (UKMO)
Reference Variant 1	A1B METO-HC-HadRM3Q0-HadCM3Q0	A1B ECHAM5 (DMI)
Reference Variant 2	A1B DMI-HIRHAM5-ECHAM5	A1B EGMAM2006 (FUB)
2°C simulation	MPI-REMO-E4	E1 ECHAM5.4 (MPI)

Table 5 summarises the climate simulations considered for each study. The specific climate models of each climate simulation are explained in section 1.

Table 5. Climate simulations in each impact area of the study[12]

Impact category	Climate simulations				
	Reference simulation	Reference variant 1	Reference variant 2	2°C Simulation	Additional simulations
Agriculture (2020-2030)		X	X		
Agriculture (2080s)	X	X	X	X	
Energy	X	X	X	X	All other
River floods	X	X	X	X	All other
Droughts	X	X	X		All other A1B
Forest fires	X	X	X	X	
Transport infrastructure	X	X	X	X	RCP8.5
Sea level rise	X			X	
Tourism	X	X	X	X	All other
Habitat suitability of forest tree species	X	X	X	X	
Human Health	X	X	X	X	

Source: JRC PESETA II project

[12] The simulations for agriculture 2080s and sea level rise are derived from climate models that are different from the other impact sectors. The agriculture 2080s simulations come from global circulation models, and are not bias corrected (see Table 4 for the mapping of climate simulations). For sea level rise, the DIVA model does not use the same circulation models, but considers the sea level rise consistent with the A1B and E1 scenarios (see Table 4). See Chapter 3.3 for details.

The selected simulations show a significant variability in the evolution of the mean climate for both temperature and precipitation (Figure 6). The temperature increase from the control period[13] (1961-1990) until the 2080s varies between 2.4°C and 3.9°C, with values of 3.1°C and 2.4°C for the reference simulation and the E1 simulation, respectively (see Table 6). The warming is highest in the Northern Europe region (even by 0.5°C to 1°C warmer than Southern Europe), and lowest in the UK & Ireland region, for all climate simulations.

Table 6. Temperature change (°C) in climate simulations for 2071-2100, compared to 1961-1990

	Reference	Reference variant 1	Reference variant 2	2°C
Northern Europe	3,8	4,8	3,4	3,2
UK & Ireland	2,1	2,9	1,7	1,4
Central Europe north	2,8	3,7	2,0	2,1
Central Europe south	3,0	3,8	2,0	2,1
Southern Europe	3,2	3,7	2,4	2,3
EU	**3,1**	**3,9**	**2,4**	**2,4**

The overall change in precipitation (Table 7) is relatively small on a yearly basis for Southern Europe, whereas all simulations simulate higher precipitation at the end of the Century for Northern Europe.

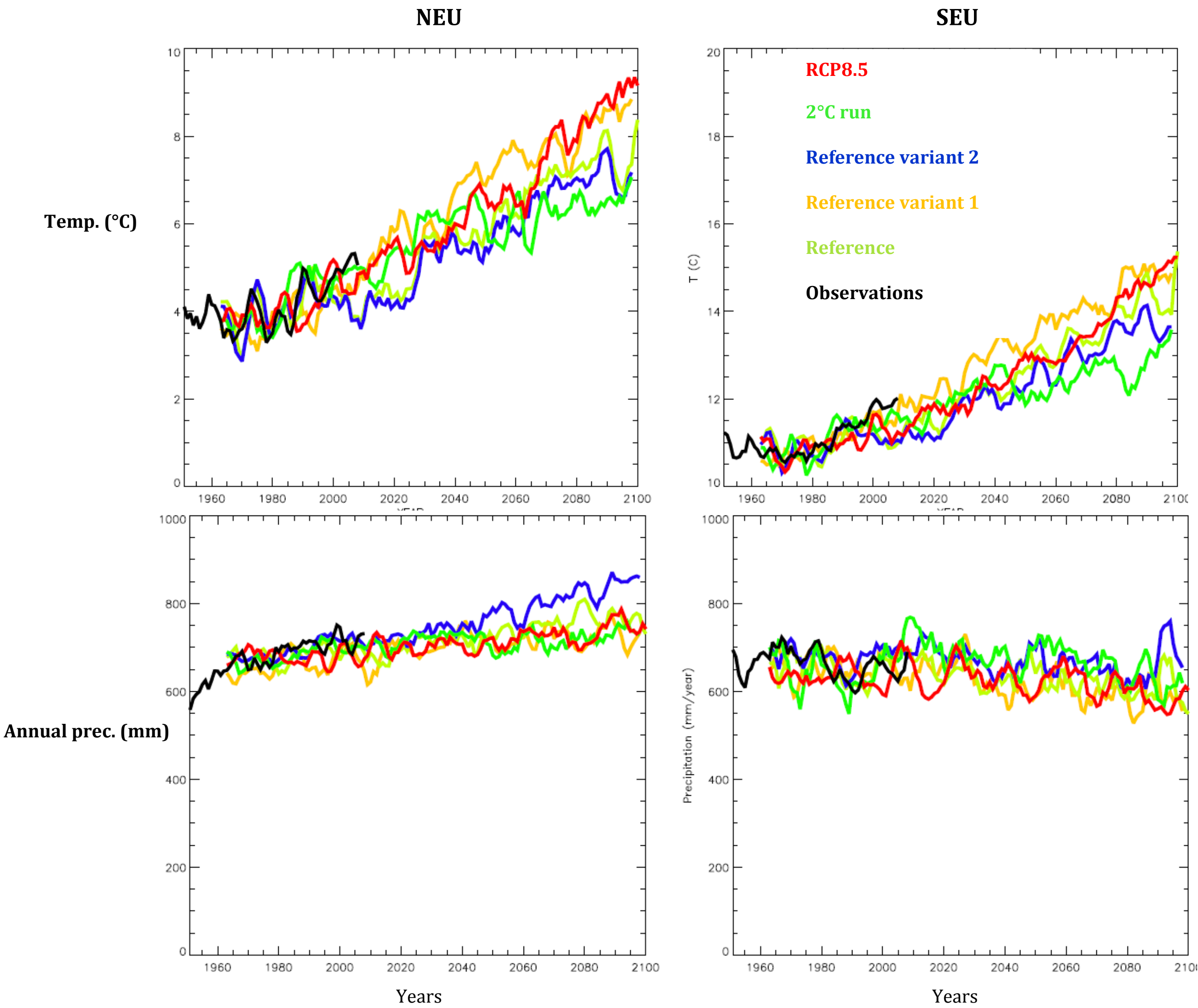
Table 7. Precipitation change (%) in climate simulations for 2071-2100, compared to 1961-1990

	Reference	Reference variant 1	Reference variant 2	2°C
Northern Europe	18	16	21	11
UK & Ireland	8	2	12	7
Central Europe north	8	1	15	3
Central Europe south	0	-7	5	-3
Southern Europe	-19	-14	-14	-14
EU	**1**	**-2**	**6**	**-1**

Annex 1 documents the temperature and precipitation variables for all the climate simulations considered in the JRC PESETA II study.

[13] Compared to the pre-industrial level the global temperature increase in 1961-1990 would be about 0.3°C.

Figure 6. Temperature and precipitation projections of the selected simulations for Northern Europe (NEU) and Southern Europe (SEU)



Note: Mean annual temperature (°C) and precipitation (mm/year) projections of the selected simulations. NEU (SEU) defined as land points with latitude higher (lower) than 50N.

Temperature and precipitation changes, however, are seasonally and geographically very heterogeneous. Table 8 shows values[14] of seasonal (winter and summer) temperature change (°C), as simulated by the core simulations, spatially averaged over the different regions. Generally the warming is highest in Northern Europe (NEU) in winter and in Southern Europe (SEU) in summer. Values vary greatly depending on regions and seasons but, generally, the Reference Variant 1 case

[14] The values reported refer to the climate simulations of the first column in Table 4.

projects the warmest climate change signal with temperature increase up to 4.5°C in winter for Northern Europa and 4.6°C for Central Europe South in summer. The 2°C scenario shows, on average, a temperature increase significantly smaller than all the A1B simulations, in winter, and similar to the Variant 2 simulation in summer. At continental level (EU) the increase is limited to 2.7°C in winter and 2.4°C in summer.

Table 8. Seasonal (winter and summer) temperature change (°C) for 2071-2100, compared to 1961-1990, as simulated by the core simulations

Winter	Reference simulation	Reference Variant 1	Reference Variant 2	2°C simulation
Northern Europe	4.1	4.5	4.3	3.3
UK & Ireland	1.8	2.4	2.2	1.4
Central Europe North	3.2	3.6	3.2	2.0
Central Europe South	3.5	4.1	3.3	2.5
Southern Europe	2.9	3.3	2.8	1.7
EU	3.5	4.0	3.6	2.7

Summer	Reference simulation	Reference Variant 1	Reference Variant 2	2°C simulation
Northern Europe	2.8	4.2	1.7	2.1
UK & Ireland	2.4	3.2	1.9	1.8
Central Europe North	3.1	3.6	0.9	2.2
Central Europe South	3.1	4.6	1.4	1.8
Southern Europe	3.9	4.2	2.8	2.6
EU	3.3	4.2	2.2	2.4

Table 9 shows values of seasonal (winter and summer) precipitation change (%), as simulated by the core simulations. In winter, all simulations show an increase in projected precipitation, a part for the 2°C scenario, which shows a slight decrease (-6.5%) over Southern Europe. The largest precipitation increase is found in Central Europe South for the Reference Variant 2 case (+31.5%), whereas over Southern Europe a very small change is expected, at the end of the century, compared to the 1961-1990 period.

Summer precipitation is projected to largely decrease in Southern Europe, according to all simulations. Larger discrepancies exist over the remaining regions, where the

Reference Variant 2 case shows a general increase in precipitation, in contrast to the other A1B and the 2°C simulations.

Table 9. Seasonal precipitation change (%) in climate simulations for 2071-2100, compared to 1961-1990, as simulated by the core simulations

Winter	Reference simulation	Reference Variant 1	Reference Variant 2	2°C simulation
Northern Europe	20.4	22.8	27.8	13.2
UK & Ireland	17.4	10.2	15.1	1.5
Central Europe North	29.3	13.5	25.2	11.9
Central Europe South	28.1	30.5	31.5	12.4
Southern Europe	4.2	1.6	1.0	-6.5
EU	12.2	11.8	14.1	1.6

Summer	Reference simulation	Reference Variant 1	Reference Variant 2	2°C simulation
Northern Europe	0.7	-4.8	14.8	0.15
UK & Ireland	-6.1	-14.5	6.1	-6.5
Central Europe North	-14.5	-12.1	11.0	-9.6
Central Europe South	-19.4	-24.4	4.8	-7.8
Southern Europe	-34.9	-30.2	-18.7	-20.9
EU	-10.1	-12.8	4.4	-6.3

The difference amongst the core simulations in the geographical distribution of seasonal temperature and precipitation change is shown in

Figure 7 and Figure 8, respectively. Projected temperature and precipitation increase (decrease) varies significantly even amongst the three simulations forced by the same A1B emission scenario. For instance, the Reference Variant 2 shows generally the coldest climate change signal, whereas the Reference Variant 1 the warmest one, especially in summer, although strong local variations exist (e.g. over Spain in summer).

Differences in the precipitation signal are more evident in summer, especially over Central and Eastern Europe, where the Reference Variant 2 predicts an increase in precipitation, whereas the Reference Simulation and the Reference Variant 1 simulations show the strongest negative signal.

Figure 7. Seasonal (winter and summer) temperature change (°C) for 2071-2100, compared to 1961-1990, as simulated by the core simulations

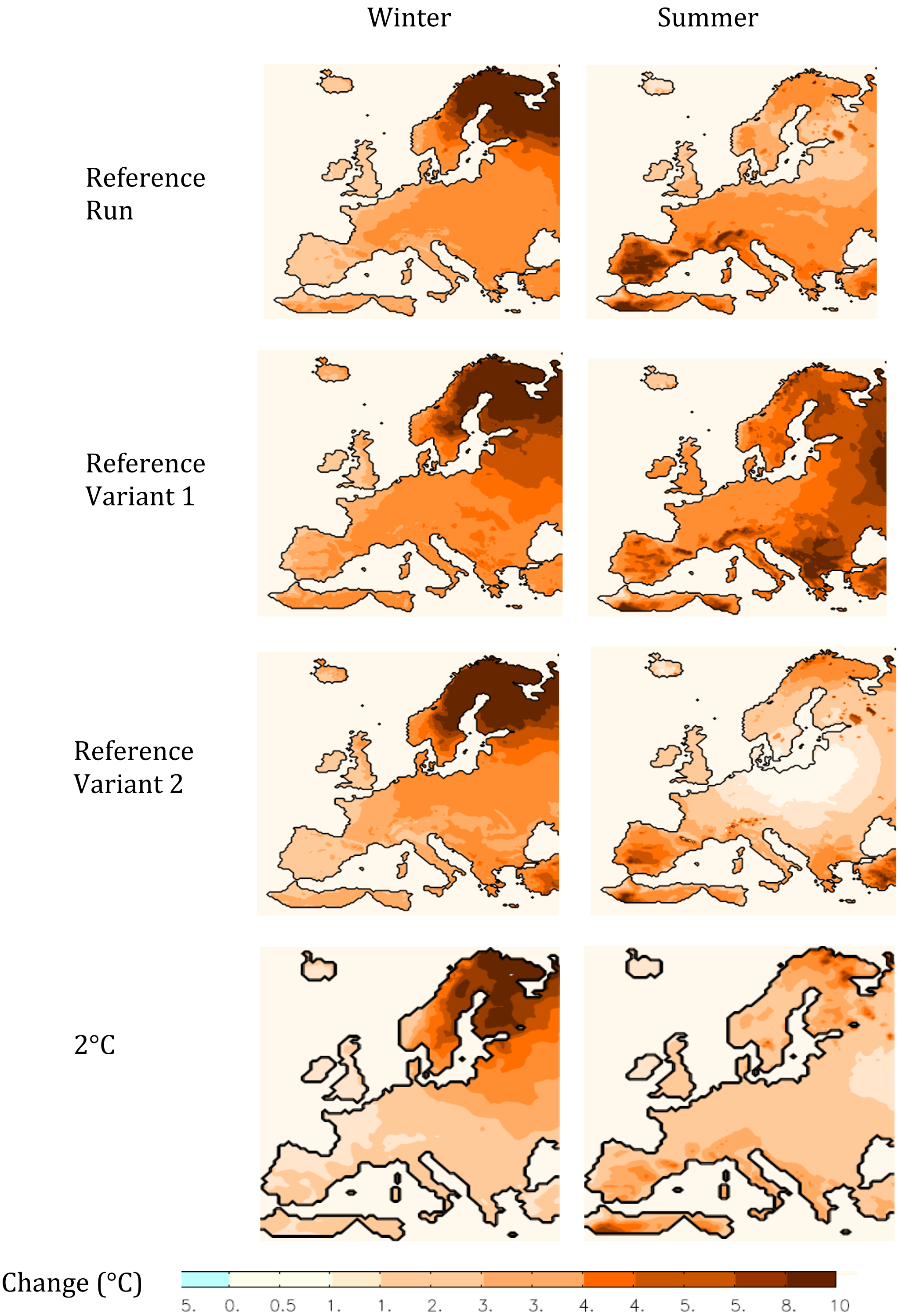


Figure 8. Seasonal precipitation change (%) in climate simulations for 2071-2100, compared to 1961-1990, as simulated by the core simulations

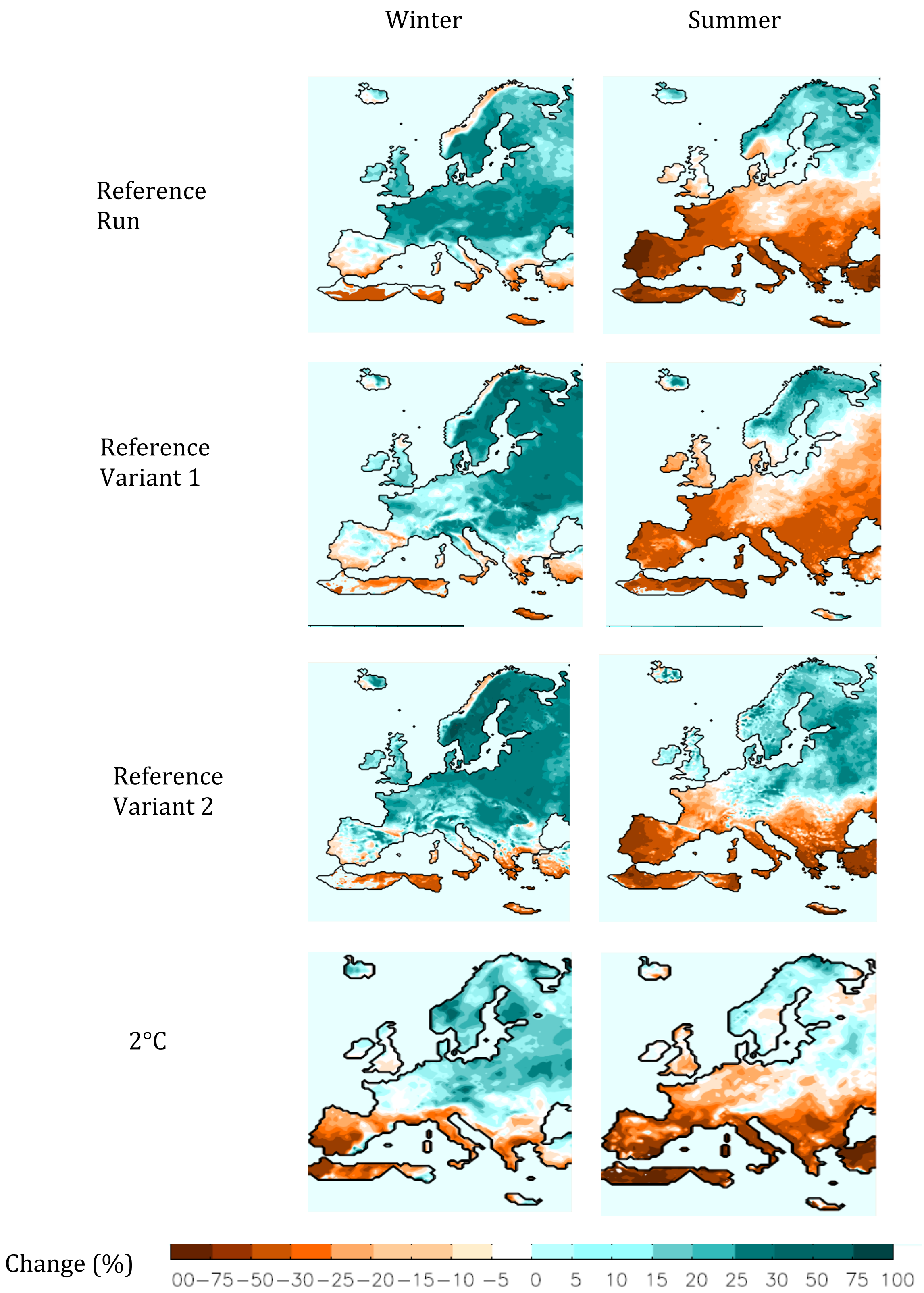
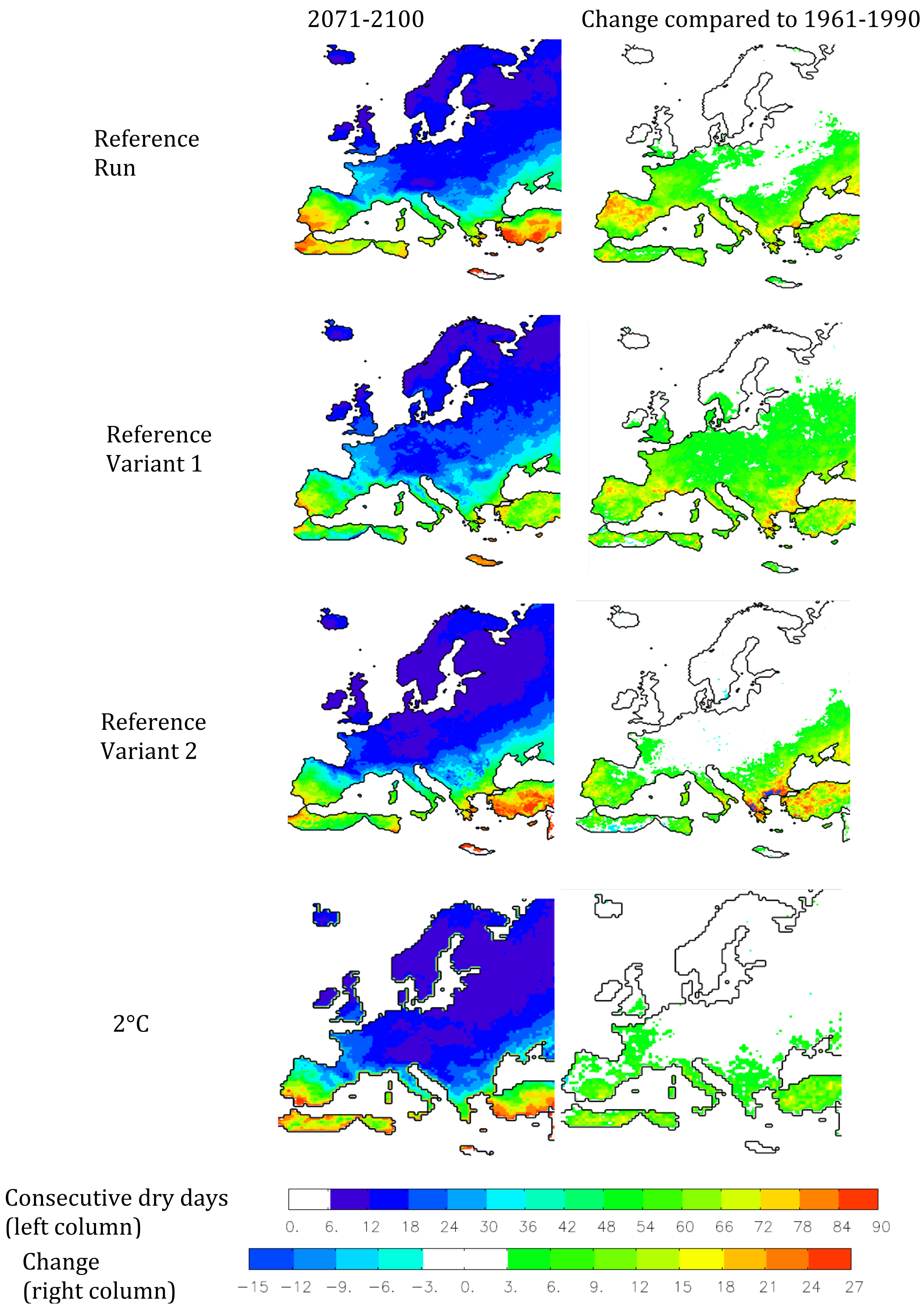


Figure 9. Number of consecutive dry days, for 2071-2100 (summer), and its change compared to 1961-1990, as simulated by the core simulations



The importance of inter model variability is evident not only for the mean climate change signal, but also for extreme events, such as the number of consecutive dry days (CDD: i.e., days with daily precipitation less than 1mm), which may have a large influence on, e.g., hydrological or crop impact models.

Results (Figure 9) show that, for the Reference Variant 1 simulation, a significant increase in the number of CDD is expected over large areas of Europe, including Central and Eastern Europe. On the contrary, the Reference Simulation shows a marked increase (more than 15 days) of CDD over Spain, and the Reference Variant 2 an increase especially over Greece and Turkey.

Summarizing, it is clear that climate models may predict very dissimilar changes in seasonal temperature and precipitation rate, even when driven by the same emission scenario. This inter model variability must be taken into account when using climate projections for impact assessment studies. However, the choice of simulations that maximise the model variability is highly subjective and it depends on many factors, including the variable, the season and the geographical area.

3.4 Climate data input for the biophysical impact models

Table 10 details the specific climate variables that have been used in each of the project sectoral studies. The coastal assessment only used sea level rise as a climate input. Most studies have used daily climate variables. While some sectors have considered a wide range of climate variables (e.g. river floods and agriculture), other sectors have required fewer variables (e.g. human health).

It is interesting to note the richness of climate variables and high resolution used in the biophysical models, compared to the approach used in top-down models that use damage functions, usually only taking into account global average temperature (Ciscar et al., 2012a).

Table 10. Climate data input for the biophysical models

Sector	Input variables	Time resolution	Spatial Resolution
Agriculture	Maximum air temperature	Daily	25*25, 50*50 Km^2
	Minimum air temperature		
	Total Precipitation		
	Global solar radiation		
	Air relative humidity maximum and minimum		
	Wind speed		
	Reference evapotranspiration		
	Vapour pressure deficit		
Energy	Average Temperature	Daily	Country
	Average Precipitation		
	Wind Speed		
River Floods, Droughts	Maximum, Minimum and Average Temperature	Daily	25*25, 50*50 Km^2
	Precipitation		
	Humidity		
	Windspeed		
	Solar + thermal radiation		
	Albedo		
	Dewpoint temperature		
Forest Fires	Average Air Temperature	Annual	25*25, 50*50 Km^2
	Relative Humidity		
	Wind Speed		
	Average Precipitation		
Transport infrastructure	Average Temperature	Daily	25*25, 50*50 Km^2
	Maximum Temperature		
	Extrene Precipitation		
Tourism	Average Temperature, wind speed, precipitation and humidity	Daily	NUTS 2 Regions
Forest Species Habitat Suitability	Average Temperature	Annual; Monthly	25*25, 50*50 Km^2
	Maximum Temperature	Monthly	
	Minimum Temperature	Monthly	
	Average Precipitation	Annual; Monthly	
Human Health	Maximum Temperature (June-September)	Daily	NUTS 2 Regions
	Average Temperature		

3.5 Sea level rise scenarios

The sea level rise (SLR) projections come from the ClimateCost project (Brown et al. 2011). For the A1B scenario, the medium projection for SLR (compared to the year 2000) in the 2080s is 30 cm, and 18 cm for the E1 medium projection. The respective values for SLR in 2100 are 37 cm and 26 cm. The coastal impacts considered in this report relate to the SLR by the 2080s (see Table 11).

Table 11. Sea level rise scenarios (cm)

Simulations	Variants	2080s	2100
Reference simulation	Low	22	26
	Medium	30	36
	High	38	48
2°C simulation	Low	12	13
	Medium	18	21
	High	25	29

Source: Brown et al. (2011), Figure 2

4 Biophysical impacts: methodologies and results

Changes in climatic conditions are converted into biophysical impacts, and in some cases into damage costs, using a number of specific assessments undertaken as part of the JRC PESETA II and ClimateCost projects. This section presents for each of the biophysical impact areas both the bottom-up methodology and the main results. The chapter provides an overview of the essential elements of each biophysical impact assessment in order to interpret the results. Further details on the methodology and results can be found in the references provided in the respective subsections. The term biophysical impact refers to the outcome of the biophysical impact. It is equivalent to the term direct impact in this report.

The following climate impact categories have been considered in the biophysical assessment: agriculture, energy, river floods, droughts, forest fires, transport infrastructure, coastal areas, tourism, habitat suitability of forest tree species, and human health.

Table 12 provides an overview of the models and academic references for each of the assessments. Table 13 details the kind of output from each model (whether it is in biophysical or economic units, and whether it has been integrated into the economic model). Note that all results are in annual terms.

Table 12. Model and related references for the biophysical impacts

Impact category	Model	Reference
Agriculture (2020-2030)	BioMA-CropSyst	Donatelli et al. (2012b)
Agriculture (2080s)	DSSAT	Iglesias et al. (2012)
Energy	POLES	Dowling (2013)
River floods	LISFLOOD	Rojas et al. (2013)
Droughts	LISFLOOD	Forzieri et al. (2014)
Forest fires	Fire Weather Index (FWI) system	Camia et al. (2013)
Transport infrastructure	Engineering-based damage functions and cost estimates	Nemry and Demirel (2012)
Coasts (Sea level rise)	DIVA	Brown et al. (2011)
Tourism	Econometric	Barrios and Ibañez (2013)
Habitat suitability of forest tree species	Process model	de Rigo et al. (2013a)
Human Health	Exposure-response functions	Paci (2014)

Source: JRC PESETA II project

Unless otherwise stated, the results of the simulations regarding the 2080s refer to the average of the 2071-2100 period, as compared to the control period (usually 1961-1990)[15].

[15] Some of the warming between the control and future periods has already occurred, so the computed effects are looking at somehow larger change than one would see compared to today.

Table 13. Kind of impacts in each impact area of the project

Impact category	Impact from the biophysical model		Impacts into the CGE model
	in biophysical units	in economic units	
Agriculture	Crop yields (t/Ha)		Yes
Energy	Households and service sector heating and cooling demand (toe)		Yes
River floods	People affected	Expected annual damage (€)	Yes
Droughts	Expected Cropland affected (1000s km^2/year), Expected People affected (million/year)		No
Forest fires	Burnt area (ha)	Restoration cost (€)	Yes
Transport infrastructure		Costs of asphalt and of bridge scouring (€) Costs of flooding and winter conditions (€) Potentially inundated roads due to sea level rise and sea storm surges (km)	Yes
Coasts (Sea level rise)		Sea floods (€) Migration costs (€)	Yes
Tourism		Tourism expenditure (€)	Yes
Habitat suitability of forest tree species	Index of habitat suitability (100)		No
Human Health	Mortality (number of deaths)		Yes

Source: JRC PESETA II project

4.1 Agriculture 2080s

Agriculture impacts in terms of crop productivity changes are simulated for two time horizons (2020s-2030s and 2080s) with different agriculture models. Regarding the 2080s, the impacts are simulated with the DSSAT model, using the results from the FP7 ClimateCost project. Process-based crop responses to climate and management are simulated by using the DSSAT crop models for wheat, maize, and soybeans[16] (see Iglesias et al. 2012). The models simulate daily phenological development and growth in response to environmental factors (such as climate, including the effect of CO_2) and management (considering crop variety, nitrogen fertilization and irrigation). The approach used statistical models of yield response to environmental variables and management variables for specific sites. Farm level adaptation has been considered in the following ways: planting date, nitrogen fertilizer, and water for irrigation. The main output of the 2080s assessment is the agriculture yield change.

Table 14 shows the agriculture yield changes. Under the Reference scenario they are negative for the EU (11%), while there are productivity gains in the Northern Europe region (21%) and the Central Europe South region (2%). The region with the highest fall in agriculture yields is Southern Europe (20%). Under the 2°C scenario, EU agriculture yields barely change (a fall of 2%). While the estimated regional pattern is similar to that of the Reference scenario, for the UK & Ireland region there is a substantial difference, with a doubling of yield under the E1 simulation.

Table 14. Impact on agriculture yields

	EU	Northern Europe	UK & Ireland	Central Europe North	Central Europe South	Southern Europe
Control	100	100	100	100	100	100
Reference	89	121	98	91	102	80
change (%)	-11	21	-2	-9	2	-20
2°C	98	132	201	97	102	82
change (%)	-2	32	101	-3	2	-18

Units: index = 100 in control period

4.2 Analysis of impacts on agriculture (2020-2030), including an evaluation of adaptation measures

Within JRC PESETA II a second assessment of agriculture impacts has been made for the 2020s and 2030s, in comparison to a baseline centred on the year 2000, on the basis of the CropSyst crop model implemented within the BioMA modelling platform at JRC. This assessment is complementary to the one of the ClimateCost project on the 2080s and provides useful additional information at 25km x 25km resolution for

16 Livestock production is not considered in the agriculture assessment.

Europe. It also allows for the analysis of chosen adaptation measures to mitigate negative effects on crop yield.

The effects of climate change on crop yield were estimated in the BioMA modelling platform[17], which simulates interactions between crop, soil, weather and agro-management. This included considering the effect of climate change with and without adaptation options, which consisted of using different plant varieties, different planting times and expansion of irrigation (for maize only) (Donatelli *et al.* 2012b). The BioMA-based results were then fed into CAPRI, a partial equilibrium model of global agriculture, which considered the effect on land use and incomes in the EU, both with and without price changes in the rest of the world (Shrestha *et al.* 2012).

The analysis has been made for two A1B climate simulations: a "warm" (Reference Variant 1 in Table 4, METO-HC-HadRM3Q0-HadCM3Q0 simulation, or Hadley) and a "cold" (Reference Variant 2 in Table 4, DMI-HIRHAM5-ECHAM5 simulation, or ECHAM) simulation with regard to the air temperature development, averaged over Europe. The two simulations differ considerably also regarding the development of precipitation, especially in the Mediterranean region. A large part of the variability within all A1B simulations (chapter 3.3) is comprised with the two chosen simulations, thus defining a corridor of plausible outcomes for the subsequent crop growth model simulations. The analysis was run on the main European crops: wheat, rapeseed, grain maize, and sunflower.

The climate data of the selected climate simulations have been post-processed to render all meteorological parameters consistent and realistic at a daily time step, and to allow for a sufficient sample size on the target horizons 2000 (baseline), 2020, and 2030. Air temperature and precipitation were taken from the climate scenarios provided. Global radiation, wind speed, and air humidity were either not consistent or not available in the climate scenarios and therefore had to be estimated separately on the basis of 1996-2005 observations, as taken from the MARS meteorological database (WikiMCYFS 2013). In order to reflect the variability around the trend of the climate scenarios, a weather generator was used, increasing the sample size and creating 30 synthetic sample years around each of the three

[17] http://bioma.jrc.ec.europa.eu/

horizons 2000, 2020, 2030. For each of the synthetic years the crop growth model CropSyst was run separately and results were subsequently combined in order to receive information on the average conditions around the time horizons envisaged (see Donatelli et al. 2012b for details).

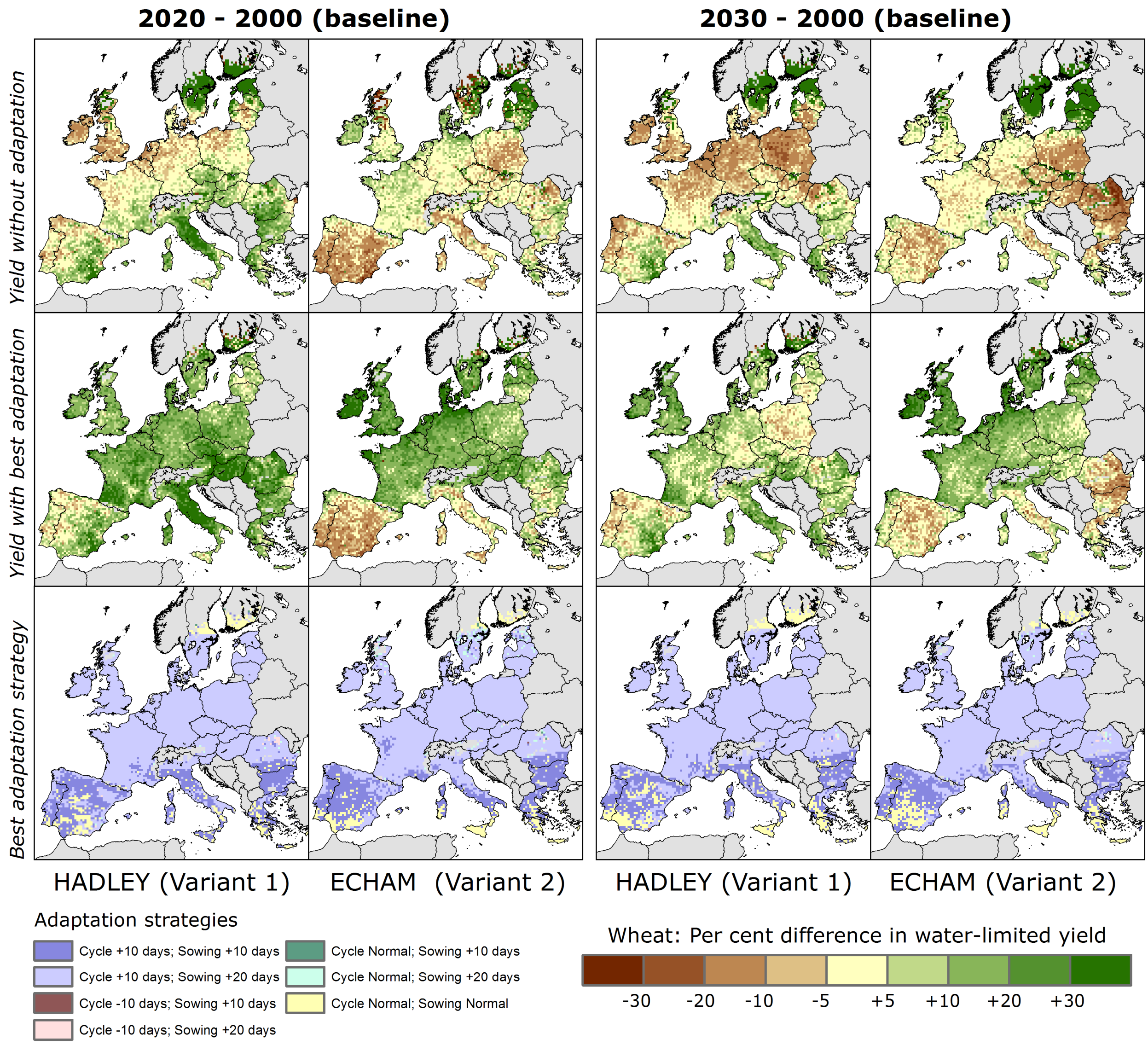
The CropSyst crop growth model was implemented at 25km grid size covering all EU-27. Crop growth model simulations were run at potential and water-limited production levels. Selected adaptation measures autonomously implemented by farmers were incorporated in a second round of crop model simulations. The measures chosen were a change in sowing date (thus anticipating or delaying sowing of crops), choosing a different crop variety with a different crop cycle length (thus shortening or lengthening the growing period), and changing the amount of irrigation water (for grain maize simulations only).

The impact assessment of climate change on crops at 25 km grid scale has shown rather contrasting results in response to the two A1B climate simulations. The key aspect has been the changing rainfall pattern in Southern Europe – rather than the increase in air temperatures –, which can lead to either an improvement or a deterioration of the performance of crops. This has been especially evident for winter-sown crops, but also for sunflower that used the first part of the year to complete its growth cycle. In terms of impact assessment under water-limited production with no adaptation simulated, the different precipitation patterns led to a different response of rain-fed crops (wheat, rapeseed, and sunflower).

The crop growth model simulation including technical adaptation has shown in many cases an alleviation of the impacts, especially under the “cold” scenario (Reference Variant 2) in Southern Europe in general, and with a more modest effectiveness in southern Spain. Yield estimates in many areas showed improvements under the “warm” scenario (Reference Variant 1) in Southern Europe, too. Wheat, rapeseed, and maize showed generalised improvements in Northern Europe, whereas sunflower did not perform well for both climate simulations of the A1B emission scenario in a large belt from central France to the most eastern area of Europe considered. It must be pointed out that such results were obtained via adjustment of technical management, without assuming a technological advance (e.g., known varieties were simulated, without exploring possibly improved varieties).

The results of the crop growth model simulations of wheat, as the dominant crop in Europe, are presented in Figure 10 in detail. The resulting wheat yields are rather different when based on the “warm” and the “cold” climate simulations of the A1B scenario (Reference Variant 1 and 2, respectively). Figure 10 summarises the expected situation of water-limited wheat yields in 2020 (the two columns of maps on the left) and 2030 (the two columns of maps on the right) according to the crop model setup used. For simulations without considering any adaptation (upper row), the differences in spatial patterns of yield reflect the substantial differences in rainfall patterns between the Hadley (Reference Variant 1) and ECHAM (Reference Variant 2) simulations (Donatelli et al. 2012a). The reason for an increase of yields in Southern Europe when rainfall is available (i.e., in the “warm” or Reference Variant 1 simulation) is the shortening of the crop cycle that may impact positively yields by improving the avoidance to summer water stress. The positive effect of avoidance of summer stress was already observed via simulation with different GCM inputs at a location of Southern Italy (Donatelli et al. 1998; Harrison and Butterfield 1996). Carbon fertilization is also expected to contribute to the increase in yield given the current estimates of CO_2 concentrations in the near future, markedly higher than the ones of the first studies of simulations of crop growth in future scenarios of the 1990’s.

Figure 10. Change (%) in simulated water-limited yield with and without adaptation measures for winter wheat in 2020 and 2030 with respect to 2000



Note: The best adaptation strategies among all tested ones are mapped in the bottom row.

The results of the crop model simulation runs with adaptation strategies implemented (middle row) show a general improvement of yields over all of Europe, except for the Iberian Peninsula based on the ECHAM (Reference Variant 2) simulation, which suffers from excessive aridity. The choice of adaptation measures (represented in the bottom row of the figure) reveals that the best yield is realized by delaying wheat planting date by 10 days, and using a variety with a longer growth cycle. It must be noted, however, that the results do not account for a possible increase in plant disease pressure such as wheat rusts.

At the 2030 horizon, the same 2020 general conclusions can be drawn. The yield increases with adaptation are slightly lower than with respect to 2020 due to a generalized increase in temperature.

An important outcome of the crop growth model simulations based on the "warm" climate simulation (Reference Variant 1), which estimates an increase in rainfall, is that yields are expected to increase in Southern Europe even without adaptation because of rainfall patterns and CO_2 fertilization. The general picture presented by these simulations – certainly to be corroborated by further analysis – shows substantially different outcomes from the generalized concept that agriculture will become unsustainable in Southern Europe. There will likely be critical spots, but possibilities deriving from climate scenarios do not exclude also opportunities at the time horizon considered. At the same time, the results confirm that the increase of temperature will both broaden agricultural management options and lead to potentially higher yield levels in Northern Europe.

4.3 Energy

The energy assessment computes the impact of changes in ambient temperature and rainfall on the energy system, focusing on heating and cooling demand for residential and commercial sectors, based on the POLES energy model. The POLES model[18] (Prospective Outlook on Long-term Energy Systems) is a global partial equilibrium simulation model. Although POLES is usually used to produce dynamic energy scenarios up to 2050, for the PESETA project, the climate of the 2080s was imposed on the present-day energy market.

Heating and cooling demand depend on the changes in degree days, as computed from the climate simulations. The POLES analysis also considered the effects of climate change on the efficiency of thermal power plants and changes in hydro, wind (both on- and off-shore) and solar PV electricity output. The changes in hydro

[18] The POLES model description can be found at http://ipts.jrc.ec.europa.eu/activities/energy-and-transport/documents/POLESdescription.pdf

production were computed using output from the LISFLOOD model[19]. The energy impacts can be considered steady-state impacts because they exclude extreme, short-lived impacts that cannot be captured because of both lack of climate data and incompatibility with the POLES energy model.

While the results presented in this report are based on a comparative static analysis (exploring how energy demand would change in today's economy, but with future climate), Dowling (2013) also conducted a dynamic assessment in the 2050 time horizon, which includes the influence of long-term socioeconomic trends (not considered in this report) but does not include the linkages between energy and the rest of the economy (included in this report's CGE analysis).

The POLES energy model projects the change in energy demand and supply as a result of climate change. The sum of the change in heating and cooling demand is reported in tons of oil equivalent, a synthesis of the outcome of the energy model[20].

Table 15 represents the energy demand indicator for the EU and various sub-regions in the two climate simulations. By the end of the century, overall EU energy demand would fall by 13% under the Reference scenario, compared to the respective control period (1961-1990). With the exception of the Southern Europe region, there would be net energy savings, being the Central Europe North region the one with the highest fall in energy consumption, by 21%. Energy demand would rise by 8% in Southern Europe. Under the 2°C scenario, EU energy consumption would fall to a lesser extent, by 7%. The regional pattern is similar to that of the Reference scenario.

[19] Variations in rainfall lead to changes in surface water at each hydropower station. These outputs from LISFLOOD were used as inputs to the hydropower module of the POLES model.

[20] The energy assessment of this study reports energy demand changes. The POLES model also computes the effects of the climate impact on hydro, wind, and solar PV electricity output, and electricity output from thermal power stations. Those supply-side effects also would influence indirectly energy demand via price effects.

Table 15. Impact on energy demand

	EU	Northern Europe	UK & Ireland	Central Europe North	Central Europe South	Southern Europe
Control	259,429	7,194	40,701	92,026	69,868	49,639
Reference	226,487	6,137	34,926	73,003	58,907	53,513
change (%)	-13	-15	-14	-21	-16	8
2°C	240,556	6,425	38,804	81,504	63,707	50,116
change (%)	-7	-11	-5	-11	-9	1

Units: ktoe/year

4.4 River floods

Estimates of changes in the frequency and severity of river floods are based on simulations with the LISFLOOD model (Rojas et al., 2013) followed by extreme value analysis (Rojas et al. 2012). LISFLOOD is a hydrological model developed for flood forecasting and impact assessment studies at European scale. Driven by meteorological input, LISFLOOD calculates actual evaporation and transpiration rates based on vegetation characteristics, leaf area index and soil properties. The model uses a 5-km grid resolution covering Europe and generates river runoff estimates for each river pixel. Flood discharges for eight return periods ranging between 2 and 500 years are computed and converted into flood inundation extents and depths. The depth estimates are then translated into direct monetary damage from contact with floodwaters using country-specific flood depth-damage functions and land use information. The main outcome of the modelling approach is twofold: the expected annual damage (EAD) and expected annual population affected (EAPA). The floods study also assesses the costs and benefits of maintaining 1 in 100-year levels of flood protection across Europe in future time periods, set against the increases in flood magnitude. This is done by transferring information from detailed flood protection studies covering a wide range of protection measures and geographical areas across Europe.

Direct economic damages from flooding for the EU are currently[21] estimated at around 5 billion Euro/year (Table 16), which compares well to the 4.4 billion Euro of annual damage reported over the period 1998-2009 (EEA, 2010). Flood damages

[21] The control period value is the average of the control period outcome under the Reference and the 2°C simulations. The same applies for the coastal impact control period.

for the Reference climate realization are projected to more than double due to climate change compared to the control period, reaching 11.4 billion Euro/year in the 2080s under the Reference scenario. This increase in damages would occur mainly in the UK & Ireland region, where damages are tripled up to 3.3 billion Euro/year and the Central Europe South region, where damages raise from ca. 2 billion Euro/year up to 5.2 billion Euro/year. Southern Europe would also experience a considerable increase in damages totalling to 1.3 billion Euro/year. Northern Europe is the only region where the assessment projects a decrease in damages (-40%), amounting to 222 million Euro/year, under the Reference simulation[22]. Regarding the climate realization for the 2°C scenario, future damages at EU-level are in general smaller compared to the realization for the Reference scenario, reaching 9.5 billion Euro/year by the end of this century.

Table 16. Impact on river flood damages

	EU	Northern Europe	UK & Ireland	Central Europe North	Central Europe South	Southern Europe
Control	4,924	370	872	1,007	2,003	673
Reference	11,338	222	3,317	1,248	5,203	1,347
change (%)	130	-40	281	24	160	100
2°C	9,537	292	3,715	1,269	3,073	1,187
change (%)	94	-21	326	26	53	76

Units: €million/year

The flood analysis also calculated the number of people affected on an annual basis by flooding. Whereas currently approximately 160,000 people/year are affected by flooding in the EU, by the end of this century this is projected to rise to 290,000 people/year under the Reference climate realization. Under the 2°C climate realization the total number of people annually affected in the EU by the 2080s would be 240,000. The largest increase in number of people affected is projected for the UK under both scenarios.

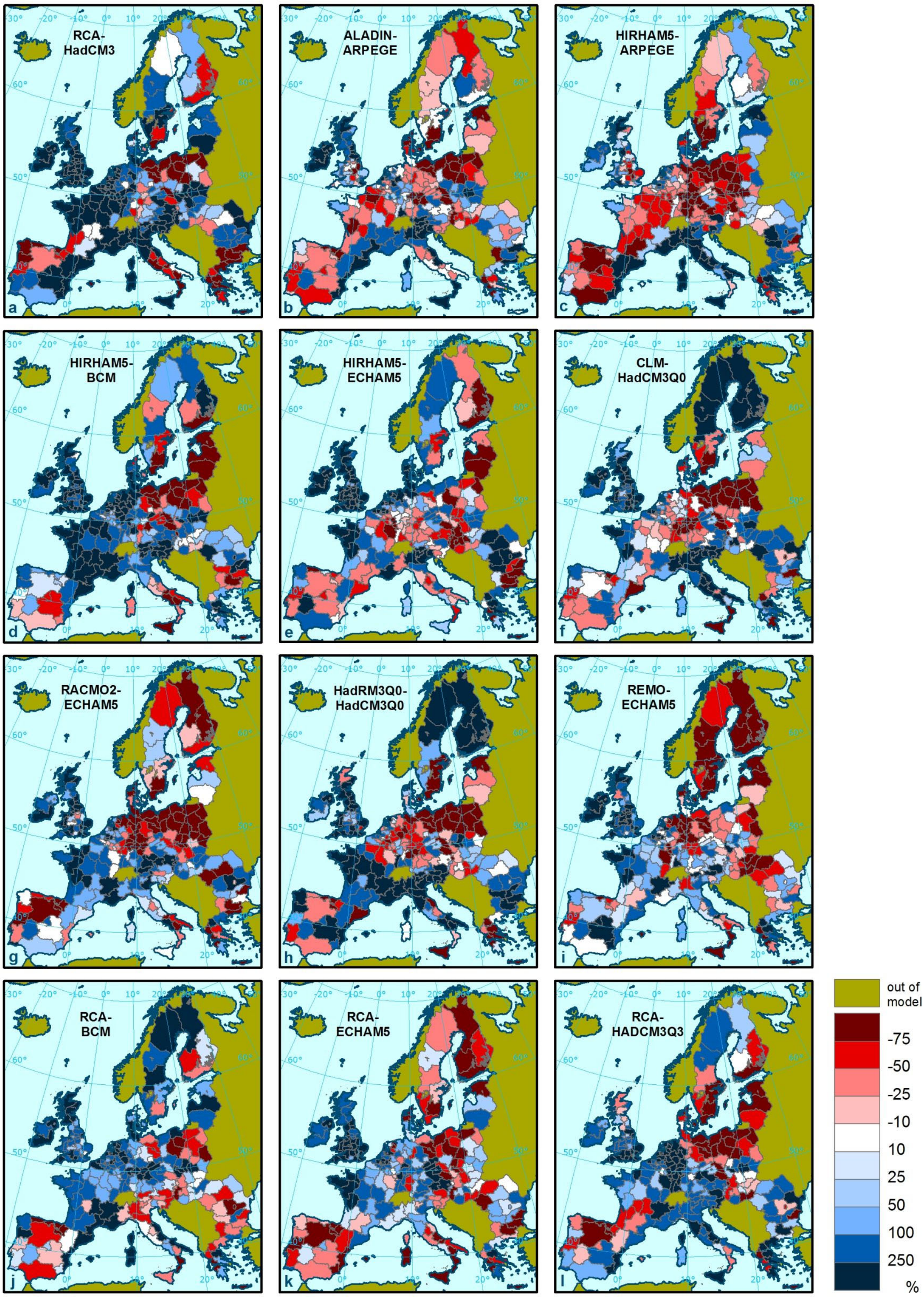
It should be noted that the above results are based on a single member (Reference Simulation) of the 12-member A1B ensemble and one realization of the 3-member E1 ensemble. As shown in Rojas et al. (2013), flood damages are strongly dependent on the choice of climate realization due to the large uncertainties in projections of

[22] For the whole ensemble, there is no reduction in the future damages for any of the regions.

future changes in precipitation and its extremes. This is even more pronounced at the regional to local scales, as shown in Figure 11. This figure shows the spatial distribution of the absolute changes in annual expected direct damages (AED) between the 2080s and control period (1961-1990) for the 12 climate realizations of the A1B ensemble (the results of the Reference climate simulation correspond to plate g of Figure 11). The results for the individual climate realizations reveal that the potential costs can vary by a factor of two (higher or lower). These differences are even more significant at the regional or country level, with some models even reporting differences in the effects of climate change (i.e., some models project relative reductions in future flood risk from climate change for some areas). The strong dependence of the results on the chosen climate realization explains for example why the 2°C climate realization shows higher future damages in the UK compared to the climate realization chosen for the Reference.

For the whole A1B ensemble of 12 climate simulations the EAD is projected to increase up to nearly 15 billion Euro/year by the 2080s due to effects of climate change, whereas for the E1 ensemble of 3 climate simulations the EAD from flooding is projected to amount to 9 billion Euro/year by the end of this century.

Figure 11. Relative change in EAD from flooding between 2080s and baseline period for the 12 climate model combinations for the A1B scenario



The floods study also assesses the damages from flooding when accounting for changes in exposure and population, as defined by the underlying socio-economic scenarios. This analysis complements the previous one, which was made in a comparative static framework. In this dynamic case, the EAD for the A1B scenario is estimated at €98 billion/year by the 2080s (mean ensemble results, current values, undiscounted) in the EU27. Hence, a large part of this is due to socio-economic change (economic growth). Analysis at the country level shows high climate-related costs in the UK, Ireland, Italy, the Netherlands and Belgium. For the 3-member E1 ensemble, EAD is projected to increase to €68 billion/year due to the combined effects of climate and socio-economic changes.

When accounting for demographic changes, the projected mean expected number of people (EAP) affected by flooding annually is 360,000 and 230,000 for the A1B and E1 scenario (ensemble average), respectively, by the 2080s in the EU27. For both scenarios this is about 30,000 people less compared to when assuming static population, due to the projected decline in population in the second halve of this century.

The benefits of adaptation (in this case upgrading to future 1 in 100-year flood levels across Europe) is estimated at €53 billion/year for the A1B by the 2080s (mean ensemble, EU27, climate and socio-economic change current values, undiscounted). It should be noted that the benefits vary with the climate variability, so there is a significant range around these values. There are also significant residual damages in later years under these minimum protection levels, and this suggests higher protection levels would be justified. The costs to maintain minimum protection levels are estimated at €7.9 billion/year for the A1B scenario and €4.7 billion/year for the E1 scenario by the 2080s for the EU27 (mean ensemble, undiscounted).

The following limitations of the floods study should be considered:

- Only one hydrological model is used to simulate river flows, hence hydrological uncertainty is not accounted for.

- Flood return levels are estimated using extreme value analysis based on simulated time series of 30 years, which may result in large extrapolation errors for high return periods.
- In the calculation of river water levels, river cross sections had to be approximated due to the absence of national or European datasets on riverbed geometries.
- Inaccuracies in the SRTM DEM may induce bias in the estimation of flood inundation levels.
- Changes in land use and land cover are not incorporated in the climate runs or in the economic impact evaluation due to the absence of reasonable macro-scale land use change scenarios for the scenarios considered herein. This may result in an underestimation of future flood risk.
- Flood protection levels vary largely across Europe and within countries. There is, however, a deplorable lack of information on flood protection standards and the probability of failure of defences in Europe. We have therefore assumed current flood protection up to the 100-year event, with the exception of the Netherlands where the 150-year event was applied. For the future time slices, we assumed the same level of protection in terms of return period (hence protection up to future 100-year, or 150 for the Netherlands, event).
- The approach used is based on direct estimated potential flood damage caused by water depths on land use typologies. Other factors that might contribute to the increase of losses, such as flood velocity, building characteristics, content of sediment in water, as well as indirect economic losses, are not included in this study.

The above list of assumptions implies that the monetary estimates of flood damage presented herein are inherently uncertain. It should be noted, however, that the goal of this study was to evaluate changes in flood damage due to climate change, rather than to estimate absolute values of flood damage. Given that most of the assumptions apply to both the control and scenario period it can be expected that estimates of changes in flood damage are relatively less affected by the assumptions compared to the absolute flood damage estimates. Furthermore, the validation of the flood damage estimates for the control period compare relatively well with the reported damage figures and estimates of flood damage from other studies.

4.5 Droughts

The streamflow droughts analysis is based on hydrological simulations performed with the LISFLOOD model (see description in subsection 4.4) driven by the A1B ensemble of 12 climate realisations. Annual minimum flows are extracted from the daily LISFLOOD simulations for all river cells across Europe, and using extreme value analysis based on the Generalised Extreme Value (GEV) distribution the changes in drought frequency and magnitude were evaluated between the 2080s and control period (see Forzieri et al., 2014). Climate impact indicators are expressed as total area and cropland affected and people exposed to droughts. As droughts are probabilistic events, the results are presented as expected annual impacts.

It should be noted that the impacts here are not monetized and do not include consequences on several other sectors that may be negatively impacted by droughts, such as energy production and navigation. It is assumed that the threshold to be affected is the current 20-year minimum flow, i.e. that crop productivity or people suffer negative impacts from low flows that occur once in 20 years or less frequent. For each of these variables it is first calculated the expected annual damage for the baseline period by integrating the impacts over events with a lower probability of occurrence than the 20-year threshold. For the 2080s, the future return period of the baseline 20-year minimum flow is calculated by inversion of the GEV function, and is then used to truncate the integration and estimate the corresponding future expected annual damage. The analysis is performed at the LISFLOOD setup 5x5 km pixel scale and results are then aggregated to NUTS2, country scale and EU regions (see Figure 2). For cropland affected, all land use classes related to crops have been selected from the refined European land use/cover map (based on Corine) at 100x100 m (Batista e Silva et al., 2013a). For population exposed we used the high-resolution (100x100 m) population grid map for Europe (Batista e Silva et al., 2013b).

Table 17 shows that the EU cropland area affected by droughts is projected to increase substantially under the A1B Reference climate simulation, reaching 700,000 km^2/year, from nearly 100,000 km^2/year in the control period. The highest absolute increase would occur in Southern Europe (from 27,000 km^2/year to 365,000 km^2/year) and Central Europe South (from 31,000 km^2/year to 242,000 km^2/year). In the UK & Ireland region the relative change is similar (almost six times more surface affected). In contrast, Northern Europe and Central Europe North show a reduction and a relatively small augmentation, respectively, in impacts on croplands in the future scenario, with respect to control period.

Table 17. Impact on Cropland affected by drought

	EU	Northern Europe	UK & Ireland	Central Europe North	Central Europe South	Southern Europe
Control	96	8	8	22	31	27
Reference	710	2	61	25	217	405
change (%)	637	-77	627	16	601	1,407

Units: Thousand km^2/year

Table 18 represents the effects on people affected by drought. The Reference simulation could mean a large increase in EU people affected[23], from 22 million/year in the control simulation to 144 million/year. The largest absolute increase would also occur in the Southern Europe region, with an increase of almost 70 million people/year. The Central Europe South and the UK & Ireland regions would also see large increases in the scenario period, more than five times the currently affected population. Interestingly, Central Europe North will experience much stronger impacts on people than cropland affected by drought (compare Table 17 and Table 18). This suggests that in this region the populated areas are more susceptible to increased drought than the agricultural areas. As with cropland, Northern Europe's exposure to drought among the population shows an opposite direction of projected impacts compared to other regions, with a reduction of ca. 80% in exposure of population to drought.

[23] Under a dynamic assessment where the evolution of population would be considered the results could be interpreted in a different way, depending on whether the population would increase or decrease compared to today.

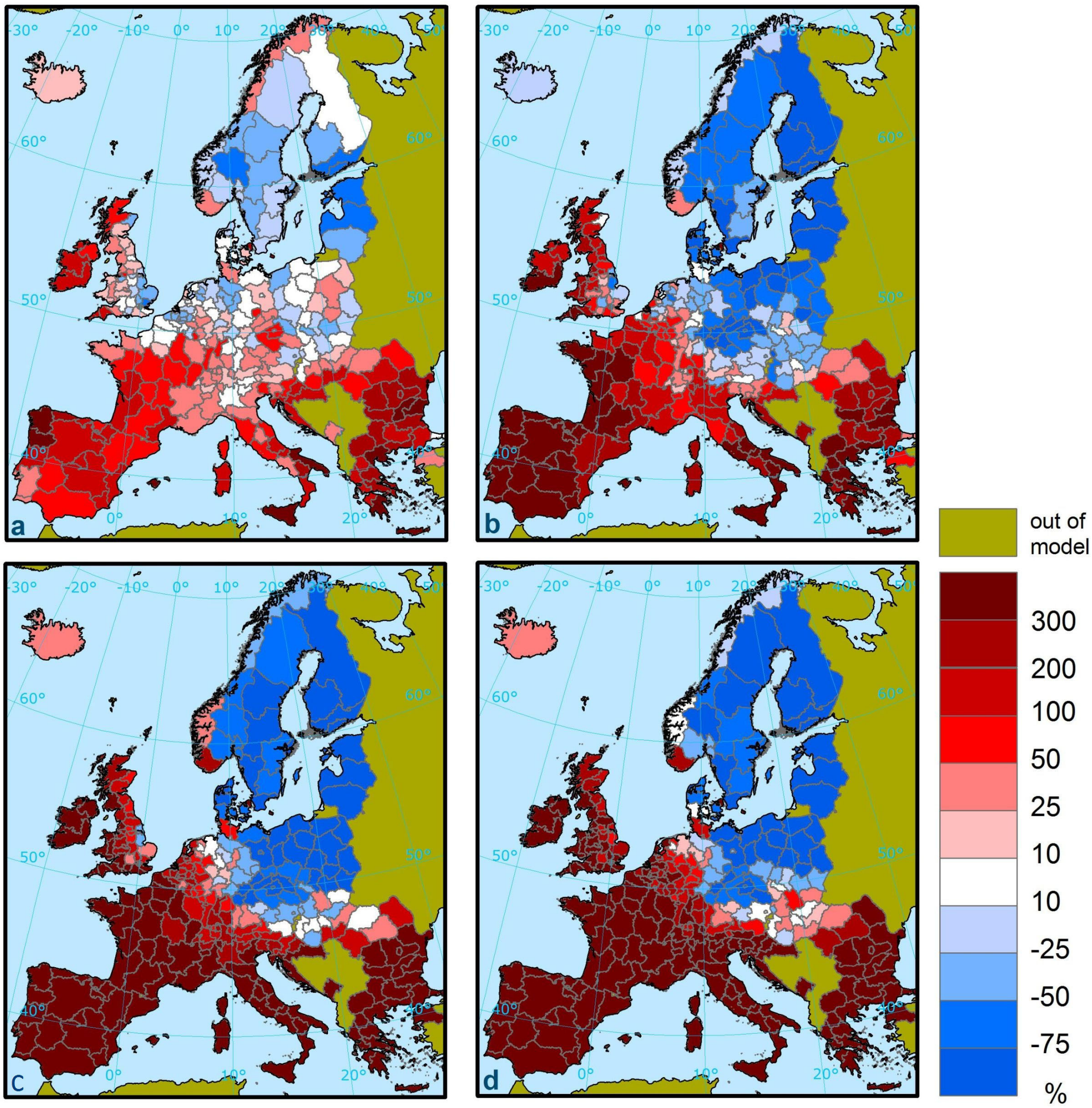
Table 18. Impact on People affected by drought

	EU	Northern Europe	UK & Ireland	Central Europe North	Central Europe South	Southern Europe
Control	22	1	3	7	6	5
Reference	153	0	18	18	37	80
change (%)	592	-66	560	153	642	1,378

Units: million people/year

It is important to note that these results relate to the specific realization (Reference) of the A1B ensemble. However, similar analysis has been conducted for twelve A1B simulations. The projections of streamflow droughts show to be very robust amongst the different climate simulations. This is because, unlike floods, changes in low-flow conditions depend on changes in precipitation on longer (i.e., monthly to seasonal) timescales rather than on single events. The evolution in this century of the changes in total area affected for the A1B ensemble of 12 climate simulations is shown in Figure 12.

Figure 12. Change in total area affected by drought due to climate change (SRES A1B scenario) between baseline period and current (a), 2020s (b), 2050s (c) and 2080s (d). Ensemble-median results based on 12 RCM/GCM combinations



The different steps in the chain "emissions → climate → extreme flow → drought hazard → impact" are subject to uncertainty. When applying the framework outlined above for macro-scale drought impact assessment it was necessary to adopt the following assumptions, which should be kept in mind when interpreting the results:

- Only one hydrological model is used to simulate river flows, hence hydrological uncertainty is not accounted for.

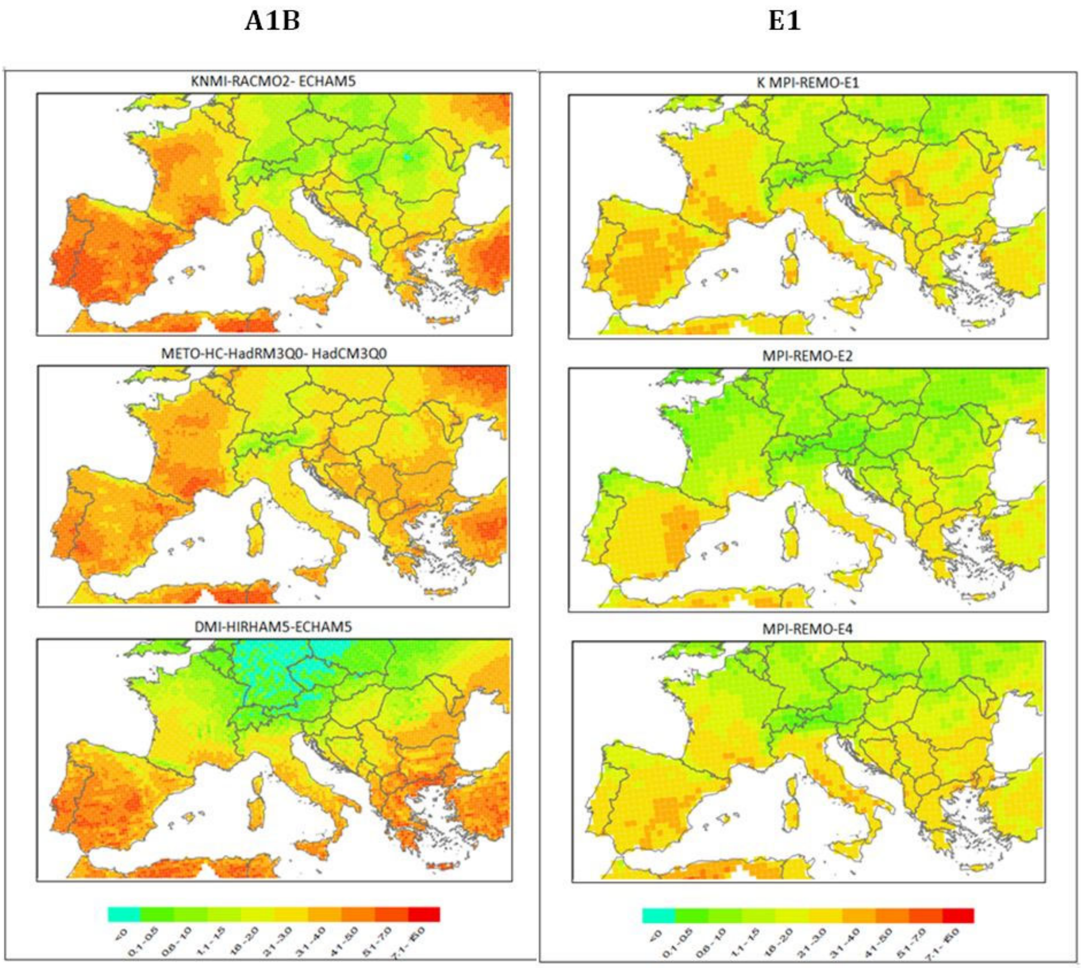
- Drought return levels are estimated using extreme value analysis based on simulated time series of 30 years, which may result in large extrapolation errors for high return periods.
- Changes in land use and land cover are not incorporated in the climate runs or in the drought impact evaluation due to the absence of reasonable macro-scale land use change scenarios for the scenarios considered herein. This may result in bias in the estimates of future drought impacts.
- Drought vulnerability is not included in the impact analysis, and may vary widely in Europe.
- Impacts of droughts go far beyond those addressed in this study. Future work will focus on addressing the effects of droughts and low flows on several other socio-economic sectors such as energy production and navigation as well as on ecological systems.

4.6 Forest fires

The assessment of the impact of forest fires is based on the statistical modelling of burnt area as a function of meteorological fire danger indices (documented in Camia et al., 2013). The study first reconstructs the historical series of the Canadian Fire Weather Index (FWI) system components to estimate past meteorological fire danger conditions and to model their relationship with the observed burnt area in Southern Europe.

In a second step the burnt area projected under climate change scenarios is simulated by feeding the statistical models with future fire danger indices projections. Figure 13 shows maps of FWI differences of 2071-2100 and 1961-1990 annual averages, which represent the climate change signal over the fire danger indicator adopted. Despite the marked differences in spatial pattern across simulations, especially for the reference scenario, it is recognizable a consistent stronger positive signal of A1B against E1.

Figure 13. Difference of FWI annual averages between 2071-2100 and 1961-1990 simulations



Based on fire danger projections and on the statistical models developed, estimates of future burnt area are simulated by country. The economic valuation of the forest fire impacts is made combining the burnt area estimates with a European map of post-fire restoration costs per hectare. Therefore the two final outputs of the appraisal are the burnt area and the restoration costs.

The estimated burnt area and the consequent restoration costs summarise the impacts of forest fires. They have been computed only for Southern European countries and Southern France, i.e. the European regions by far most affected by forest fires (85% of the current total EU burnt area), therefore this indicator is not reported for other EU regions.

Table 19 shows the area burnt by forest fires in the most affected regions of the EU i.e., Southern European countries and Southern France. In this regions the burnt area is estimated to double under the Reference scenario (from 377 thousand ha under the control to 787 thousand ha under the Reference simulation), and could increase by near 50% under the 2°C simulation.

Table 19. Impact on forest fires (burnt area)

	Southern Europe
Control	361,203
Reference change (%)	734,889 103
2°C change (%)	526,002 46

Units: ha

Several uncertainties hold when projecting long-term climate change impacts on forest fires. The current assessment is based on the main driver of fire regime in Mediterranean Europe (weather) which explains most of the year by year variation of fire activity but does not take into account longer term changes such as fuel conditions (vegetation), ignitions, and human activities that may influence burnt area and thus wildfire impact. The uncertainties of future projections are also intrinsic to the empirical nature of the models developed, since extreme conditions simulated in future climate scenarios can be outside the data range used to build and calibrate the models with today observations.

With respect to the economic impact, the restoration cost approach, which has been followed to assess the damage value, underestimates the actual economic losses. Costs which are not accounted for are those incurred because of the missed benefits until the forest is restored (i.e., temporary loss of ecosystem services), or the direct cost of firefighting. Other associated costs related to indirect effects of wildfires on aspects such as human health or secondary effects on other natural hazards, such as e.g. increased potential for flooding, are also not accounted for.

Adaptation measures could not be included in the models since no comprehensive baseline information is currently available on wildfire prevention in Europe hence, the current quantitative knowledge about the effectiveness of different fire prevention options is still limited.

4.7 Transport infrastructure

In the future, transport could be affected by one or several simultaneous changes in the climate conditions, including hotter summers, extreme precipitation events, increased storminess and sea level rise. If such impacts are not anticipated in future transport infrastructure design and maintenance, those changing weather conditions could, in some regions, accelerate their deterioration, increase severe damages risks, traffic interruption and accidents which could, on their turn, affect economic activities.

Methodology

The transport infrastructure assessment by Nemry and Demirel (2012) considered the effects of change in temperature, precipitation, river floods and of sea level rise (including storm surges) on the future costs of road and rail networks. It has drawn some future trends regarding changing exposure of road and rail infrastructures to weather-induced risk under climate change, considering two future time intervals (2040-2070 and 2070-2100), and future infrastructure deterioration and damage costs. Costs associated with some selected adaptation cases were also assessed, covering different aspects of climate change, infrastructure types and involved life spans. This has been performed at high geographical resolution and higher aggregation level.

The following impacts and adaptation measures were considered:

- Extreme precipitation was analysed by adjusting estimates of current costs to road infrastructures to take account the estimated future precipitation conditions.
- The effects of higher road temperatures were analysed in two ways. Firstly, the cost of maintaining roads under higher temperatures (using asphalt binder upgrades) was made by applying a method developed by Chinowski et al. (2013), making use of the information about the EU road network using the Transtools model. Secondly, the consequences of milder winter conditions on road maintenance costs were estimated based on analysis by the US Highways Administration (FHWA, 2006).

- The increased risk of heat-induced rail track buckling was calculated by estimating the number of days at which country-specific "stress-free" temperatures would be exceeded. These are then converted into number of hours delay due to additional speed restrictions, which are monetised on a value-of-time basis.

- The effect of bridge scour (damage to the foundations of bridges from increased river flow causing removal of sediment) was estimated using the outputs from LISFLOOD hydrological model combined with transport network information and estimates of the need for additional expenditure on riprap (placing large blocks at the base of bridge piers) or concrete reinforcement (Wright et al, 2012) .

- Finally, the vulnerability of the road transport infrastructure to a 1 meter sea level rise (permanent inundation) and storm surges (episodic inundation) was analysed using a combination of digital elevation data from the NASA Shuttle Radar Topography Mission (SRTM), storm surge estimates from the DIVA model database and road network data from Teleatlas. Vulnerability of transport network to coastal inundation was estimated as the cost of reconstruction.

The damage to roads, railways and bridges has been retained as a proper indicator of damage to transport infrastructure. Other transportation infrastructure, such as airports, ports, pipelines is not explored.

Future weather-induced impacts on road infrastructures

Even though integrity and serviceability of transport infrastructure, including their resilience to current weather conditions, are key objectives in infrastructures construction and maintenance standards, complete avoidance of weather-induced infrastructure deterioration and failures is not economically feasible. For road transport infrastructures, weather stresses currently represent from 30% to 50% of current road maintenance costs in Europe (8 to 13 billon €/year). About 10% of these costs (~0.9 billion €/year) are associated with extreme weather events alone, in which extreme heavy rainfalls & floods events represent the first contribution.

The JRC/IPTS study concludes that, at EU27 aggregated level, average precipitation-induced normal degradation of road transport infrastructures will only slightly increase in the future. However, more frequent extreme precipitations (and river floods and pluvial floods) as projected in different regions in Europe could represent an extra cost for road transport infrastructures (50-192 million €/year for the A1B scenarios, period 2040-2100).

The increase in annual damage costs to road infrastructure from extreme precipitation for 2070-2100 (compared to the present) is represented in **Table** 20. This expenditure is projected to increase by 50% in the Reference scenario, to €932 million. The increase is similar across the considered EU regions, but for the Southern Europe area, where it barely changes. Under the 2°C scenario, the overall EU increase is lower, to €773 million. The regional changes compared to the control simulation are similar to those of the Reference scenario, with the exception of the Central Europe North region (with a lower increase in expenditure, of 4% under the 2°C simulation versus 70% in the Reference simulation) and Southern Europe (a fall of 16% under the 2°C simulation[24], while it was more or less stable in the Reference simulation).

Table 20. Additional flood-induced damages to road infrastructure for the period 2070-2100

	EU	Northern Europe	UK & Ireland	Central Europe North	Central Europe South	Southern Europe
Control	629	130	59	209	109	122
Reference	932	210	89	356	156	121
change (%)	48	61	52	70	44	-1
2°C	773	210	90	218	152	102
change (%)	23	62	53	4	40	-16

Units: million Euro/year

Milder winter conditions are projected to result in reduced costs for road infrastructure (-170 to -508 million €/year for the A1B scenarios). On the contrary, increasing average temperature could require changes in maintenance operations and practices and represent extra costs for both road transports.

The reduction in road infrastructure costs due to warmer temperatures is shown in **Table** 21. This consists of cost reduction due to reductions in winter conditions (the incidence of freezing days) and cost increase due to the need to upgrade asphalt

[24] This fall could be due to less precipitation.

binder. As the table shows, the cost reduction related to winter conditions is expected to exceed the cost of asphalt binder upgrade in each region[25].

Table 21. Annual change in costs to road network associated with changing extreme temperatures

	EU	Northern Europe	UK & Ireland	Central Europe North	Central Europe South	Southern Europe
Change in winter damage costs						
Reference	-327	-3	-6	-50	-69	-199
2°C	-260	-16	-7	-127	-73	-127
Change in asphalt binder costs						
Reference	193	1	2	80	68	42
2°C	68	1	0	16	21	29

Units: million Euro/year

Protection of river bridges against scour risk may be needed over the next decades for about 20% of the river bridge stock because of increasing intensity of peak river discharges. Given the long bridge design life (>100 years) and long maintenance planning cycle, future climate-related risk should be included in corresponding prior cost-benefit studies. The annual cost of protecting bridges is estimated at €541 million for the period 2040-2070 and €383 million for the period 2070-2100.

For heat-induced rail buckling risk and derailment risk, the most commonly applied adaptation measure consists in speed limitation. Today the entailed delays represent a small cost for transport users. Due to more intense and frequent hot days in summer, this could induce more frequent trip delays for rail transport (doubled or quadrupled for the A1B and RCP8.5 scenarios respectively). The study estimates the cost of speed restrictions - calculated to €31-39 million.

Altogether, the impacts noted above suggest an additional net annual cost of around €590 million at EU level for the period 2070-2100.

For the case of road infrastructure adaptations considered, compared with maintenance costs, the adaptation costs estimated for the A1B scenarios (314-560 million €/year) represent a small percentage of current road maintenance costs (1.2% to 2.2%). However, damage costs which would be avoided by such adaptation

[25] It is to be noted that reduced costs for Southern regions might be overestimated due to the poor representativeness of data for those regions.

measures could be several times higher. The cost of bridge failure could easily reach 2 to 10 times the cost of the bridge itself.

Vulnerability to sea level rise and sea storm surges

This study has produced an initial estimate of future risk of sea level rise and sea storm surges on road transport infrastructures. This assessed risk is based on infrastructure settled in areas lying below a level defined by the sum of sea level rise (1 m) and 100-year sea storm surge height. The infrastructure at risk of permanent or episodic inundation represents 4.1% of the coastal infrastructure. The value of that infrastructure is estimated to ~18.5 billion €.

Overall, these costs provide a highly aggregated picture of the possible trends for road transport in Europe. More severe consequences at local or regional level are not excluded, implying both more significant increase in repairing and maintaining infrastructures spending, and indirect consequences (e.g. fatalities due to extreme weather events) where infrastructures would collapse. For instance, current patterns about extreme precipitation show a very uneven spatial distribution.

4.8 Coasts

Coastal impacts are in general derived from the DIVA (Dynamic Interactive Vulnerability Assessment) model, as simulated in the ClimateCost project (Brown et al. 2011). DIVA is an integrated model of coastal systems that assesses the biophysical and socioeconomic impacts of sea level rise and socio-economic development. Depending on the relative sea level rise, several types of bio-physical impacts are evaluated for each coastline segment, including dry land loss due to coastal erosion, and flooding due to surges and the backwater effect on rivers. The model can consider two public adaptation options: dike building/raising and beach/shore nourishment. The model results used in the JRC PESETA II project assume that there is not public adaptation. The model computes impacts in monetary terms such as migration costs and sea floods costs.

The cost of damages from sea floods is one of two the main economic impact categories from the DIVA model. The other main category is cost of migration, which is correlated to damage costs but is not reported here. The other impact categories, such as land losses have less relative importance in economic terms. The results without public adaptation are reported here.

Table 22 represents the estimated damages due to sea floods. For the EU they could more than triple under the Reference simulation, mainly due to the increase of projected damages in the Central Europe North region, the region with the highest sea flood damages across the EU. In that region the sea flood damages could increase from €2.6 billion/year in the control period to €9.4 billion/year in the Reference simulation. The relative increase in damages is the highest in the Southern Europe region (from €163 million /year in the control simulation to over €1 billion/year in the Reference simulation, an increase of almost 600%). The Northern Europe region also experiences a large increase of sea flood damages (from €225 million/year in the control simulation to over €1billion/year in the Reference simulation, an increase of over 300%).

Under the 2°C simulation, associated with lower increases in sea level, the sea flood damages are lower for the EU and for each of the EU regions, when compared to the Reference simulation damages. Still the damages increase substantially compared to the control simulation, with EU damages more than doubling to reach €13.8 billion/year.

Table 22. Impact on sea floods damage

	EU	Northern Europe	UK & Ireland	Central Europe North	Central Europe South	Southern Europe
Control	4,963	225	966	2,613	997	163
Reference	17,159	1,035	2,987	9,438	2,634	1,065
change (%)	246	361	209	261	164	555
2°C	13,787	553	2,464	7,778	2,089	903
change (%)	178	146	155	198	110	455

Units: million Euro/year

4.9 Tourism

The tourism study is documented in Barrios and Ibañez (2013). The tourism model estimates changes in tourism revenues according to an econometric analysis of the relationship between regional tourism demand (bednights at NUTS2 level) and regional climate conditions. The tourism demand equation considers as explanatory variables the tourists´ valuation of climatic conditions (a hedonic price index) including the transport[26] and accommodation[27] cost dimension of tourism demand. Such modelling system allows one to consider adaptation options in terms of timing and duration of holiday's patterns.

The analysis is organised in three main steps. In the first step the hedonic price equations are econometrically estimated to derive the hedonic price index of tourism services and associated marginal willingness to pay (MWTP) of tourists for climate amenities in EU regions. Four different climate explanatory variables are used taking monthly average of daily figures: average temperature level, average level of precipitation, average humidity and average wind speed. These variables are interacted with monthly dummy variables such that the estimated MWTP for each of these climatic characteristics is month-specific. These hedonic price equations are estimated separately for each region of origin of tourists following the literature on the recreational demand using hedonic price to value site-specific amenities, see in particular Brown and Mendelsohn (1984). The dependent variable in these equations is the sum of two components: the travel cost between each origin and destination region (estimated using the TRANS-TOOLS model) and of the monthly average price of a standard hotel bedroom, taken from a database provided by the online booking company hotelscombined (www.hotelscombined.com) covering 53211 hotels across 233 EU NUTS2 regions (including Swiss and Croatian regions) [28].

Considering that holiday stays may vary in length, four different values of the dependent variables are calculated according to the length of holiday stays, thus considering alternatively one-night, four-night, one-week and two-week stays. The average of the estimated hedonic prices and estimated MWTP for climatic services are then calculated for each region of destination, region of origin and length of stay.

In a second step these estimated MWTP are averaged across regions of destination using weighted average where the weights are given by the bilateral regional

[26] The estimation of transport cost are based on the TRANS-TOOLS model, http://energy.jrc.ec.europa.eu/transtools/.

[27] The cost of accommodation is based on a highly detailed database on hotel prices at regional level, over 50,000 hotels in 233 EU NUTS2 regions.

[28] The hotel price indices were constructed in order to ensure geographical representativeness at metropolitan (i.e. NUTS3) level.

tourists' flows. In a third step the tourists demand equation are estimated for each region of destination using the total number of monthly bednights as dependent variable and the monthly hedonic price of holiday estimated previously. The average population of the origin region is added as control variable to reflect the size of the potential tourism demand (using weighted average based on bilateral tourism flows and 2010 data on tourist´s expenditures from EUROSTAT). These equations are estimated using monthly data and the estimated coefficients are used to make the long run projection according to four different climate model runs. The estimated propensity to pay for each specific climatic variable are used to extrapolate the value of the climatic variables. The latter means that the long-term projections of tourism demand are performed as if current conditions other than climate prevailed.

The tourism model computes then how much tourism expenditure will change due to climate change. This is an indicator of the expected impact of climate change on tourism demand translated into expected variation in tourists´ expenditures (and thus expected revenue loss for the tourism industry).

Table 23 represents the simulated effects of climate change on tourism expenditure. It is assumed that there is full adaptation in both the duration and monthly distribution of holidays. The changes in the Reference and 2°C simulations are quite similar, compared to the control simulation, with a drop of €15 billion/year. In Southern Europe there is an estimated loss of €6 billion/year under the Reference simulation (similar to that under the 2°C simulation), a loss of €4 billion/year in Central Europe North and a loss of €5 billion/year in Central Europe South. In the UK & Ireland region, there is a simulated gain of €0.5 billion/year under the Reference simulation.

Table 23. Impact on tourism expenditure

	EU	Northern Europe	UK & Ireland	Central Europe North	Central Europe South	Southern Europe
Control	334,810	30,882	46,626	109,440	89,101	58,762
Reference	318,889	30,642	47,040	105,355	83,462	52,389
change (%)	-5	-1	1	-4	-6	-11
2°C	319,639	30,702	46,771	105,349	84,303	52,514
change (%)	-5	-1	0	-4	-5	-11

Units: million Euro/year

4.10 Habitat suitability

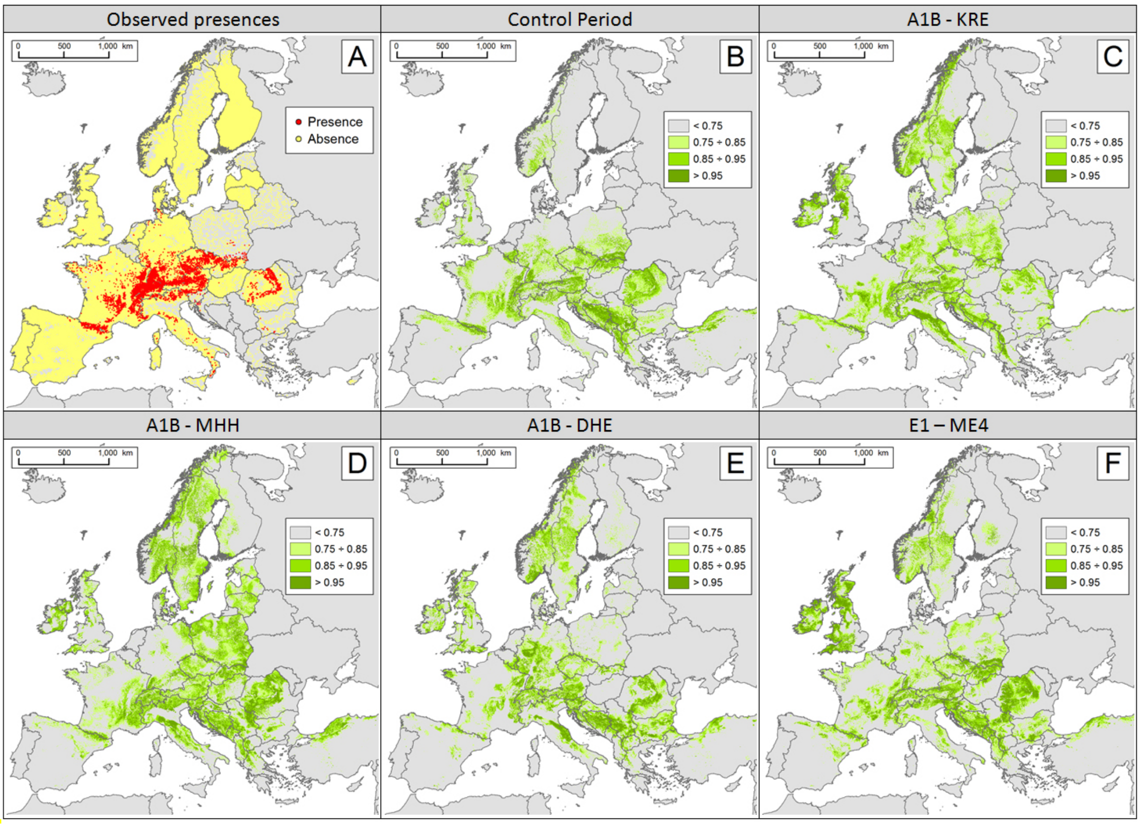
The habitat suitability (HS) of forest tree species study has been implemented using the Relative Distance Similarity-Maximum Habitat Suitability method (RDS-MHS [de Rigo et al. 2013a]). The RDS-MHS method is based on the Semantic Array Programming paradigm (de Rigo, 2012a; 2012b) applied to geospatial European-wide data on tree species distribution (from the European Forest Data Centre, EFDAC: National Forest Inventories and BioSoil data [Durrant et al., 2011]), high-resolution bioclimatic factors (WorldClim [Hijmans et al., 2005]) and geographic ones (topography from SRTM [Farr et al., 2007]) and solar irradiation [Hofierka et al., 2007]). Bioclimatic projections have been disaggregated at high-resolution (1 km2) with the change factor method (Tabor and Williams, 2010; Klausmeyer and Shaw, 2009) based on WorldClim current baseline and the future climate scenarios referring to the period 2069-2099 (A1B: KRE, MHH, DHE; E1: ME4, see Table 2 and Table 3).

Geospatial semantic array programming (GeoSemAP, de Rigo et al., 2013b) has been applied to estimate European-wide current and future geo-climatic similarity to the local conditions observed for the available field data of a reference tree species (European silver fir - *Abies alba*[29]). The similarity has been computed with the Mastrave RDS method (widely applied in different environmental problems, de Rigo et al., 2013c; Bosco et al., 2013a; 2013b). Areas with high dissimilarity from the currently observed geo-climatic conditions of forest field-data have been identified. Future climate scenarios predict large areas of Europe to possibly shift toward geo-climatic patterns which are far from any currently observed pattern in Europe. This wide shift introduces an intrinsic source of modelling uncertainty due to climate-driven extrapolation. Statistical resampling has been applied in order for the overall uncertainty of RDS-MHS estimates to be assessed with a robust ensemble approach (designed to address multiple sources of uncertainty in environmental problems, e.g. see [Rodriguez-Aseretto et al., 2013; de Rigo et al., 2013d; Di Leo et al., 2013]).

[29] *Abies alba* was selected because the plant is considered a good environmental indicator. In addition *Abies alba* is important for pulpwood and construction use in Europe. The population and distribution of *Abies alba* is stable and there is no evidence suggesting continuous decline. Nevertheless, major threats of this species are pollution and climate change. Furthermore it is included as a threatened species (least concern) in the International Union for the Conservation of Nature (IUCN) Red List.

The most salient finding of this study is a shift towards northern and higher elevation areas of potential future habitat of *Abies alba* under scenario A1B in 2080s. Figure 14 (B to F) shows the resulting HS maps implemented for *Abies alba*. The maps show HS of *Abies alba* under current climate, A1B and E1 future scenario conditions. In Figure 14 (B to F) HS is represented as a continuous probabilistic function with values ranging from 0 to 1 from less suitable to more suitable. Figure 14-A shows observed presence of *Abies alba*, Figure 14 B to F shows areas of high HS (>= 0.75) of *Abies alba* under current climate (B) and future scenarios A1B (C to E) and E1 (F). A shift in high suitable areas towards Northern regions is evident in the A1B scenario maps (Figure 14 C to E). New suitable areas are in the Scandinavian Peninsula, Poland, Northern British Islands and Ireland. Differences between different realisations of the scenario A1B are also evident in these figures, something that should be considered in assessing the uncertainty of using specific models simulations instead of ensemble data. Differences between current HS and scenario E1 are less evident. However, new suitable areas are in the Scandinavian Peninsula and Northern British Islands and Ireland. In addition to the shift to northern regions of suitable areas under the A1B scenario it is also remarkable a shrinking of suitable areas in mountain regions such as the Pyrenees, Alps and Carpathian. This is consistent with an upslope shift towards higher elevation.

Figure 14. Abies alba observed presence (A) and areas of high habitat suitability (>= 0.75) under current climate (B) and future scenarios A1B: KRE, MHH and DHE models (C, D and E) and E1: ME4 model (F). Source: JRC - EFDAC in the framework of JRC PESETA-II project



Results of this study are subject to a number of limitations and assumptions adopted. First, HS defines the regions where tree species actually or potentially lives. Therefore areas exhibiting high values of HS will likely host individuals of the species. However, several factors could make that the species is not present in suitable areas e.g. competition between species, anthropic land cover changes and disturbances. Hence, HS should not be understood as the actual current (or future) distribution of species. Second, migration of tree species is not considered in our modelling approach. Spatial shifts of HS as consequence of anthropogenic climate change can overpass natural dispersal capability of tree species, thus increasing extinction risk. Finally, interactions between tree species are not considered in the computation of HS.

An HS index was computed from the HS maps shown in Figure 14. The HS index is defined according to the percentage of land surface in each range (five classes) of HS. The scope of this assessment is measuring changes in the magnitude of HS between the control period and future scenarios. The index represents a balance between new, lost and stable suitable areas. HS describes the potential habitat of forest tree species across the landscape, thus HS is represented as a continuous variable (from 0% to 100%) in the geographical space. Low scores are associated with geo-climatic conditions outside the observed range of survivability of the reference species, in this case *Abies alba*. It is worth mentioning that the index of HS is a synthetic index that should be assessed carefully because it may hinder relevant local level shifts of HS due to the final aggregation in the macro regions in which local losses and gains (and consequent local impacts) might cancel each other out. Furthermore, even if all new suitable areas are considered positively, they can be colonized by the species only assuming infinite migration capacity or man-made seeding. Thus the effects of climatic changes on the distribution of the species under natural migration could be larger than as depicted in the index. Therefore, the proposed index is very conservative in assessing climate change impacts. From an ecological perspective, both HS gains and losses may cause negative effects to forest ecosystems.

Table 24 shows the habitat suitability index for *Abies alba* (silver fir). Over the whole EU the suitability index would increase by 5% under the Reference simulation. The Northern Europe region is the one with the highest increase (by 25%). In the two regions in the south of Europe (Central Europe South and Southern Europe) the model projects a slight fall in the suitability index. The EU change in the index is similar in the 2°C simulation, while the regional pattern has a bigger gain in the UK & Ireland region.

Table 24. Impact on habitat suitability index (*Abies alba*)

	EU	Northern Europe	UK & Ireland	Central Europe North	Central Europe South	Southern Europe
Control	100	100	100	100	100	100
Reference	105	125	108	103	98	95
change (%)	5	25	8	3	-2	-5
2°C	104	124	123	99	106	92
change (%)	4	24	23	-1	6	-8

Units: index = 100 in control period

Those large-scale results are reasonably in line with a closer look of HS at local level, where a shift of *Abies alba* HS towards northern regions and higher elevation is suggested under future climate scenarios. The shifts are more relevant in Reference than 2°C. Although the HS index is useful for representing a summarised overview of the situation in the whole European domain, some limitations should be considered. First, the index assumes infinite dispersal capacity of *Abies alba* so that new suitable areas compensate lost suitable areas even where their distance exceed the velocity of natural propagation. Decreasing HS, or disappearing areas of HS, are in reality not necessarily compensated by gains of HS in other areas. In fact our model provides potential suitable habitats and should not be interpreted as actual changes in the distribution of *Abies alba*. Natural dispersion is a very slow process (centuries) and could be limited by several factors such as the presence of agricultural areas, the competition with other dominant tree species which might produce outperforming growth and dispersion, presence of forest plantations (in which actually the future HS gain of a currently unsuitable species might impact as the introduction of an invasive species), etc. Second, the forest ecosystem damage resulting from species loss is not accounted in the index. In addition, the migration of species into new habitats could be problematic regarding species interactions in no-analogue communities (Urban et al., 2012). Having these limitations in mind, it is suggested that the assessment of HS is considered also on the light of spatial changes at local level and shifts as reported in de Rigo et al. (2013a). Therefore, from an ecological perspective, both HS gains and losses may cause negative effects to forest ecosystems.

4.11 Human health

The assessment of human health impacts (Paci, 2014) follows a similar methodology to that of the PESETA project (Watkiss and Hunt, 2012). Empirical exposure-response functions are used to relate changes in climate variables to mortality and morbidity change estimates. These relationships include acclimatisation, but they do not include any other form of adaptation (e.g. awareness campaigns, heat waves early warning systems, etc.), which could contribute to reduce the negative impact of climate change on health. The current population density (divided into three age groups) across Europe is taken into account and assumed to be constant in the future. The analysis relies on data at NUTS2 level.

Heat-related mortality and morbidity (due to cardiovascular and respiratory causes) and due to heatwaves (additional heat stress) are considered in the assessment. The evaluation includes also projection of morbidity due to food and water-borne diseases (salmonellosis and campylobacteriosis). Human health impacts of cold-related and reduced extreme cold days are not included in the assessment. The economic costs of the projected health impacts are calculated using multiple techniques to account for direct healthcare costs; productivity losses and the value of lives lost and years lost due to premature death.

Mortality projections due to heat stress and heatwaves provide a main indicator of how much climate change can affect human health.

Table 25 represents the estimated levels of mortality due to heat-related events per year (by the end of the century) in the various scenarios. Under the Reference simulation, this type of mortality more than doubles compared to the control simulation: change in climate condition is thus calculated to be responsible for more than 100,000 additional deaths per year at EU level. Most of the increase is simulated to happen in Central and Southern Europe, where the mortality doubles or more than doubles. The increase in mortality in the remaining two regions is much smaller, both in absolute and relative terms.

The 2°C simulation change in mortality is smaller than the Reference changes. The EU mortality increases by 79%, and more than one third of the absolute EU increase in climate-related deaths is simulated to occur in the Central Europe South region. Compared to the Reference scenario, Southern Europe is simulated to have a much lower increase in mortality, passing from 22,000 to 14,000 additional deaths attributable to climate change.

Table 25. Impact on mortality due to heat-related events

	EU	Northern Europe	UK & Ireland	Central Europe North	Central Europe South	Southern Europe
Control	98,968	6,412	13,127	30,911	26,861	21,657
Reference	200,507	8,825	18,299	60,411	69,484	43,489
change (%)	103	38	39	95	159	101
2°C	177,178	8,040	16,039	55,915	61,428	35,756
change (%)	79	25	22	81	129	65

Units: deaths/year

The results confirm to a large extent the results of earlier assessments (in particular, those from the PESETA and ClimateCost projects), although with slightly higher impacts (both in physical and economic terms). The reduction of mortality induced by cold is not included here unlike previous studies, which partly explains the overall higher mortality. Some important changes like the inclusion of more impacts (mainly heat wave stress on mortality and morbidity, and campylobacteriosis) and the exposure-response functions at the regional level (NUTS2) could add to the difference in the results.

The following points summarise the main limitations of the assessment:

- Because of data constraints, maximum temperature is used as the relevant climate variable. This is consistent with the exposure-response functions used in the model, however, the use of a thermal comfort index (e.g. Wet Bulb Globe Temperature or Discomfort Index), could have led to more accurate predictions and would have allowed to a more complete assessment of health impacts on labor productivity.
- The exposure-response functions are assumed to be linear and constant over time, except for the thresholds which varies in order to include acclimatisation.
- Socio-economic changes are exogenous in the model: no interaction between health and population in the different scenarios is accounted for.

Some of the climate change effects on human health have not been modelled and this may have an impact in the final results. The health impact of extreme events, except heat waves, is not estimated. Sea floods and river floods and other climate-change related natural disaster may have a significant impact on health which is not included in current results.

The model does not capture the impact of change in air quality due to climate change. For instance, tropospheric ozone concentration is known to increase with temperature and could result in higher mortality and morbidity projections.

4.12 Dynamic linkages land-water-energy

While the results presented in this report are based on a comparative static analysis (e.g.: exploring how energy demand would change in today's economy, but with future climate), a preliminary dynamic assessment was carried out to evaluate the potential for linking models for future impact assessments. The exercise focused on the impact of climate change on energy production and involved the coupling of the energy model POLES, the hydrological model LISFLOOD and the Land Use Modelling Platform LUMP[30]. For the sake of simplicity other linkages between energy and the rest of the economy (as included in the CGE analysis reported elsewhere in this document) were not included.

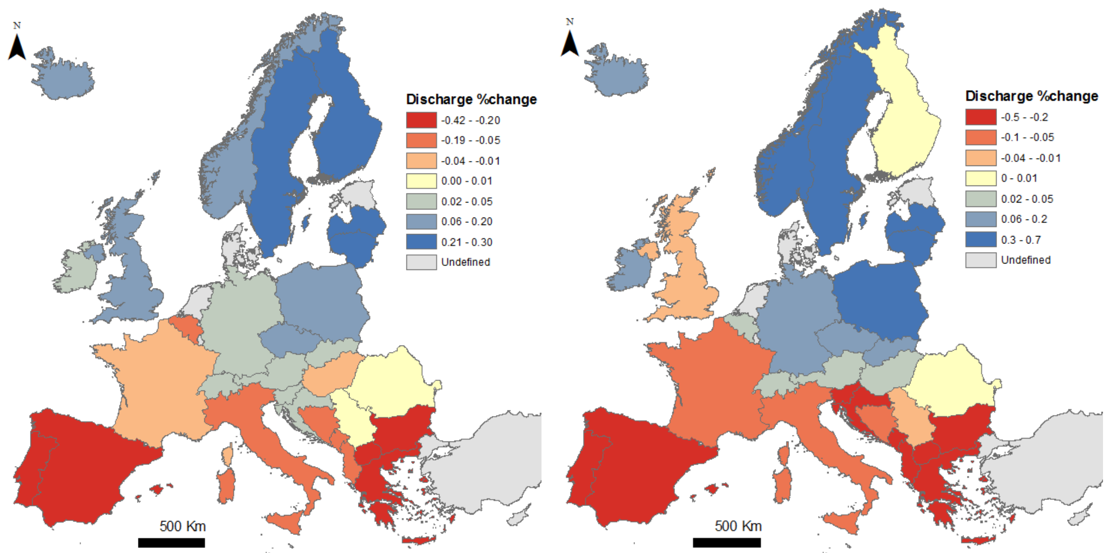
The dynamic assessment (Dowling, 2013) was performed considering several climatic factors affecting energy production. First, changes in demand for heating and cooling were modelled with POLES based on the changes in degree days computed from the climate simulations. Second, changes in energy production from hydropower were computed by POLES based on the climate-driven changes in hydrological regimes at hydropower stations as computed using outputs from the LISFLOOD model. The analysis also considered the effects of climate change on the efficiency of thermal power plants and changes in hydro, wind (both on- and off-shore) and solar PV electricity output. These energy impacts can however be considered steady-state impacts because they exclude extreme, short-lived impacts that cannot be captured because of both lack of climate data and incompatibility with the POLES energy model.

[30] http://ies.jrc.ec.europa.eu/our-activities/scientific-achievements/Land-Use-Modelling-Platform.html

The possible impact of the climate scenarios on future hydropower potential was done by assessing the evolution of predicted river discharges in 1387 hydropower stations[31] for the whole of Europe (including non EU member states).

Average annual discharge values were modelled in LISFLOOD for the period 2000-2050 for each climate scenarios and were summed per country and per hydropower plant type (run-of-river/hydro or pumped storage). These values have been than used in POLES. The computed changes in discharge are shown in Figure 15 for the averaged A1B scenario and the 2°C scenario. Number and capacity of stations have been assumed to remain constant over time.

Figure 15. Average annual change in river discharge for run-of-river stations, based on the average station discharge per country over the period 2000 - 2050

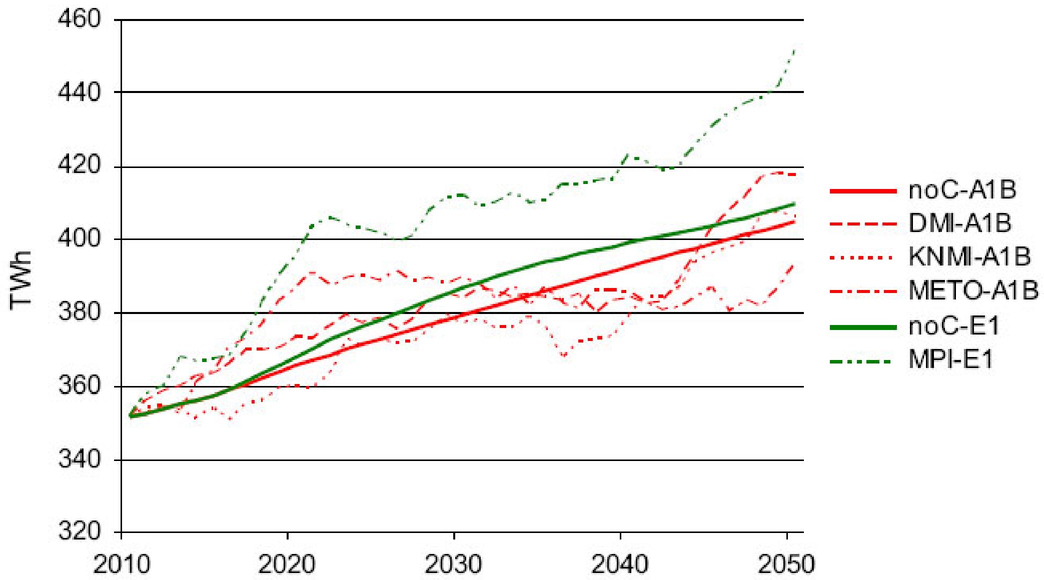


Note: The average of the values derived from the A1B scenario simulations (left) are compared to those from the 2°C scenario (right). Countries which are shown as being undefined in the figures lacked sufficient data to compute the factor (i.e. had an insufficient number of hydropower stations).

The results, as reported by Dowling, 2013 (Figure 16) suggests that the impacts of precipitation changes on hydropower in the EU are an order of magnitude less important than other climate related impacts such as temperature for what concerns heating and cooling demand and power plant outputs.

[31] Locations are reported in the Major Industrial Plant Database (IHS) and the World Electric Power Plants Database (PLATTS).

Figure 16. EU27 total electricity production from hydro, per scenario (TWh)

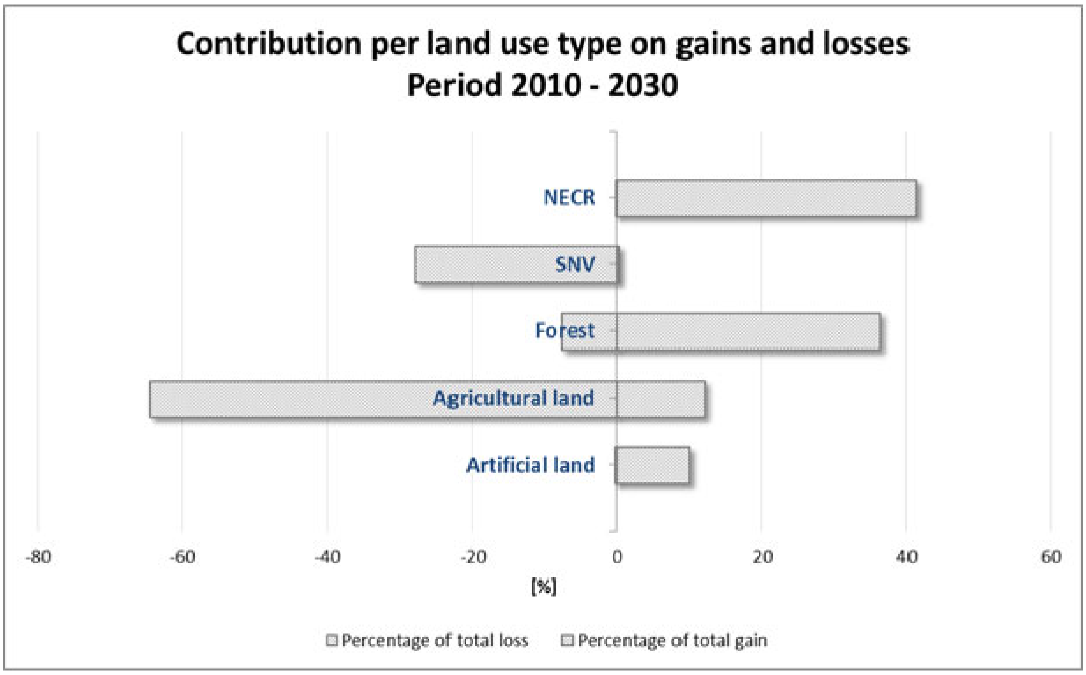


Source: Dowling (2013)

Additionally, land use changes driven by future population structure and economic outlook, as depicted for specific climate scenarios have been analysed using the European Land Use Modelling Platform[32]. A linkage was developed between LUMP and POLES to include biomass supply in the evaluation of future energy shares. Projected land use/cover classes for urban, natural and semi-natural, forest, agricultural and water areas were modelled by LUMP taking into account both static and dynamic factors in order to model investments and natural succession processes. Employment, population and GDP figures driving LUMP are coming from the A1B scenario to guarantee internal consistency in the simulations. Climate impacts are included in LUMP via these variables since for this experiment climate is not considered for land-use allocations and can therefore be considered a 'no climate change' baseline. The land use changes for the period 2010-2030, as produced by LUMP, are synthetized in Figure 17.

[32] http://ies.jrc.ec.europa.eu/our-activities/scientific-achievements/Land-Use-Modelling-Platform.html

Figure 17.Gains and losses of aggregated land-use classes, at European level and under the A1B Scenario

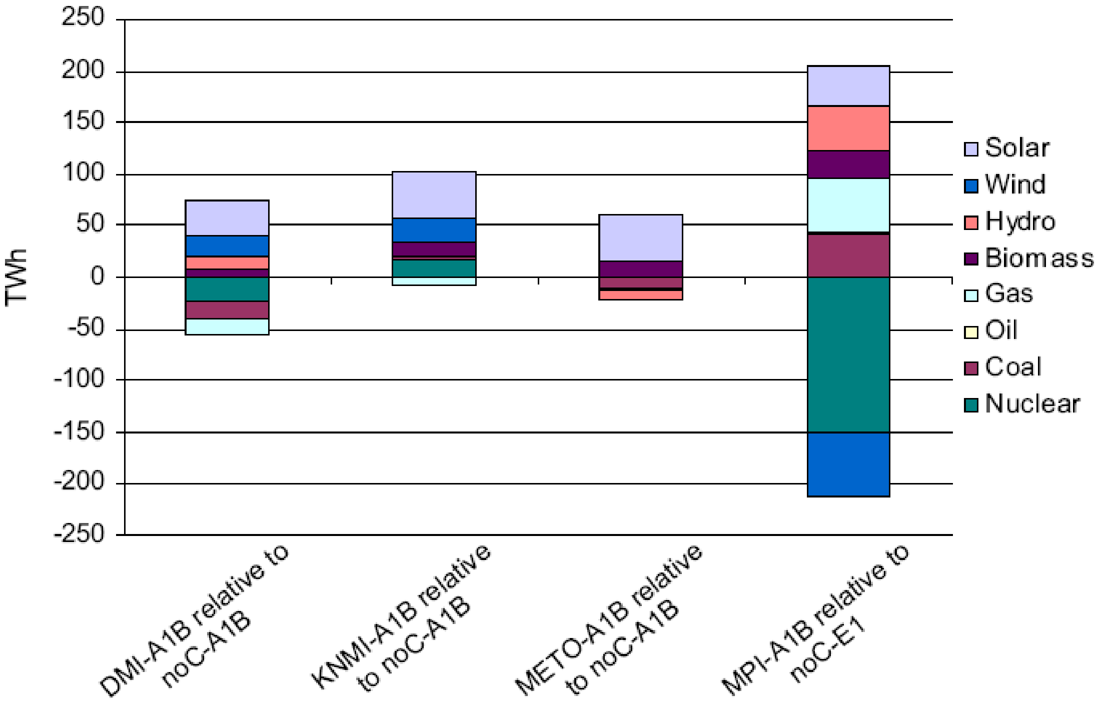


Note: NECR=New Energy Crops, SNV=Semi-natural Vegetation.

Three land uses (namely: forest land, arable land and permanent crops) can provide biomass availability for use in the energy sector. Changes in biomass supply are translated into changes in biomass prices via the POLES-endogenous biomass cost curves.

For the exercise performed in PESETA II, the changes in biomass land area (as produced by LUMP) have been considered to retrieve the biomass cost-curves in POLES for the scenario A1B, and then extrapolated to other scenarios. The changes in the EU energy mixing, as produced by POLES is below reported.

Figure 18.Change in EU27 total electricity generation by source in 2050, per climate change scenario compared to no climate change scenarios



Source: Dowling (2013).

As observed by Dowling (2013), the climate impacts on thermal and nuclear power generation, where increased cooling requirements lead to lower efficiencies, is the main driver of these results. The climatic impact on renewables is relatively minor and due the less competitive thermal and nuclear power generation, rather than due to increased renewable supply from climate change.

The analysis has focused on the implementation of the A1B scenario and aimed to test the feasibility and the interconnections between the macro-economic and the bio-physical models. Eventually this should evolve towards a fully integrated dynamic system, which is aimed to be accomplished in the next phases of the PESETA work at the JRC.

5 Economic impact: methodology and results

The previous section has compared the various direct or biophysical impacts across climate simulations and EU regions. Different impacts have different metrics and can be considered in their own right, without necessarily having to monetise them[33]. In this section, most of the sectoral direct impacts[34] are integrated into the computable general equilibrium (CGE) economic model GEM-E3 in order to make them comparable under a common economic framework (Ciscar et al. 2014). Previous studies have made a similar integration of biophysical climate impacts into a CGE model; recent references are e.g. Bosello et al. (2012) and Reilly et al. (2013)[35].

The CGE framework is relevant as it provides a mean of assessing the relative economic importance of a number of different heterogeneous direct impacts (for example, allowing to compare the relative importance of a 2% increase in tourism expenditure and a 3% fall in crop yields).

5.1 Economic integration methodology: multi-sectoral general equilibrium analysis

The CGE analysis allows accounting for a broader set of impacts, beyond the direct effects. Indeed, the direct impacts, as studied in the previous section, only take into account the effects within the market where the impacts are occurring. For instance, in the case of the agriculture model the change in yields (in terms of tons per hectare), as computed from the agriculture biophysical model, only consider the effects within the agriculture markets and within the country.

Two other categories of indirect effects are relevant: cross-sectoral and cross-country. Firstly, the cross-sectoral impacts are effects on other economic sectors or markets of the economy that are linked with the sector upon which the shock is imposed on (in the case of the previous example, the agriculture sector) via commercial relations. One of those sectors can be for instance the agri-food industry

[33] They could be introduced in a more elaborate multi-criteria assessment of climate change impacts, which is however outside the scope of this report.
[34] This section considers only the impacts for which economic analysis was undertaken. Therefore droughts and habitat suitability are not included.
[35] For a review of the literature see Vivid Economics (2013).

sector, whose main input comes from the agriculture sector, i.e. purchases of agriculture goods, which the agri-food industry transform to produce elaborated products.

Secondly, there are also indirect effects in other economies due to the trade flows between countries (both imports and exports). For instance, if one country faces a large negative shock, its production level will fall, which will lead to less imports from other economies. This kind of analysis is applied to the assessment of the size of the possible transboundary or cross-country climate impacts within Europe (see subsection 5.6).

Both categories of indirect effects can be computed with a CGE model[36]. Therefore, the direct effects are integrated into an economic CGE model, yielding total impacts, composed of the direct and indirect effects. The use of a multi-sector, multi-country general equilibrium model such as GEM-E3 permits that the estimated economic impacts include both the direct impact of climate change (e.g. the losses in the agriculture sector due to lower yields) and the indirect consequences in the rest of the sectors (e.g. in the agrofood industry) and the rest of the EU (considered via trade flows). This kind of general equilibrium effects are explored in this section.

The GEM-E3 model[37] is used to compute the overall economic impacts of climate change (see Annex II for further details on the model). The model uses a computable general equilibrium (CGE) approach that allows exploring not only the direct effects, but also the indirect, economy-wide economic impact, taking into account cross-sectoral feedback mechanisms.

The GEM-E3 CGE model analyses the interactions between the economy, the energy system and the environment. The current EU version is based on EUROSTAT data (base year 2005), with most member states individually modelled. The countries are linked through endogenous bilateral trade flows. The GEM-E3 model integrates micro-economic behaviour into a macro-economic framework and allows the assessment of medium to long-term implications for policies.

[36] The CGE methodology allows to consider many other mechanisms at play in an economy, such as factor substitution and the adjustments in the labour and capital markets.
[37] Capros et al. (2013). Visit also www.gem-e3.net.

It should also be noted that while EU countries are affected by climate change in the modelling setup, it is assumed that the rest of the world is not. Moreover, as explained in subsection 2.2, a comparative static analysis is implemented, shocking the current economy with future climate changes.

5.2 Implementation of the climate shocks into the economic model

The various impact categories are integrated by changing specific elements of the GEM-E3 model depending on the effect of climate impact on the real economy. In particular, changes have been made to the production structure of the firms, the supply of capital, labour and technological progress as well as to the structure of household consumption and bilateral trade preferences of certain sectors. Table 26 summarizes how the different impact categories have been interpreted and implemented in the GEM-E3 model[38].

Agriculture, river flood and coastal impacts have been integrated in the same way as in the PESETA project (Ciscar et al. 2012b). First, the agriculture model produces estimates of agriculture yields, implemented in the model as changes in productivity in the agriculture sector[39]. Second, the effects due to river floods have two main components: damages to residential buildings and damages to production sectors. The former component is interpreted as an additional obliged consumption of households, which leads to a welfare loss[40]. The latter component has been implemented in the model as a capital loss. Third, coastal impacts have also two main damage categories. Sea flood damages are interpreted as capital losses. The migration costs are modelled as a change in obliged consumption, leading to a welfare loss. When people migrate, they undergo certain migration costs, which reduce the consumption possibilities of the households. In other words, maintaining the same level of welfare will now require additional spending due to migration costs.

[38] A similar methodology was followed in the PESETA project (see Ciscar et al., 2012b).

[39] The model has a unique agriculture sector, so there is no distinction across crops. The price of the agriculture good changes as a response to the productivity change.

[40] Due to the fact that there is now less money available for the (non-obliged) consumption of (other) goods.

Fourth, heating and cooling demand changes are modelled as changes in residential and service sectors energy demand. A fifth impact category relates to transport infrastructure. Additional costs for road asphalt (due to heat stress) and bridge scour (due to river flows) are modelled as additional obliged consumption, implicitly assuming that the households would ultimately undergo those costs. All other damages to transport infrastructure, associated with extreme floods and winter conditions, are interpreted as capital losses in GEM-E3, because they can be interpreted as affecting firms (the capital stock of the economy). A sixth impact category deals with forest fires: the burned area damages are implemented as capital losses[41] and the restoration costs as obliged consumption of households.

Seventh, tourism impacts are modelled in terms of trade shocks (change in imports and a shift in origin countries) to the sectors involved in tourism activities (market services and non-market services)[42].

Finally, regarding human health impacts, four kinds of effects are considered. The first effect is a change in labour productivity (associated with warmer temperatures) which leads at first to lower productivity in the sectors with predominant outdoor activity, i.e. agriculture and construction. This approach is based on the relationship between WBGT (a combined measure of heat and humidity exposure) and labour productivity (Kovats and Lloyd, 2011). The baseline regional Wet Bulb Globe Temperature (WBGT) index has been adapted to the increase in average mean temperature in the region according to the climate simulation, from which then a change in labour productivity has been computed.

A second effect is the increase in household health system expenditures due to morbidity, which is imposed on households as additional obliged consumption that does not lead to an increase in welfare due to increased consumption volumes. The third effect is the reduction in total available hours (working and leisure hours) due to both morbidity and mortality of the working age population. The fourth effect is a typical non-market impact due to mortality, which does not affect the price system,

[41] The capital loss is allocated to the agriculture-&-forestry sector of the economy. The primary factor values from the GTAP database were used to calculate the contribution of the forest "natural resource" to this sector.

[42] The changes of tourism expenditure by destination country are introduced into the model by changing the share parameters of the Armington specification for trade. These parameters affect the share of goods that is produced domestically, the share that is imported and the origin of the imports.

and therefore does not affect the general equilibrium of the model. The number of premature deaths is considered as damage to the total welfare of the population. This damage is calculated by using the statistical value of life method. Therefore the overall welfare loss is the number of premature deaths times the value of statistical life (VSL). That is an ex-post[43] change in welfare level. The VSL has been assumed to be €1.09 million (same value for all member states), the low-end of the range of estimates considered in the recent review of the European Clean Air Policy Package (European Commission, 2013b). The assumed value is lower than the low-end of the range for the EU found in the meta-analysis of the literature made by OECD (2012)[44].

[43] Ex-post in the sense that it is not introduced into the CGE model. It is a change of the welfare level made once the model has been run.

[44] For EU-27 the base range for the average VSL is $1.8–5.4 million ($2005), with a base value of $3.6 million.

Table 26 Implementation of sectoral climate impacts in GEM-E3

Impact	Biophysical model output	Model implementation
Agriculture	Yield	Productivity change for crops
Energy	Heating and cooling demand	Energy demand changes in residential and service sectors
River floods	Residential buildings damages	Additional obliged consumption
	Production activities losses	Capital loss
Forest Fires	Burnt area	Capital loss
	Reconstruction costs	Additional obliged consumption
Transport infrastructure	Changes in cost of road asphalt binder application and bridge scouring	Additional obliged consumption
	Net change in costs related to extreme flooding and winter conditions	Capital loss[45]
Coastal areas	Migration cost	Additional obliged consumption
	Sea floods cost	Capital loss
Tourism	Tourism expenditure	Changes in destination and tourism expenditure by bilateral import preferences
Human health	Hours lost due to Morbidity and mortality	Change in labour supply
	Additional health expenditures (morbidity)	Additional obliged consumption of health services
	Warmer temperature	Labour productivity change in agriculture and construction sectors
	Mortality	Welfare loss (ex-post)

5.3 Impacts on GDP and welfare

This section presents the main economic results of the integrated modelling exercise[46], comparing the range of climate impacts for the European economy of 2010 with and without the expected climate change of the 2071-2100 period (a 30-

[45] Capital loss can be negative when combined changes in winter conditions and extreme flooding create conditions that are more benign than the baseline.
[46] The results here presented are very similar to those published in the Impact Assessment, with the exception of transport infrastructure, which have been revised.

year average)[47]. Two main metrics of economic results are considered: effects on household welfare and Gross Domestic Product (GDP).

Welfare is obtained by consumers when they choose to spend their time either on working (in order to earn income for the purchase of goods and services) or on not working (thereby "consuming" leisure). Consumers have a total endowment of time which they distribute between these two possibilities depending on their preferences and incomes, the value of their labour (the real wage), and the prices of goods and services. It is assumed that each consumer must consume a subsistence amount of each good (including leisure) which does not contribute towards welfare (obliged consumption and obliged leisure). Therefore welfare is derived from consumption of goods, services and leisure above the subsistence level. Change in welfare in monetary terms is calculated using the concept of equivalent variation. This measures the cost (at constant baseline prices) of restoring households' baseline welfare levels once climate changes have occurred. The welfare changes are reported relative to GDP in order to compare results across regions.

GDP is a measure of the value of production of the economy, and it is interesting to report also the climate impacts in that dimension or metrics. The GDP change provides an indication of the adjustment made in the supply side of the economy due to the consequences of climate change in different parts of the economic system. Climate change can affect the supply side of the economy (e.g. productivity of agriculture or capital losses due to river floods) and the demand of goods and services (the cooling demand of households).

GDP and welfare impacts are provided in monetary terms, are presented undiscounted (in 2005 Euros), and are on an annual basis. It is important to recall that they are one-off impacts and cannot be interpreted as impacts affecting economic growth because the economic analysis is in comparative static terms.

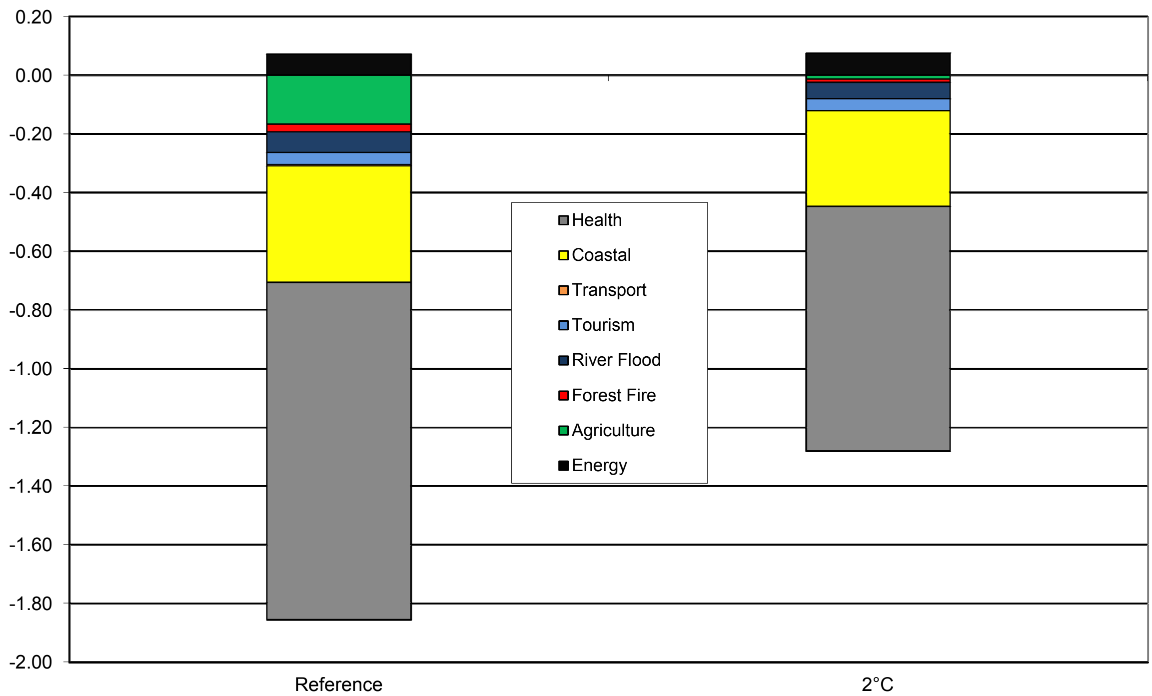
For a CGE analysis the welfare metrics seems more appropriate because the model assumes that households are optimizing their utility or welfare level. Changes in welfare are therefore closely linked to the level of welfare of the citizens or households of the country. On the contrary, in some cases changes in GDP can be

[47] In more precise terms, the impacts derived of comparing the future climate scenarios of the 2071-2100 with the climate of 1961-1990 are computed and imposed on the 2010 economy.

positive while implying a loss in welfare. For instance, if there is a damage that is restored, it is generating increased expenditure demand and thereby increased production in the economy (i.e. GDP) but households are worse off compared to the situation without the climate shock. In addition, the opposite effect can result, whereby GDP reduces due to an increase in wages and thus deterioration of trade competitiveness but at the same time welfare can improve due to a higher disposable income for the households.

Figure 19 presents the range of welfare changes for the eight impact categories[48] in the Reference and 2°C simulations across the EU as a whole. The vertical axis represents welfare changes (in Equivalent Variation (EV) terms) as % of GDP. In reading Figure 19 and the following figures, it should be kept in mind that the level of uncertainty analysis available for individual sectors is very different.

Figure 19. EU welfare impacts in Reference and 2°C simulations (EV as % of GDP)



Source: Results of JRC PESETA II project

The net welfare loss is estimated to be 1.8% of GDP under the reference simulation. The greatest negative impacts (2/3 of the total) are associated with the damages to human health, being mostly due to premature mortality. In this respect, a similar result in terms of the dominance of the health impacts over other impact categories

[48] Impacts related to habitat suitability and droughts were not considered in the economic CGE analysis.

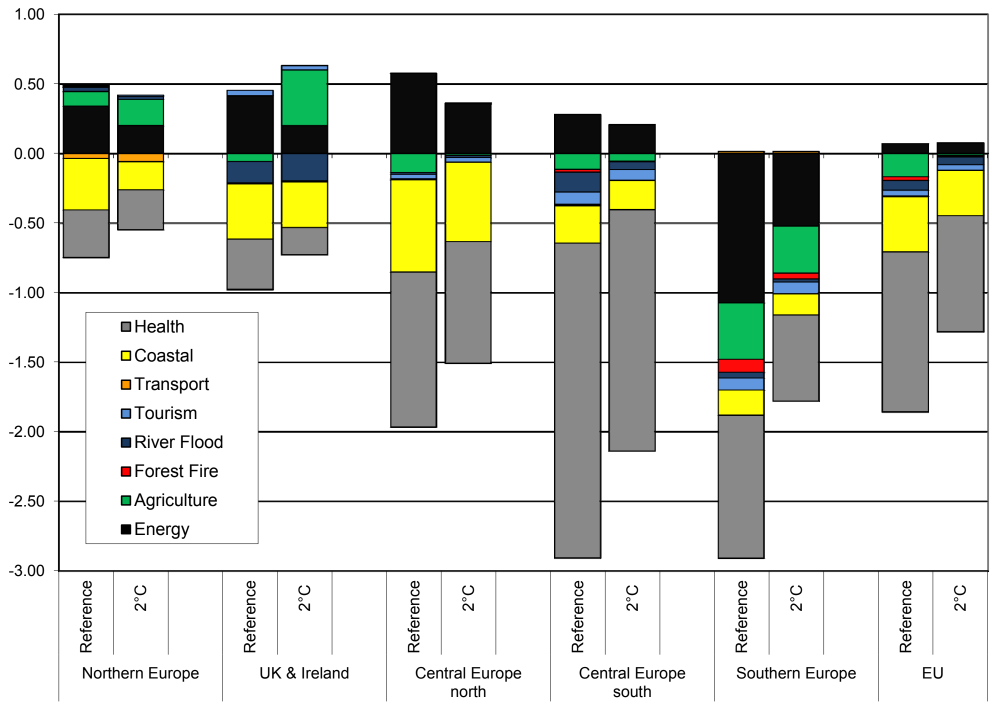
was obtained in the recent review of the European Clean Air Package[49]. Moreover, this also illustrates the fact that ignoring non-market impacts in the economic analysis of climate impacts can lead to severe underestimation of the overall climate damages. In this assessment only one category of non-market impact has been considered (higher premature mortality due to increased temperature and heat waves), but it amounts to twice the total of all the market impacts. Therefore it becomes essential to include in future analysis other non-market effects, as noted in section 8.

Coastal areas and agriculture have lower relative importance, while river floods, forest fires, tourism impacts and damage to transport infrastructure represent a small share of the overall damage. The only positive impact is energy — due largely to the reduction in heating demand and thus to ability of the households to diverge their consumption to other goods and services. Moving to a 2°C simulation would reduce the net welfare loss to 1.2 % of GDP, mainly due to the reduction of the impacts on human health, coastal areas and agriculture and, to a lesser extent, river floods.

The overall EU climate impacts are disaggregated by EU region in Figure 20 for the reference and 2°C simulations. Regarding the reference simulation, in all regions, with the exception of Southern Europe, energy impacts are positive. As one moves from the North to the South of Europe the welfare losses in terms of GDP become much higher, ranging from 0.2% in the Northern Europe region to 3% both in Central Europe South and Southern Europe.

[49] When implemented, the European Clear Air Package (European Commission, 2013), is estimated to avoid 58,000 premature deaths, which can be monetized in resulting in about €40-140 billion. The rest of the direct benefits to society include the higher labour productivity of the workforce (€1850 million), lower healthcare costs (€650 million), higher agriculture yields (€230 million) and less damage to buildings (€120 million), and around 100 000 additional jobs due to increased productivity and competitiveness because of fewer workdays lost.

Figure 20. Welfare impacts for EU regions in Reference and 2°C simulations (% GDP)



Source: Results of JRC PESETA II project

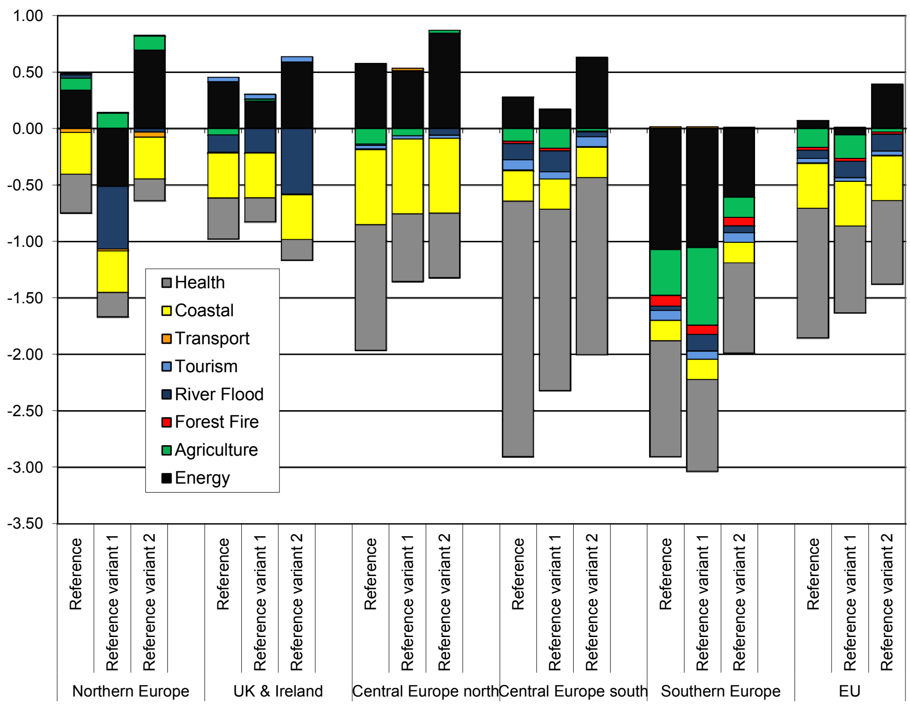
For the reference simulation, reading from left to right of Figure 20, Northern Europe could have welfare gains associated mainly with lower energy expenditure. Impacts in human health and coastal areas are the main negative climate impacts, while damage to transport infrastructure is relatively less relevant. The negative climate impacts in UK & Ireland are due to sea level rise in coastal areas, human health and river floods. The negative impacts in the Central Europe North area bigger than in the noted regions, and are mainly provoked by human health and sea level rise.

The EU regions in the south of Europe would experience the highest welfare losses in relative terms in the reference simulation, reaching almost 3% of GDP. The Central Europe South region could register very large impacts due to human health. This is associated with the assumption that the economic valuation of life is the same for all EU regions and thus relatively higher for Central Europe South in terms of income, resulting then in significant economic impacts.

All other sectoral impacts are comparatively much less important in that region. The Southern Europe region impacts appear to be driven mainly by the energy and human health effects and, to a lesser extent, by agriculture, coastal damages, forest fires and river floods. The negative impacts become generally smaller under the 2°C simulation, with the highest relative fall in the Southern Europe region.

Figure 21 represents how impacts change in the two variants of the reference simulation (variant 1 is warmer than the reference and variant 2 colder, subsection 3.3). Some specific impact categories experience large changes in damages between the variants, e.g. energy in Northern Europe (where cooling demand in variant 1 is considerably higher), river floods in the Northern Europe and UK & Ireland regions, and human health in most regions. This issue is further explored in a later section dealing with uncertainty (section 7).

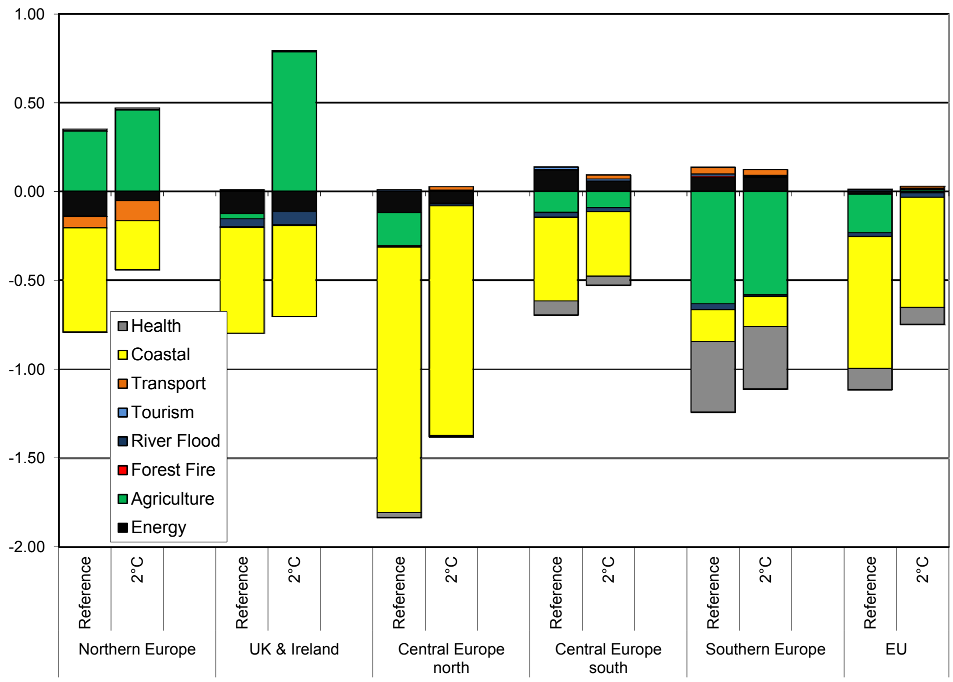
Figure 21. Welfare impacts for EU regions in Reference simulation and variants (% GDP)



Source: Results of JRC PESETA II project

Figure 22 shows the GDP effects for the EU. Under the Reference simulation, EU losses could reach 1.1% of GDP (compared to the GDP of 2010 in the simulation without climate change) mainly because of impacts on coastal areas and, to a lesser extent, agriculture and human health. The overall GDP loss is reduced to 0.7% under the 2°C simulation. Regarding the regional pattern of the Reference simulation impacts, the Central Europe North is the area most affected in terms of GDP losses (up to 1.8% of GDP), due to sea level rise. Southern Europe GDP losses are close to 1.3% of GDP, mainly led by agriculture impacts and decreased outdoor labour productivity. Overall, the activity levels of the agriculture sector due to deterioration of both land and labour productivity are heavily affected in Southern Europe, the EU region with the highest share of agriculture in the economy.

Figure 22. GDP impacts (%)



Source: Results of JRC PESETA II project

Regarding human health, the predominant economic effect, among those analysed, is the negative impact of increased temperature and humidity on labour productivity of outdoor economic activities. This effect is most significant in the Southern European region, where temperature rise is the highest (e.g. an increase in summer close to 4°C, Table 8).

In all considered regions, GDP losses become smaller when one moves from the reference simulation to the 2°C simulation.

Recall that when comparing economic damages across sectors, it is essential to consider both welfare and GDP, since the choice of metric has a large influence on the relative importance of the sectoral damages (as shown by comparing Figure 20 and Figure 22). In GDP terms, the greatest damages are caused by coastal impacts and agriculture while the effect of energy demand and river floods appears relatively unimportant. GDP effects are larger in cases where damages are felt by the productive side of the economy. This includes coastal impacts, which are implemented in the CGE model as destruction of productive capital, and agriculture, where changes in yield are considered as changes in productivity.

However, in terms of welfare the effects of human health (all over Europe), coasts (UK and Ireland, Central Europe North), energy demand (Southern Europe) and river floods (UK & Ireland) are among the most important.

Of the two metrics, welfare is considered to be the most appropriate since the GEM-E3 model is rooted in neoclassical economics, where households pursue the maximisation of their welfare levels. In cases where damage consists primarily of compulsory consumption (e.g. river floods, energy[50] and health expenditure) the welfare effects are much more notable than GDP, since the household is obliged to consume goods due to climate change for which it does not gain any additional utility or welfare but at the same time reduces the consumption of other goods due to the budget constraint. For example, in the case of river floods, households spend money repairing the flood damages in the residential buildings, instead of allocating that money to other purposes. In the end, the overall level of production and demand in the economy remains similar to baseline levels, but the welfare level is lower.

Regarding human health impacts it should be noted that most of the damage in welfare terms is due to the non-market component of the analysis, i.e. the valuation of premature deaths. That effect is captured by the welfare measure, but not by the GDP metrics.

In GDP terms, the effect of lower outdoor labour productivity predominates. It should be taken into consideration that the relative importance of welfare losses associated with mortality are higher in the EU regions with relatively lower per capita income levels, as the same value of statistical life is applied to all member states. However, this does not affect the relative results significantly since these regions appear to also have the most significant health impacts, according to the biophysical study.

[50] In the case of energy, the compulsory consumption consists of a change in the amounts of heating and cooling. For the other sectors, compulsory consumption refers to expenditure needed to repair climate change damages (e.g. by repairing roads, or moving house in response to flooding).

Concerning energy, it can be seen that the fall in welfare is greatest in regions where energy demand rises the most (such as in Southern Europe, due to increased cooling demand[51]), thus causing a large increase in compulsory expenditure[52], displacing consumption for other goods. However, this increase in demand for energy services also increases GDP. Therefore, the energy shock is associated with both an increase in GDP and a fall in welfare. This effect is mainly driven by the economy's capacity to produce its own energy, the levels of imports or exports of other consumption goods, and the degree to which domestic industries can benefit or not from (or be harmed by) an increased domestic energy demand.

5.4 Hot spots analysis

This section identifies the areas where the simulated climate impacts can be more severe, in terms of both geographical areas and impact types. Table 27 represents the distribution of the overall impact (normalised to 100 = overall EU impact) for the two dimensions. The overall EU welfare loss is estimated to be €190 billion. With respect to the impact types, negative impacts on human health become the most important ones (€122 billion, 64% of the overall impact), followed by those on coastal areas (€42 billion, 22% of the overall impact) and agriculture (€18 billion, 9% of the overall impact).

Regarding the geographical dimension of impacts, the most affected region is Southern Europe (39% of overall damage). In that region, energy damages alone account for 15% of the welfare loss experienced in the whole EU, and human health 14%. The second most affected region is Central Europe South (31% of overall damage), where the main impact is due to human health, which contributes to 27% of the net EU welfare loss. Central Europe North undergoes 24% of the EU damage (19% of the EU welfare loss due to human health and 11% due to coastal areas, partly compensated by a positive 10% in energy). In the UK & Ireland region the greatest negative impact is human health and sea level rise.

[51] As the additional cooling demand is mainly in terms of electricity, it also leads to relatively higher primary energy demand because there are transformation loses.

[52] Additional spending on energy in order to maintain the same level of comfort as the control case is considered compulsory expenditure.

Table 27. Share of climate welfare impacts per category and region in total impact (reference simulation)

	Coastal Areas	Energy	Agriculture	Forest Fires	River Floods	Tourism	Transport	Human Health	Sum of impacts
Northern Europe	-1	1	0	0	0	0	0	-1	-1
UK & Ireland	-4	4	-1	0	-2	0	0	-4	-5
Central Europe north	-11	10	-2	0	0	-1	0	-19	-24
Central Europe south	-3	3	-1	0	-2	-1	0	-27	-31
Southern Europe	-2	-15	-5	-1	-1	-1	0	-14	-39
EU	**-22**	**4**	**-9**	**-1**	**-4**	**-2**	**0**	**-64**	**-100**

Source: results of JRC PESETA II project

Looking at the potential for hotspots due to climate change (highest values in Table 27), human health appears as the most important impact driver (27% of overall damage in Central Europe South, 19% in Central Europe North and 14% in Southern Europe). Energy impacts in Southern Europe (15% of the overall EU impact) and the coastal impacts in Central Europe North (11% of the overall EU impact) are key areas that would also deserve particular attention in order to minimise the adverse effects of climate change. Areas that are also potentially relevant for climate change adaptation seem to be coastal impacts and agriculture.

Under the E1 scenario simulation, where global warming is limited to 2°C, total welfare damages would fall by €60 billion, reaching €128 billion, compared to €190 billion in the Reference A1B scenario. In the 2°C scenario, human health impacts are the most important impact category, representing 69% of the overall net damage (Table 28). This compares to 64% in the reference simulation (Table 27). That shows that even under a climate future with lower emissions, human health related impacts appear to drive most of damages in Europe, with the Central Europe South region remaining the most vulnerable to human health (34% of the EU total net damage in the 2°C scenario). The main benefit from E1 scenario compared to the reference is the reduction in welfare loss in human health (€34 billion reduction), agriculture (€16 billion reduction), and coastal areas (€8 billion reduction).

Table 28. Share of climate welfare impacts per category and region in total impact (2°C simulation)

	Coastal Areas	Energy	Agriculture	Forest Fires	River Floods	Tourism	Transport	Human Health	Sum of impacts
Northern Europe	-1	1	1	0	0	0	0	-1	-1
UK & Ireland	-5	3	6	0	-3	0	0	-3	-1
Central Europe north	-14	9	0	0	0	-1	0	-22	-29
Central Europe south	-4	4	-1	0	-1	-1	0	-30	-34
Southern Europe	-3	-10	-7	-1	0	-2	0	-12	-35
EU	**-27**	**6**	**-1**	**-1**	**-5**	**-3**	**0**	**-69**	**-100**

Source: results of JRC PESETA II project

5.5 Adaptation implications in coastal impacts (2080s)

Public adaptation measures considered in the DIVA coastal impacts model include dike building and beach nourishments. The adaptation measures considered in DIVA relate to building dikes and beach nourishments. The GEM-E3 model has been run for the reference case when there is public adaptation to sea level rise. In that case (Table 29) the overall welfare loss in the EU would be reduced from 42 billion Euros (under no adaptation) to 1.6 billion (with adaptation). This shows that there is large scope to avoid the coastal damage costs incurred in the Reference scenario.

Table 29. Effects of adaptation in coastal impacts (reference simulation)

	No Adaptation	Adaptation
Northern Europe	-2,485	-43
UK & Ireland	-7,616	-181
Central Europe north	-21,483	-844
Central Europe south	-6,011	-378
Southern Europe	-4,659	-132
EU	**-42,253**	**-1,577**

Source: results of JRC PESETA II project

These types of adaptation measures would themselves incur both capital and maintenance costs. The DIVA model estimates the total cost of additional beach nourishment and dikes for the period 2005-2095 to be €193 billion[53], consisting of

[53] The €193 billion is calculated in cash terms (€2005) and is additional to the cost of protection needed under a No Climate Change scenario. The net present value of this expenditure, using a 5% discount rate, comes to €27 billion.

average annual expenditure of around €1 billion up to the 2020s, €2 billion in the 2050s and over €2.5 billion in the 2080s. The DIVA analysis considered only 'hard' adaptation measures, though in practice these would need to be considered alongside softer measures such as improved building standards or gradual relocation of formerly coastal assets towards the end of their useful lives.

5.6 Adaptation implications in agriculture (2020)

Climate change is expected to increase EU average crop yields by 2020 (as discussed in subsection 4.2), though variation between regions, crop types, and climate scenarios is considerable. Under the Reference Variant 1 and Variant 2 versions of the A1B SRES scenario[54], yield changes per crop of between -70% and +90% are expected at NUTS2 level, though variation is lower at EU level (between -37% and +20%). As Figure 23 shows, yield changes without adaptation are broadly positive, with falls confined mainly to sunflower.

Economic analysis suggests a change of between -0.3% and +8% in EU agricultural income, but with a large regional variation. Small positive impacts are observed in total welfare (up to 0.2%). However, it is important to note that this analysis does not take into account the impacts of climate change on yields outside the EU, which have some influence on agricultural production in the EU.

Adaptation is capable of increasing yields above baseline[55] levels for all crops examined (maize, sunflower, rapeseed and wheat) thus having important implication for prices and income. It is important to note that in this analysis adaptation consists predominantly of changes in growing cycle length and sowing date[56], which do not require any increase in inputs[57].

[54] Reference Variant 1 consists of the HADCM3 GCM nested with the HadRM3 RCM. Reference Variant 2 consists of the ECHAM5 GCM coupled with the HIRHAM5 RCM. This is consistent with the Other Impacts classification given in Table 4.

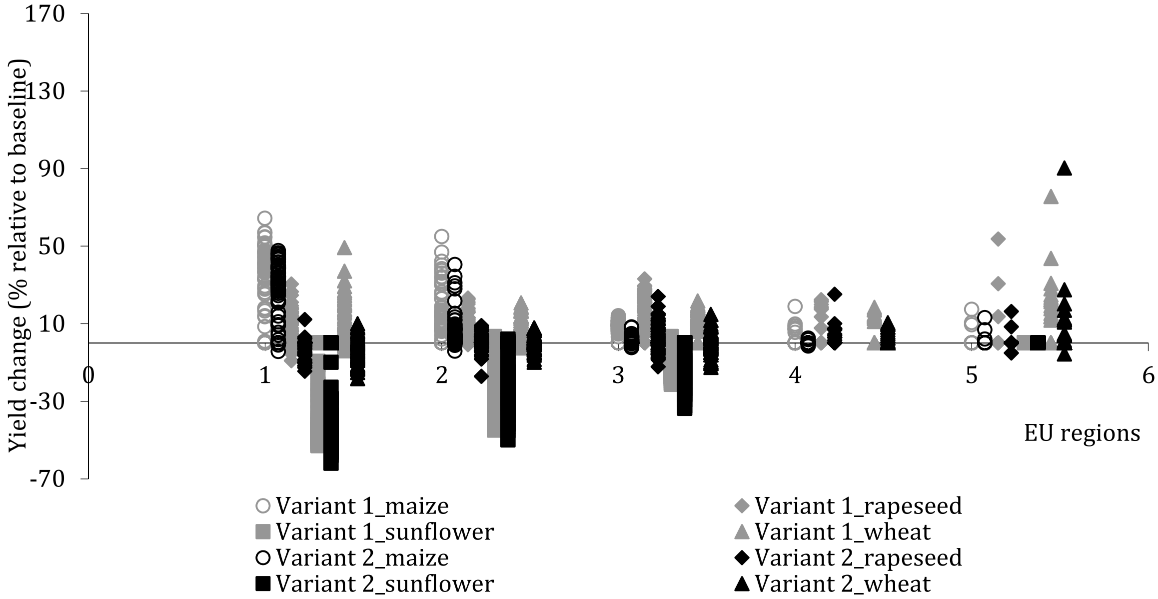
[55] The baseline period is 1993-2007.

[56] In subsection 5.1, costless measures are assumed to be taken up by rational farmers. Therefore they do not count as additional adaptation. The CAPRI analysis takes a different approach, deliberately presenting the difference between costless adaptation and a (purely hypothetical) scenario where farmers do not adapt at all.

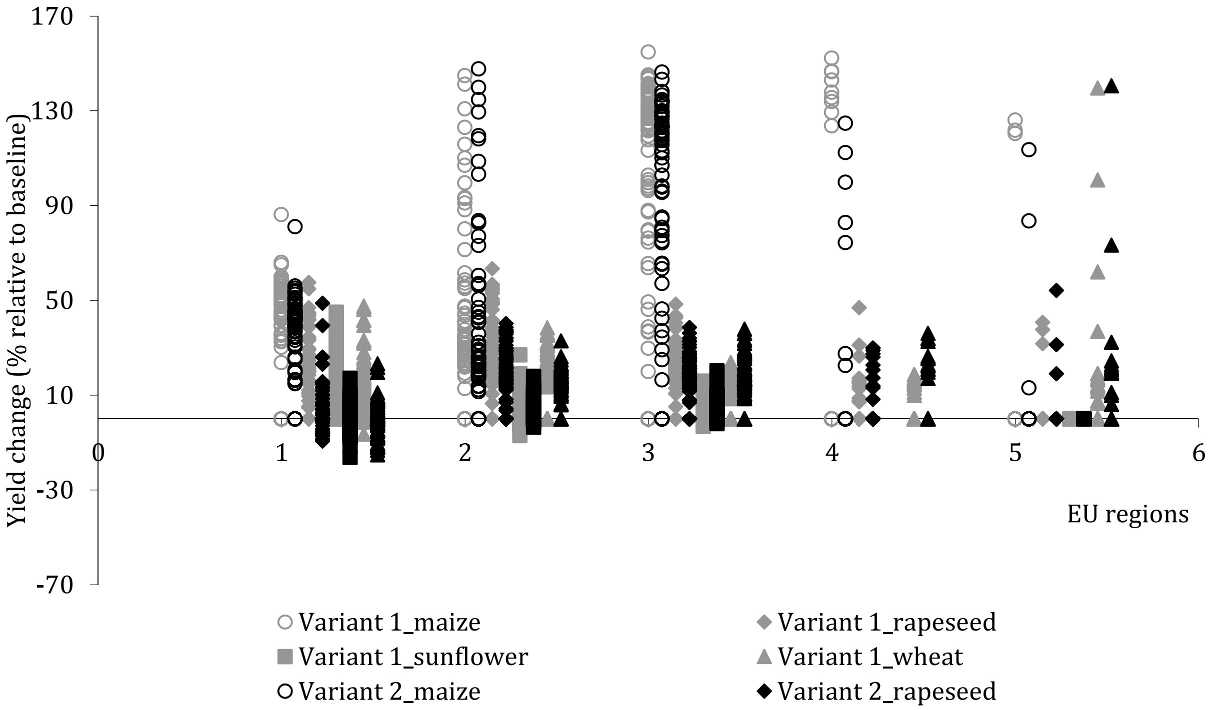
[57] Additional irrigation up to 2700 m^3/ha is permitted for maize only.

Figure 23. Yield changes in climate change scenarios by NUTS2 and EU zones (% change relative to baseline)

a) No-adaptation



a) Best-adaptation

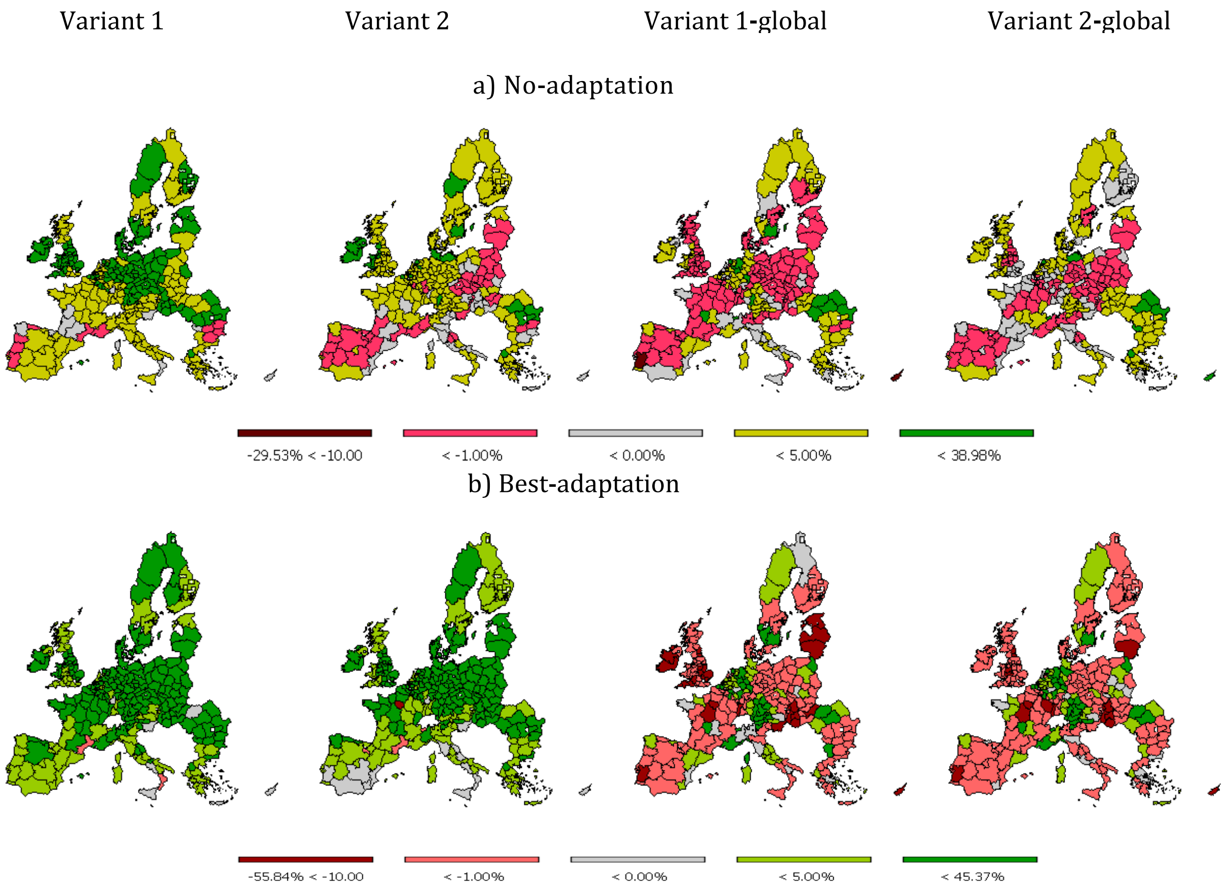


Notes: 1 = Southern Europe; 2 = Central Europe South; 3 = Central Europe North; 4 = British Isles; and 5 = Northern Europe.

Source: Shrestha *et al.* 2013

The CAPRI analysis considered two types of price assumptions in order to estimate the economic impacts of the yield changes shown at NUTS2 level in Figure 24. The first assumption is to fix agricultural commodity prices so that they do not respond to climate change. In this case, agricultural income increases in most EU regions once the effects of adaptation are included, though increases are lower (<5%) in most of Southern Europe, particularly in the Variant 2 scenario. The second assumption (named "global"), allows world agricultural commodity prices to respond to the supply shock created by the climate-induced yield change. This causes prices to fall relative to the baseline, and consequently changes in agricultural income are generally below 1%. It is important to note that both price assumptions are purely hypothetical since the first ignores the effect of yields on prices, while the second ignores the effects of yield changes outside the EU[58] – which could either reinforce or counteract the price effects of EU yield changes.

Figure 24. Income change at NUTS2 in EU-27 (a) under no-adaptation and (b) under best-adaptation (% change relative to baseline)



Source: Shrestha *et al.* 2013

[58] There are no yield effects outside EU due to climate change. There are prices effects outside the EU but they are not attributed to a yield-climate effect. It is because of the interaction with the changes in production and price in the EU.

The results at EU level show that for agricultural incomes (Table 30), gains in the fixed-price scenario are entirely wiped out once the effect on world prices is taken into account, whether farmers adapt or not. This underlines the importance of including yield changes outside the EU (and their effects on prices) in future economic analysis of climate change and agriculture.

Table 30. Agriculture income in EU-27 (% change relative to baseline)

	No Adaptation	Best Adaptation
Variant 1	3.3%	8.0%
Variant 2	0.8%	6.8%
Variant 1-global	-0.2%	-0.1%
Variant 2-global	-0.2%	-0.3%

Source: Shrestha *et al.* 2013

The estimated gains in total welfare (which includes gains to consumers) are shown in Table 31. These results are obtained by feeding the estimated agriculture yield changes into the GEM-E3 CGE model. Welfare gains are in the range of €1.5 to €9 billion without adaptation (Table 31). With adaptation measures in place the yields were improved, leading to welfare gains of around €18-20 billion, mostly in the Central Europe regions.

Table 31. Agriculture 2020 welfare changes without and with adaptation (€ billion)

	No Adaptation		Adaptation	
	Variant 1	Variant 2	Variant 1	Variant 2
Northern Europe	790	238	1,157	1,126
UK & Ireland	1,484	480	2,145	2,562
Central Europe north	2,983	402	7,541	7,300
Central Europe south	2,277	556	6,228	4,973
Southern Europe	1,469	-107	3,284	1,973
EU	**9,003**	**1,569**	**20,356**	**17,934**

Source: results of JRC PESETA II project

5.7 Possible transboundary effects

An interesting issue to analyse is to what extent climate impacts occurring in one EU region could affect the rest of the EU. Intuitively, impacts in one region would affect production and welfare elsewhere through trade effects, given the high degree of economic integration between the EU member states. Two simulations with the reference setting have been made to explore the role played by these trade effects.

In the first analysis (first column of Table 32), one can imagine a counterfactual situation where sea level rise affects only Central Europe North (the most low-lowing region, where the impact of sea level rise is expected to be most severe), while the rest of the EU regions do not suffer any direct impact. Under such a case, the economic modelling results with the GEM-E3 model suggest that Central Europe North would have a welfare loss of 20.5 billion Euros. There would be an additional 30% welfare loss (5.6 billion Euros) in the rest of the EU due to the economic linkages between EU regions.

Table 32. Transboundary effects (reference simulation)

	Coast Central Europe North	Agriculture Southern Europe
Northern Europe	-491	-173
UK & Ireland	-1,677	-798
Central Europe north	-20,518	-1,380
Central Europe south	-1,966	-1,209
Southern Europe	-1,530	-14,979
EU	**-26,181**	**-18,540**

Source: results of JRC PESETA II project

A similar simulation regarding agriculture impacts has been made, the hypothetical case being that yield change occurs only in the Southern Europe region. In that case the impact in Southern Europe could be 15 billion Euros. There would be an additional loss of 20% (3.5 billion Euros) in the rest of the EU regions, leading to an overall welfare loss estimated at 18.5 billion Euros (second column of Table 32).

The first results on this respect can indicate that it is not only in the self-interest of countries/regions to develop the right adaptation framework, but also in the interest of their economic partners. This reinforces the need for coordination and cooperation at EU level to ensure an effective level of preparedness across the whole EU territory.

5.8 Influence of climate model uncertainty

Uncertainty influences largely the results. In this subsection some insight is provided into the influence of the projected climate amongst different RCM simulations driven by the same Reference scenario.

In the river flood assessment, A1B scenario results are available from twelve separate climate models. Table 33 shows the welfare impacts for the reference simulation and the worst and best cases, where the variability in results is exclusively due to a different choice of climate model. The best case is defined as that with the lowest EU damage and the worst case the climate simulation with the highest EU damage. It is interesting to note the wide variability of impacts. Impacts for the whole EU could be four times bigger or half the reference value. The range of variation is even larger for the EU regions. For instance, the Central Europe North region would have a welfare loss more than ten times bigger in the worst case simulation, compared to the reference, while Southern Europe suffers nearly three times more in the best case (even though this is the least damaging outcome for the EU as a whole).

Table 33. Welfare impacts of river floods in worst, reference and best cases (€ million)

	Worst case	Reference	Best case
Northern Europe	-493	212	-26
UK & Ireland	-13,462	-2,965	110
Central Europe north	-3,702	-469	-383
Central Europe south	-9,818	-3,210	-57
Southern Europe	-4,489	-1,037	-2,603
EU	**-31,965**	**-7,469**	**-2,958**

Source: results of JRC PESETA II project

Table 34 presents the related GDP changes. The GDP loss could be 0.1% in the worst case simulation, being 0.2% in UK & Ireland.

Table 34. GDP Impact of river floods in worst, reference and best cases (% GDP)

	Worst case	Reference	Best case
Northern Europe	-0.1%	0.0%	0.0%
UK & Ireland	-0.2%	0.0%	0.0%
Central Europe north	0.0%	0.0%	0.0%
Central Europe south	-0.1%	0.0%	0.0%
Southern Europe	-0.1%	0.0%	-0.1%
EU	**-0.1%**	**0.0%**	**0.0%**

Source: results of JRC PESETA II project

For the energy assessment, temperature and precipitation changes from twelve different A1B scenarios are used to estimate demand changes in the POLES model which are fed in turn into the GEM-E3 model. The best and worst cases are shown in Table 35 and Table 36 in terms of changes in absolute welfare and percentage GDP.

Table 35. Welfare impacts of energy demand changes in worst, reference and best cases (€million)

	Worst Case	Reference	Best Case
Northern Europe	**-5,307**	**2,283**	**4,678**
UK & Ireland	-881	8,047	11,327
Central Europe North	7,647	18,771	27,438
Central Europe South	-3,074	6,428	14,234
Southern Europe	-50,439	-27,524	12,606
EU	**-52,055**	**8,004**	**70,284**

Table 36. GDP impact of energy demand changes in worst, reference and best cases (%)

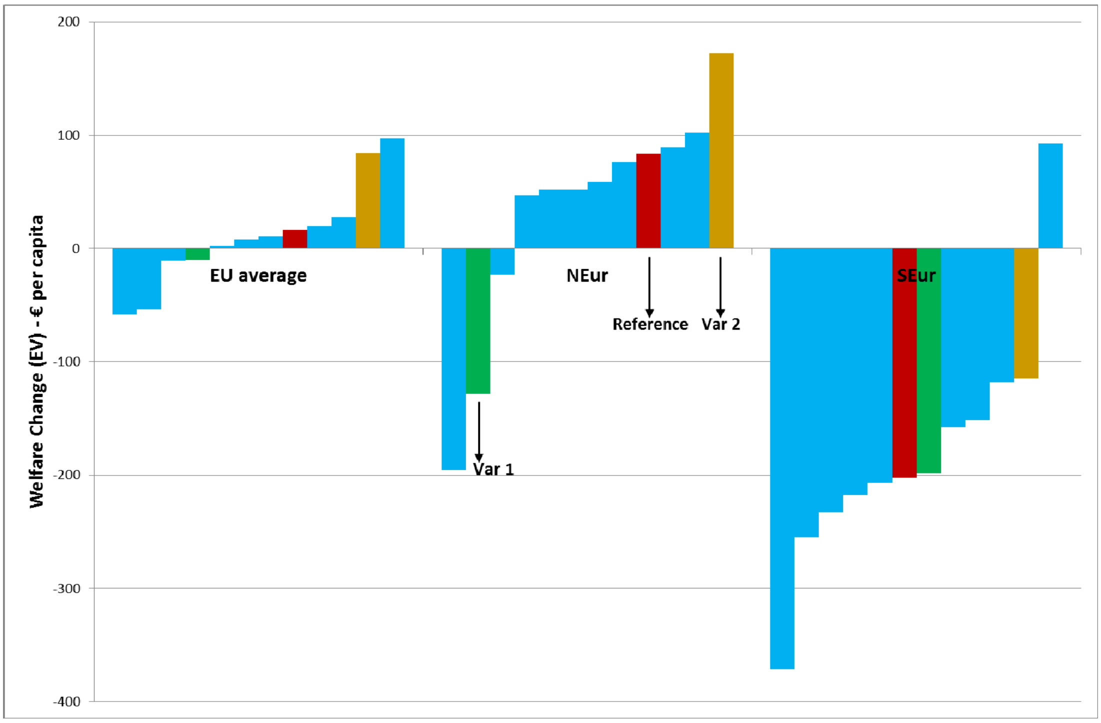
	Worst Case	Reference	Best Case
Northern Europe	**-0.2%**	**-0.1%**	**0.1%**
UK & Ireland	-0.7%	-0.1%	0.1%
Central Europe North	-0.2%	-0.1%	0.1%
Central Europe South	0.0%	0.1%	0.2%
Southern Europe	0.0%	0.1%	0.2%
EU	**-1.0%**	**-0.1%**	**0.7%**

The added value of using a large number of climate simulations[59] can be seen more clearly in Figure 25, where the welfare and GDP impacts of each A1B shock to

[59] Where different climate models (GCMs and RCMs) are fed with the same socioeconomic and emissions inputs.

energy demand are shown in ascending order. At regional level, there is agreement between most of the climate simulations (but not all) as to whether the effect of the energy demand shock will be positive or negative. Once spread across the whole EU the impacts tend to be smaller, in terms of GDP percentage points. However, at EU level there is also less agreement over whether the impact would be positive or negative.

Figure 25. Welfare impact of A1B energy demand changes in ascending order (€ per capita)



6 The impacts on Europe of crossing climate tipping points

Recent research efforts have led to the proposal that additional model-based research is needed into climate tipping points. There are events where the response of the earth system components (e.g. Greenland ice sheet, West Antarctic ice sheet, thermohaline circulation) to climate change may be nonlinear and irreversible beyond certain warming level (Huybrecht et al, 2011; Driesschart et al, 2007, Goelzer et al, 2011; Robinson et al, 2012). Assessments based on observations and paleoclimatic data (Smith et al., 2009), expert elicitation (Lenton et al. 2008, Kriegler et al., 2009) or higher temperature projections (Parry et al., 2009) are giving an increased prominence to these events.

An exploratory study attempting to assess the economic impact of nonlinear consequences of climate change in Europe was initiated as part of the overall PESETA II project. Modelling the economic impact of such abrupt events has been difficult[60] due to the large uncertainties about probabilities and consequences (US CCSP, 2008; Keller et al., 2008, Weitzman 2009). Initiating an economic assessment of abrupt changes in the absence of a scientifically-based consensus remains exploratory research and it can best be based on a combination of carefully elicited expert judgment. With this aim, IPTS organised an expert workshop to discuss potential consequences in Europe from crossing selected climate tipping points. These nonlinear consequences of climate change are defined using tipping points, thresholds above which a small change could cause a major shift in the climate system (Lenton et al 2008).

Levermann et al (2010, 2012) had already assessed the probabilities of the tipping points with high expected impact on Europe. After further research and discussions with experts, IPTS made a selection of the 5 tipping points mentioned below, in line with the assessment produced by Levermann et al (2012). In addition, a more speculative (but still plausible) scenario of an increased frequency of persistent blocking events over Europe was considered. The final list of the six tipping points investigated was as follows:

- Arctic Sea-Ice melting (ASI)

[60] See e.g. Lenton and Ciscar (2013).

- Melting of Alpine glaciers (MAG)
- Greenland Ice sheet meltdown (GIS)
- West Antarctic ice sheet collapse (WAIS)
- Collapse of the Atlantic Thermohaline Circulation (THC)
- Persistent blocking events of the jet stream (BLK)

Once the potential tipping points had been selected, the next step was to describe the global consequences in a time frame short enough to make an economic assessment plausible. Since there is no model or sound scientific agreement on when (or even "if") these tipping points will be reached and their consequences, expert judgement was pursued to produce a credible "best current estimate" of scientific knowledge (Keith 1996). The results of the expert judgment exercise are presented below. The economic assessment component was not finally made.

In order to collect expert views, a workshop titled "Impacts on Europe of crossing climate tipping points" took place at IPTS on 1 June 2012 with the aim to discuss the potential for these selected tipping points being crossed.

The tipping points to be investigated were each presented by an expert researcher in the field. They were asked about the probability and main consequences of crossing the selected tipping points. The description of each tipping point selected for the study and a summary of the views presented during the workshop combined with background research is included below.

6.1 Arctic Sea-Ice melting (ASI)

Higher temperatures lower the extent and thickness of Arctic sea ice in turn accelerating regional warming and increasing the variability of sea ice cover. The record sea-ice minimum extents observed during the summers of 2007 and 2012 seem to evidence the accelerated sea-ice loss during the last decade (Devasthale et al. 2013). According to L.H. Smedsrud (U. of Bergen, Norway), in the RCP 8.5 scenario, the Norwegian Earth System Model (NorESM) predicts that the summer Arctic will be summer ice-free by 2040.

According to a number of studies (Cohen et al. 2013) the consequences of ASI melting would include colder winters in Europe, which might increase morbidity and mortality, although the actual impact of this effect in the context of global warming is still very uncertain. A potential southward push of the jet stream will shift storm tracks, leaving the south of Europe even drier, affecting agricultural production. Gas and oil reservoirs made available by ice melt will eventually alter energy market and maritime transport (made possible because of ice retreat). Potential methane release from permafrost melting is also a concern (Wadhams, 2013).

6.2 Melting of Alpine glaciers (MAG)

Different model approaches indicate that an increase in global mean air temperature of 2 ºC will lead to an almost complete loss of glacier ice volume in the Alps (Zemp et al. 2006; Le Meur et al. 2007; Jouvet et al. 2009, Huss 2011). Current projections, regardless of the different temperature increase projected for all the RCPs scenarios, expect 60% of glacier surface, as compared to 2003, to disappear by 2050 and total glacier area to be reduced to 4% (RCP8.5) or 18% (RCP2.6) by 2100 (Huss 2012).

Prof. Haberli (University of Zurich, Switzerland) attended the IPTS workshop and presented an overview of the main impacts expected. Alpine glacier melting will only contribute about 0.3 mm SLR (sea level rise) (Haeberli and Hoelzle 1995; Haeberli and Linsbauer, 2013), so it is of no importance concerning the global ocean. The main impacts will be on the hydrological regime (Huss 2011), especially the seasonal patterns of runoff and fresh-water supply. These changes in the hydrological regime affect hydropower potential in the area. There will be a temporary increase because of the additional water from accelerating glacier melt but after a few years or decades hydropower potential will decrease irreversibly (even under cooling conditions with positive mass balances) with decreasing glacier surface. With the glaciers disappearing, it is anticipated that the year-to-year variability in discharge from higher altitudes will approach similar levels to lowland basins. Hydropower companies will see production levels affected with longer periods with no water.

An increasing number of new lakes forming in de-glaciating areas may initially be used to compensate for losses (Terrier et al. 2011), but the total volume for all the new lakes is only equivalent to about one year's meltwater runoff under present-day conditions.

Agriculture production might be favored at the beginning, but water stress may later on decrease productivity. Inland navigation is mainly influenced by water depth. Low river discharges will therefore negatively impact transportation. Present Alpine glacier landscapes as a primary attraction will change into new landscapes of sparsely vegetation-covered debris and rocks with lakes. There will be more debris input into rivers and an increasing frequency of large rock falls – now about 1 event with more than 1 million m3 every 4 to 5 years (cf. Fischer et al. 2011). This is important for e.g. transportation, construction, road maintenance in high mountains. The risk of catastrophic damage from floods as a consequence of impact waves in new lakes forming at the foot of large destabilizing icy slopes may appear small now but is steadily increasing for long time periods to come.

6.3 Greenland Ice sheet meltdown (GIS)

Melting at the glacial margins lowers the edge of an ice sheet to elevations that are warmer and where more melting will occur. If the surface mass balance becomes negative, the ice sheet will inevitably shrink, and could disappear nearly completely.

One of the main concerns over GIS, as discussed by Dr. Lowe (Hadley Centre, Met Office, UK) is its possible irreversibility. A Met Office Hadley Centre study (Ridley et al. 2009) has looked at a partially or completely melted Greenland ice sheet, putting melted Greenland (with different % of mass loss) back into a climate model with pre-industrial greenhouse gas concentrations. If GIS melts completely, it would only recover 25% of its mass at pre-industrial CO_2 concentrations.

While the complete melting of Greenland ice-sheet could take over 3000 years (Ridley et al. 2009), a loss of up to 15% of ice volume could occur within 300 years. The expected sea level rise from future loss of ice from the Greenland and Antarctic ice sheets might occur fast enough during the 21st century to cause significant coastal impacts. Future contribution of Greenland to sea level rise is uncertain, but several studies try to provide upper bounds based on physical plausibility. A total

21st century sea level rise of 2 m cannot be ruled out but current estimates give this upper limit an extremely low probability.

Another consequence of GIS meltdown is its interaction with THC (thermohaline circulation). Fresh water from the ice sheet might trigger slowdown of AMOC (Atlantic meridional overturning circulation) with impacts on European weather. This is described in more detail in subsection 6.5.

Main impacts for Europe will be caused by changing extremes (increased storm surges and changes in tidal characteristics aggravated by SLR (North Sea coastal regions will be more affected), inundation of low lying areas, salt water intrusion (with consequences for ground water and agriculture), erosion of coastal zones (allowing wave energy to propagate further) and loss of wetlands (Mediterranean region especially vulnerable).

6.4 West Antarctic ice sheet (WAIS) collapse

Most of the WAIS is grounded below sea level on reversed bed slopes, and its collapse could raise global sea level (GSL) between 3.3-5 meters (Alley and Whillans 1991, Bamber et al. 2009, Lythe et al. 2001).

T. Payne (University of Bristol, UK) discussed this issue at the IPTS workshop. Concern about ice sheet melting associated with Antarctic is linked to the possible instability of the West Antarctic ice sheet which is mainly resting on ground below sea level. While the understanding of physical mechanisms is improved, modelling ice sheet grounding line migration is still challenging, notably due to the high spatial resolution required (better than 1 km).

Results of recent modelling experiments were presented in which the process chain was simulated from near coastal ocean and air temperature (as projected with regional models) to resulting subshelf melt rates and grounding line retreat. Initial results based on a 80-member ensemble provide a first indicative probability distribution function of contribution to sea level rise by 2100. This suggests a very flat, long ill-defined tail distribution with for instance a 68% probability that SLR contribution would be lower than 20 cm, but, also a 5% probability for a 1 m SLR. The distribution depends on e.g. snowfall intensity which would transfer curve from one side to the other, as this process is in competition with all those leading to increased ice-loss and SLR. Sea level rise is very likely to continue beyond 2100 and 2200.

6.5 Collapse of the Atlantic Thermohaline Circulation (THC)

The term "thermohaline circulation" (THC) refers to a key physical driving mechanism of the ocean circulation—resulting from fluxes of heat and freshwater across the sea surface, and the physical transport of heat and salt by the circulation itself – which can give rise to multiple stable states. In the Atlantic, it is manifested in the Atlantic meridional overturning circulation (AMOC), which transports surface water northwards across the equator and then via the Gulf Stream and North Atlantic Current contributes to the warming of Northern Europe. Deep water forms in the North Atlantic and returns southward at depth. Models simulate a weakening of the THC in response to surface warming and freshening at high latitudes, and some suggest a complete breakdown of the THC under additional fresh water input into the North Atlantic. A gradual weakening of the North Atlantic THC by 18-44% is expected for 2100 (Schmittner et al. 2005; Weaver et al., 2012).

A THC collapse would have a global imprint, but the signal would be the largest in eastern North Atlantic. European coastal areas would suffer the most. Compared with the unforced model simulations, the surface air temperature in the Netherlands experiences a rapid decrease (~4ºC). The THC overturning would thus completely outweigh the global warming effect expected.

Northern Hemisphere storm tracks would shift to the south and intensify. Over the northern half of Europe, decreased zonal winds and reduced moisture advection would cause drying over land, especially in winter. Cloud feedbacks would enhance cooling over sea and temperature cooling over land. This precipitation and storm track changes (decreased water availability) would cause a decrease in agricultural production.

With THC decrease, the availability of nutrients in North Sea will be affected as a consequence of decreased deep water mixing. With fewer nutrients around, zooplankton will decrease affecting fisheries.

After 20 years of THC collapse, temperature increase would then resume but would remain lower compared with the unforced THC projection case. For the next century, only few models predict strong response of THC to global warming. The range of responses over CMIP5 models is about -20% to -60% THC weakening by 2100 and -30% to -80% by 2200 in the RCP8.5 scenario.

6.6 Persistent blocking events of the jet stream (BLK)

Atmospheric blocking can induce extremely high or low temperatures and severe precipitation anomalies over the surrounding area, e.g. the European heat wave of 2003 (Black et al., 2004), the heavy precipitations in California (Neiman et al., 2004), or the intense heat wave over Eastern Europe and Russia in the summer of 2010 (Matsueda 2011). This blocking consists of a persistent high pressure anomaly that displaces northward the mid-latitude jet, hence blocking it from hitting a particular region (Xoplaki et al 2011), which tends to appear with a certain frequency in well-defined regions of the world (D'Andrea et al., 1998; Barriopedro et al., 2010), namely over northeastern Atlantic Ocean and Europe, and over the northern Pacific Ocean. Europe is considered one the most important regions for blocking because it is the only place in the world where a storm track and a jet stream end (Woollings 2010).

Identification methods for blocking have been refined and applied for reanalysis in CMIP3 and CMIP5 models. These studies point to a robust reduction in blocking frequency under global warming, while the duration of the blocking remains nearly constant (Barnes et al 2012, Anstey et al 2012). However, there is considerable uncertainty since other approaches suggest less agreement between models. For example, Masato et al (2012) find little decrease in European summer blocking in RCP8.5 by 2100, and even signs of a small increase over Northeast Europe.

BLK in summer will cause heat waves and droughts on one side and increased precipitation on the other. The heat waves will affect agriculture production, in addition, if water too scarce or weather too hot, it will be a problem for tourism and households (there will be increased mortality and morbidity caused by heat). Outside the blocking, higher precipitation will lead to floods.

6.7 Worst cases analysis

Finally, the envisaged individual worst cases associated with the different systems susceptible to experience profound changes, with possibly the passing of tipping points were discussed at the workshop. Experts agreed on assumptions regarding the expected changes and consequences on sea level rise that can be partly supported by the above-mentioned research findings. However, the associated uncertainty implies inevitable subjective judgement. The workshop held in June 2012 was meant to frame and define the large scale consequences of passing each tipping point and how far they would add to the currently available climate change projections (assuming A1B, A2 (or RCP8.5)). As a result of discussions, "worst" case scenario(s) for A1B by respectively 2100 was broadly defined, though consensus on RCP 8.5 projections was not reached and are not included (Table 37).

Table 37. Worst impacts expected for each tipping point in A1B climate scenarios

	A1B - 2100		
	worst case main assumptions	**extremely low probability scenario(*)**	Units
SLR Thermal expansion	*0.32*		m eq-SLR
Glaciers and small ice caps	*0.12*		m eq-SLR
Tipping points:			
Greenland Ice Sheet	0.2	*0.54*	m eq-SLR
West Antarctic Ice Sheet	0.2	*0.62*	m eq-SLR
Thermohaline Circulation	-20%	-100%	% weakening
	0.1	0.1	m regional SLR
Summer Arctic Sea	2025		date for near-complete melting
Alpine Glaciers	2070		date for near-complete melting
Blocking events	20%		frequency of summer blocking events (% change)
	10%		average duration (% change)
	1		increase in average temperature during blocking events (degree C) to be superimposed to the larger background warming
Combined scenario for SLR(**)	0.8	1.6	m eq-SLR

(*) this scenario is considered as a "no regret" scenario

(**) Thermal expansion + melting glaciers + ice sheet melting

6.8 Conclusion and possible next steps

The agreement reached by the experts was however not sufficient for a further economic assessment of the consequences, since the biophysical consequences could not be defined with sufficient specificity. The expert consensus was inconclusive, with the added difficulty in quantifying the impacts. For example, in the case of THC, it is difficult to translate changes in temperature into regional climate consequences. In the case of BLK, it was also complicated to quantify and to obtain a solid enough consensus to further the assessment. Besides, there was even a lack of agreement on definition and it proved difficult to finally include it as a tipping point.

As a conclusion, to maximize the value of the results and in view of the impossibility to define the biophysical consequences of the scenarios proposed, future research efforts could concentrate on the impacts from WAIS and GIS as priority areas with an assessment of the consequences on the SLR, before addressing the other tipping points.

Only SLR projections were specific enough to be used in an economic assessment, which is planned to be made at a later stage. This economic assessment has already been done elsewhere (Brown et al 2011, Nicholls et al 2011) but further efforts to more comprehensively assess coastal impacts are needed. For instance, the issue of regional deviation from global mean SLR is usually not considered in global assessments (Slangen et al. 2012). A current gap on assessing SLR impacts seems to be that wave climate, storm surges, winds and currents, river discharge and run-off are rarely considered (Losada et al 2013). The main agent considered on climate change coastal impact has been sea level rise but it should not be considered alone but together with changes in storm surges and extreme events. Predicted rising sea levels will lead to increases in inundated areas (Nicholls and Cazenave, 2010) but increases in extreme sea levels are a more significant threat. Extreme sea levels are the result of several coinciding processes, including astronomical tides and severe weather events such as tropical cyclones, which generate elevated coastal sea levels through storm surge and high waves (Walsh et al 2012).

7 Limitations

The results of this study should be taken with care, due to the inherent uncertainties of the integrated assessment. Uncertainties in impact assessment results are accumulated throughout the process of producing climate change projections and the subsequent biophysical and economic impact assessments, as a cascading pyramid (e.g. Lung et al., 2013). The initial source of uncertainty is due to the assumptions on different pathways of anthropogenic emissions and resulting atmospheric concentrations, followed by the ability of general circulation models to simulate changes in climatic parameters. A second layer of uncertainty is added by regional climate models (RCMs). When bias correction is applied, it may cause some additional uncertainty. Uncertainty is further increased when using climate projections as inputs to impact models that use biophysical and economic data and models, which also have their intrinsic uncertainties. The degree of the latter uncertainties and the thoroughness by which they are analysed varies from sector to sector. Uncertainties related to flood impacts is arguably best documented (e.g. Rojas et al. 2013). This analysis has provided an illustration of the variability created only by using different climate models and emissions scenarios, but not by using different impact models.

Another limitation comes from the fact that the sectoral biophysical impact models are calibrated based on observed data. Yet the projected climate impacts can be outside the range of historical observations. This is a major difficulty in any climate impact assessment.

A key issue to bear also in mind is also the limited scope of the JRC PESETA II climate impact assessment. The analysis carried out is constrained by the state-of-the-art modelling capabilities, given the available data and the quantitative understanding of biophysical and economic processes. Several dimensions regarding the limited scope should be considered when interpreting the results. Firstly, the impact areas of the study do not include all relevant impacts. For instance the effects of temperature extremes on agriculture have not been considered, while they can be of paramount importance. Schlenker and Roberts (2009) note that yields for soybeans and cotton can be largely negatively affected for temperatures above certain thresholds.

Secondly, several potentially large climate impact categories have not been modelled. That is notably the case of all the impacts affecting ecosystems, and biodiversity, for which there are not market prices.

Thirdly, the consequences of abrupt climate change, including climate tipping points, have not been either taken into account (National Research Council, 2013). Pricing climate risk appropriately becomes a fundamental issue in this respect.

This impact study offers incomplete estimates of climate damages. From this perspective, the assessment severely underestimates the potential damages of climate change in Europe.

Moreover, comparing the welfare impacts in the Reference simulation (or do nothing case) with those of the 2°C scenario does not represent a proper analysis of the benefits of mitigation or reducing GHG emissions to attain the 2°C scenario. This is partly because some of the key omitted impacts mentioned above (such as extremes and abrupt climate change) may be more important in the Reference simulation compared to the 2°C scenario. In addition, ancillary benefits associated with lower EU energy imports and air pollution are not considered. The 2°C scenario would lead to a substantial reduction in net energy imports in the EU (compared to the Reference simulation), which would reduce the EU energy dependence on fossil fuels. This would reduce the macroeconomic vulnerability of the EU economy to energy price shocks. The additional benefits due to lower air pollution of the 2°C scenario can be also very large and have not been studied. Last but not least, the climate impact analysis runs to the year 2100, while impacts occurring later would matter in the analysis. In particular, the difference in impacts between the Reference simulation and the 2°C scenario would get bigger as time passes beyond 2100.

Another issue is that the economic impacts refer to a hypothetical, counterfactual situation where future climate of the 2080s occurs in today's economy. In this respect, the assessment is computing one-off impacts, and not dynamic impacts such as changes in the rate of economic growth (Fankhauser and Tol, 2006; Hallegatte, 2012). As already noted, the simulated economic impacts (both in welfare and GDP terms) represent a level shift or one-off change, and not a change in the growth rate.

Effects on savings and investments should be included in the analysis to explore the impact on economic growth (Stern, 2013). Other potential changes that could affect damages in the future include population (more or less population exposed to damages) and valuation of impacts that may change with economic growth (e.g. higher value of coastal properties).

Another methodological difficulty relates to the proper modelling of adaptation and its economic costs. The state-of-the-art in adaptation cost-benefit analysis is a developing field and further research is required in this area to better understand how and by how much adaptation options can reduce climate vulnerabilities in particular hot spots.

Finally, the analysis has assumed that the economies of the rest of the world remain unchanged in spite of climate change. Yet changes in trade flows and international prices due to impacts in the rest of the world would affect Europe. For instance, the impacts of climate change on agriculture production can be quite large in some world regions, with a substantial influence on agriculture prices world-wide (e.g. Hertel et al., 2010). In this respect, for each of the sectoral studies it would be interesting to explore how impacts in the EU differ depending on how climate change affects the rest of the world.

8 Further research

There is a number of areas that deserve further attention from the research perspective, in order to derive useful insights for policymakers. Firstly, there is a need both to deepen the analysis of the considered impacts and also to enlarge the set of impact categories. The analyses related to climate extremes, and the effects on ecosystem services and human health (e.g. Nam et al.,2010), impacts on migration, and the effects of passing tipping points (Lenton et al., 2008) become fundamental research priorities to better understand what is at stake in terms of benefits of climate policy action.

It is necessary to better understand the economics of climate adaptation in order to improve the resilience of the economic system. Many current investment infrastructures with long time horizons will require the analysis of how climate change will affect those investment decisions. Yet the available cost-benefit analysis of climate adaptation remains quite limited.

From a methodological perspective there is a need to further integrate the various impacts using horizontal consistent frameworks relating water and land-use. Another topic is the possibility to derive reduced-form damage functions, which could be used in top-down integrated assessment models of climate and the economy.

Thirdly, while most of the PESETA sectoral assessments are made in a static context, it is important to move towards a dynamic framework, where impacts on economic growth and the land-water-energy nexus can be better assessed[61].

Fourthly, a global sound assessment of climate impacts is also a research priority. Understanding better how changes in the climate system could affect the key players in international negotiations would help in the design of the appropriate policies to address the climate change threat.

[61] Those areas are to be covered by the on-going OECD Costs of Inaction and Resource scarcity: Consequences for Long-term Economic growth (CIRCLE) project, http://www.oecd.org/env/indicators-modelling-outlooks/circle.htm

Finally, given the broad range of uncertainties involved in the modelling there is a clear need to do a systematic stochastic analysis of climate impacts, a task that will require close cooperation and integration among the many involved disciplines.

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Annex I Main climate features of the JRC PESETA II climate simulations

Table 40. Temperature change (°C) in all climate simulations, compared to 1961-1990

	Full name	Project name	2011-2040	2041-2070	2071-2100
A1B	C4I_A1B_METO		1,7	3,2	5,0
	CNRM-A1B-ARPEGE		1,1	2,2	3,0
	DMI-A1B-ECHAM5		0,8	1,7	2,7
	DMI-A1B-ARPEGE		0,9	1,9	2,3
	DMI-A1B-BCM	Reference variant 2	0,6	1,7	2,4
	ETHZ-A1B-METO		1,5	2,6	3,4
	KNMI-A1B-ECHAM5	Reference	1,0	2,0	3,1
	METO-HC_A1B	Reference variant 1	1,7	3,0	3,9
	MPI-A1B-ECHAM5		1,0	2,2	3,4
	SMHI-A1B-BCM		0,7	1,8	2,6
	SMHI-A1B-ECHAM5		0,9	2,2	3,4
	SMHI-A1B-METO		1,3	2,1	2,8
RCP8,5	DMI-RCP8.5-ECEARTH		1,2	2,3	3,9
E1	MPI-E1-ECEARTH		1,6	2,1	2,4
	MPI-E2-ECEARTH		1,2	1,6	2,1
	MPI-E4-ECEARTH	2°C	1,4	1,6	2,4

Table 41. Precipitation change (%) in all climate simulations, compared to 1961-1990

	Full name	Project name	2011-2040	2041-2070	2071-2100
A1B	C4I_A1B_METO		5	3	7
	CNRM-A1B-ARPEGE		1	-3	-7
	DMI-A1B-ECHAM5		3	5	8
	DMI-A1B-ARPEGE		0	-4	-10
	DMI-A1B-BCM	Reference variant 2	3	5	6
	ETHZ-A1B-METO		0	-1	0
	KNMI-A1B-ECHAM5	Reference	-1	0	1
	METO-HC_A1B	Reference variant 1	1	-2	-2
	MPI-A1B-ECHAM5		-1	-1	-1
	SMHI-A1B-BCM		2	4	4
	SMHI-A1B-ECHAM5		0	2	3
	SMHI-A1B-METO		4	6	8
RCP8,5	DMI-RCP8.5-ECEARTH		1	0	-2
E1	MPI-E1-ECEARTH		2	-3	-3
	MPI-E2-ECEARTH		8	6	3
	MPI-E4-ECEARTH	2°C	0	1	-1

Annex II The GEM-E3 Model

This annex explains the basic features of the GEM-E3 General Equilibrium Model for Energy-Economy-Environment interactions. The model has been developed as a multinational collaboration project, partly funded by the Commission of the European Communities, DG Research, and by national authorities, and further developments are continuously under way. Applications of the model have been (or are currently being) carried out for several Directorate Generals of the European Commission (economic affairs, competition, environment, taxation, research) and for national authorities. The most recent one has been the analysis of the 2030 framework for European climate policies (European Commission, 2014).

The GEM-E3 Europe model is an applied general equilibrium model, representing the European countries, which are also linked through endogenous bilateral trade. The model computes simultaneously the competitive market equilibrium for all markets (primary inputs, intermediate goods and final goods and services).

The model has the following general features. Firstly, it is a general model because it includes all interrelated markets and represents the system at the appropriate level with respect to geography, the sub-system (energy, environment, economy) and the dynamic mechanisms of the agents' behaviour.

Secondly, the model formulates separately the supply or demand behaviour of the economic agents, which are supposed to optimise individually their objective (maximising welfare for households and profits for firms), while market derived prices guarantee global equilibrium. The public sector and the rest of the world are exogenous in the European model.

Thirdly, it considers explicitly the market clearing mechanism and the related price formation in the energy, environment and economy markets. Therefore prices are computed by the model as a result of supply and demand interactions in the markets.

The model is simultaneously multinational (for the EU) and specific for each country; appropriate markets clear European, while country-specific policies and distributional analysis are supported, including the study of the impacts due to climate change.

The model is also multi-sectoral (eighteen sectors in total, with a particular focus on energy intensive sectors; Table 42), with structural features of energy/environment and policy-oriented instruments (e.g. taxation). The model formulates production technologies in an endogenous way allowing for price-driven derivation of all intermediate consumption and the services from capital and labour. Regarding the demand-side, the model formulates consumer behaviour and distinguishes between durable (equipment) and consumable goods and services.

Table 42. Sectors of the GEM-E3 model

Agriculture
Coal
Oil
Gas
Electricity
Ferrous and non ferrous metals
Chemical Products
Other energy intensive
Electric Goods
Transport equipment
Other Equipment Goods
Consumer Goods Industries
Construction
Telecommunication Services
Transport
Services of credit and insurances
Other Market Services
Non Market Services

The model is dynamic, recursive over time, driven by accumulation of capital and equipment. Technology progress is explicitly represented in the production function, either exogenous or endogenous, depending on R&D expenditure by private and public sector and with the possibility of taking into account spillovers effects.

Regarding trade, the models consider the endogenous trade flows across countries, with bilateral trade matrixes by production sectors.

The economic, energy, and emissions data of the GEM-E3 model are based on EUROSTAT databases (input–output tables, national accounts data, and energy balances). Twenty-four EU economies have been modeled individually (the whole EU, with the exception of Malta, Cyprus, and Luxemburg[62]).

As a benchmark, it was assumed in the JRC PESETA II project that all markets are fully flexible, i.e., prices in all markets adjust so that demand equals supply. Such a neoclassical paradigm has been used to represent the new equilibrium in the long term when all market adjustments have occurred.

A baseline scenario has been run to 2010 assuming there is not climate change. The alternative scenario considers the influence of climate change in the economy, climate impact scenario. The reported results compare the values of welfare and GDP of the climate impact scenario with those of the baseline scenario.

[62] These three economies are relatively small in size and at the time of the economic runs were made they were not integrated in the model. Croatia was not a member state when the runs were made.

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Abstract

The objective of the JRC PESETA II project is to gain insights into the sectoral and regional patterns of climate change impacts in Europe by the end of this century. The study uses a large set of climate model runs and impact categories (ten categories: agriculture, energy, river floods, droughts, forest fires, transport infrastructure, coasts, tourism, habitat suitability of forest tree species and human health). The project integrates biophysical direct climate impacts (from eight of the impact categories) into a macroeconomic economic model, which enables the comparison of the different impacts based on common metrics (household welfare and economic activity).

If the 2080s climate would happen today and without public adaptation, the EU household welfare losses would amount to around €190 billion, almost 2% of EU GDP. The geographical distribution of the climate damages is very asymmetric with a clear bias towards the southern European regions. More than half of the overall EU damages are estimated to be due to additional premature mortality (€120 billion). Moving to a 2°C world would reduce climate damages by €60 billion, to €120 billion (1.2% of GDP).

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