Quantifying projected impacts under 2°C warming

Instrument Large-scale Integrating Project
Thematic Priority FP7-ENV.2011.1.1.6-1

D11.1. Synthesis report on cross-sectoral analysis and case studies, including European vulnerability maps

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Authors

Paul Watkiss, Alistair Hunt, Federica Cimato (PWA), Paul Bowyer (HZG), Ioannis K. Tsanis, Aristeidis G. Koutoulis, Manolis G. Grillakis, Ioannis N. Daliakopoulos (TUC), Susan Hanson and Sally Brown (SOTON), Fulco Ludwig (WU), Ruth Butterfield and Sukaina Bharwani (SEI-Oxford), Fulco Ludwig, Diana Rechid, Thomas Mendlik Paul Boyer, Paul Watkiss and Iwan Supit (11.4)

Objectives

The objectives of Work Package 11 - Cross sector assessments and synthesis for Europe – are to consider impacts from a cross-sectoral perspective,

i) undertaking cross-sectoral analysis to link the sectoral pan-European analysis

ii) focusing on particularly vulnerable areas in Europe, especially those that are subject to multiple impacts where cumulative effects may arise and

iii) in relation to cross-cutting themes to address issues in an alternative way to the traditional sector analysis (e.g. water, cities and the built environment).

The task has also brought the impacts, vulnerability and cross-sectoral information together in a synthesis, allowing the integration of all the study findings in a consistent way, to provide some of the key statements for policy information, providing succinct overview of the project.

Summary

In Europe, the impacts of climate change have been typically assessed using scenario-Based Impact-Assessment. This approach combines climate model outputs with sector impact models (or functional relationships) to estimate physical impacts, which are then valued to estimate welfare costs. However, a consequence of this approach is that the potential interaction across sectors is omitted, as are the potential effects of cumulative impacts from sectors acting on a single hot-spot or receptor. Furthermore, the focus on sectors presents information in a way which may not be obviously relevant to all stakeholders. This work package addresses these issues in a number of ways, undertaking five tasks. These activities undertaken and findings are outlined below.

Task 11.1: Integrating the sectoral pan-European assessments into a cross-sectoral analysis

This task mapped the various models and impact assessments being undertaken in IMPACT2C, to outline the overall project landscape, but more importantly, to enable linkages of inputs and outputs across the models. This led to the integration of various modelling aspects across different WP of the project. It then provided common guidance on the sampling of RCP and SSP scenarios, for the impact modelling in WP6 - 10. This information was also used in delivering WP11.2 for the cross-sectoral analysis, in terms of the overall mapping, and for the case studies in 11.2 and 11.3

Task 11.2: Vulnerable regions exposed to multiple (cross-sectoral) impacts.

The impacts of climate change will fall disproportionately on certain regions, i.e. where multiple impacts occur, potentially leading to cumulative effects (e.g. Mediterranean region, Alpine region, etc.). This work package has considered these potential effects by combining the information from WPs 6-8 and WPs 9-10 and overlaying these to identify potential hotspots. This was used to produce
hot-spot maps for Europe, of both negative and positive consequences. The maps show a strong
distributional pattern across Europe. The major losers from a plus two degree world, using the
metrics analysed in this study, are located in southern Europe, with Spain, France, Bulgaria, Romania,
and Greece being the major 'losers'. There are also large areas of eastern Europe in Hungary and
Poland where a number of negative impacts may be expected. The major winners from a plus two
degree world, using the metrics analysed in this study, are located in far northern Europe, with some
areas of Norway and Sweden having positive impacts for all metrics considered. There is also a
cluster of winners in north-eastern Europe in Poland, eastern Germany, the Czech Republic and the
Baltic states. Accompanying these, a case study for the water sector looking at seasonal changes in
water availability and potential interactions with other sectors has been completed.

Further cross-sectoral analysis has been undertaken on water, due to its cross-sectoral dimensions,
at European level and with a case study. A cross-sectoral case study synthesis on the impacts of
climate change on water availability and European water management was undertaken. Water is
used by different sectors and changes in water availability due to climate changes affects a range of
different sectors. The analysis selected various water use sectors and presented critical hydrological
indices for each sector (under climate change). This included analysis of Risk and Safety (floods and
streamflow droughts), Agriculture (streamflow and soil moisture droughts), Energy (hydropower
potential and cooling water availability) and the Environment (water temperature, dissolved oxygen
concentrations, nutrient loads). The analysis used the Hydrological Predictions for the Environment
(HYPE) hydrological model set up for Europe (E-HYPE) and Variable Infiltration Capacity (VIC) land
surface scheme linked to the stream temperature model RBM to simulate hydrology and some
aspects of water quality. Both hydrological models were used to produce an ensemble of water
resources projections based on climate scenarios developed within the project, extending the work
in WP6. In general, the findings are that projected climate change impacts on water use sectors are
most extensive in southern Europe. Water availability will reduce and droughts will increase. This is
likely to have serious impacts on the Energy and Agricultural sectors. Changes in water availability
will also affect the pressure on the environment, in particular in areas where water is already a
limiting factor. In Northern Europe most of the climate impact will be from increased risks and
reduced safety levels due to higher flood risks. However in some parts of Northern Europe,
streamflow droughts could increase and also water temperatures will be higher. These changes will
impact the energy and agricultural sector. Results show that Europe will face significant changes in
the water use sector already at two degree warming with potentially large impacts on especially the
agricultural and energy sector.

Finally, a more in-depth regional case study was also completed on Cross sectoral impacts on water
availability at +2°C and +3°C for east Mediterranean island states: the case of Crete. This case study
investigated how impacts will fall disproportionately on certain regions in Europe, looking at south
Eastern Europe, which is projected to experience a more intense warming, and is highly vulnerable to
climatic and anthropogenic changes due to decreasing rainfall trends and a gradual warming leading
to a progressive decline in average stream flows and groundwater. Changes in average climate
conditions will increase current stresses with a projected 10–30% decline in freshwater resources.
The case study focused on small island states, where accessibility to freshwater resources is limited
and thus impacts will be more pronounced. It used a cross-sectoral framework to assess the impact
of climatic and socioeconomic futures on the water resources of Crete. A set of representative
regional climate models simulations from the EURO-CORDEX initiative driven by different RCP2.6,
RCP 4.5, and RCP8.5 GCMs were used to form a comparable set of results and for the assessment of
uncertainties. A generalized framework of a cross-sectoral water resources analysis was developed in
collaboration with the local water authority exploring and costing adaptation measures associated
with a set of socioeconomic pathways (SSPs). Transient hydrological modeling was performed to
describe the projected hydro-climatological regime and water availability for each warming level. The
robust signal of less precipitation and higher temperatures that is projected by climate simulations result in a severe decrease of local water resources. Awareness of the practical implications of plausible hydro-climatic and socio-economic scenarios in the not so distant future may be the key to shift perception and preference towards a more sustainable direction.

**Task 11.3: Cross cutting analysis, and integrated adaptation.**

The use of sector based impact assessments – and the way that climate change risks are identified and grouped in these - influences their relevance to agents in the public or private sectors. It also influences the multiple effects that may arise to specific receptors or groups, that maybe missed by individual sector assessments. Therefore, alternative groupings (to sectors) are interesting and have been considered in IMPACT2C. Following a review, the most interesting areas for exploration were considered to be for specific end-users and for cross-sectoral themes. A number of case studies were used to explore and analyse these.

The first case study considered impacts from the perspective of an end-user/end-receptor, by focusing on households. This was undertaken as a policy case study, working with the UK Committee on Climate Change, as an input to the cross-cutting chapter of the UK’s Second Climate Change Risk Assessment and the Joseph Rowntree Foundation. Two issues were investigated. First, the potential impacts of climate change on the cost of living and wider societal welfare for UK households. Second, the potential differences in these impacts between the average and poorest households. The case study used UK and IMPACT2C impact assessment results, combining these with UK household expenditure data, but also undertook a new econometric analysis, to investigate the observed links between climate and major household expenditure items in the UK. It also compared the results to Italy, to provide a European comparison.

The case study found that there are likely to be relatively modest impacts from climate change on the costs of living in the UK up to the middle of the century. The early effects are likely to be dominated by a small number of major effects (each with a modest impact of up to 5% of the current average household budget), with negative effects from food prices, flood related housing costs and cooling demand, but positive effects from reduced heating demand. The total effects will be negative in aggregate. There are also net negative (societal welfare costs) from increased health impacts. It is stressed that the actual effects borne by household will be determined by future socio-economic changes (notably income levels), and are subject to high uncertainty. Perhaps more importantly, a clear and consistent finding was that low income households will be most affected by these climate change impacts, though they will also benefit most from the positives. In all areas, there were large and disproportionate impacts on low income households, either because of the reduction in disposable income (e.g. from rising food prices), the reduction in quality of life (e.g. from relative higher negative health outcomes) or because of differentiated patterns of risks (e.g. higher flood vulnerability), though low income households will also benefit most from reduced winter heating (increasing disposable income). The overall negative effects of these changes will have important impacts for low income households, even with the relatively modest changes expected in future decades, and could be substantial for the higher warming scenarios later in the century (noting the underlying socio-economic situation will be very different to today). Moreover, for some impacts, there were very large individual costs which are more likely to affect low-income households, notably from the risks of uninsured flood losses. These will have major (life-changing) consequences for those affected. Such shocks have the potential to increase the number of people in poverty and the fact that they fall disproportionately on the most vulnerable groups in society are a particular concern.
Finally, a comparison was made between the effects of climate change on households in the UK and in Italy. The analysis of the potential impacts of climate change on households in Italy leads to different results. In contrast to the UK, Italian households are affected by much stronger impacts on average, due to the strong negative signals from cooling demand and potentially also water supply costs as well as high levels of (river) flooding. There are also higher welfare costs due to the stronger heat related mortality signal. When the costs to households for Italy from climate change are added together, it is clear that the impacts could have substantial impacts on household budgets by 2050 (noting the need to consider future socio-economic trends and changes in incomes over time), and potentially very major effects under higher warming scenarios. These impacts would be exacerbated for low income households. This case study highlights that using alternative cross-cutting receptors can provide highly policy relevant and interesting results: a key finding for future assessments. It also highlights a strong policy issue that the distributional impacts of climate change should be considered in national, regional and local assessments, and that these issues should be reflected when designing adaptation policy.

The second case study focused on a geographical cross-cutting theme, looking at port cities. It assessed the population exposure to 1:100 year storm for the world’s large coastal port cities under future climate change, with reference to a 2°C change in global temperature. The case study found that coastal cities will face significant challenges in managing the growth in exposure that will come about from both population and climate change. European port cities with high potential exposure, driven by flooding experience and economic influences (Rotterdam, Amsterdam and Hamburg being among the busiest ports in Europe), have already addressed this hazard with well-developed long-term strategies for minimising impacts. Other cities, particularly the rapidly expanding cities in Africa and Asia, are not so well prepared. For these cities, global climate mitigation can slow and limit the exacerbating effects of climate change on coastal flood risk, but does not eliminate the need for putting similar long-term adaptation measures in place.

The final case study focused on how the interaction between land use change and climate change will affect future water use for food and energy and how this affects expansion of irrigated area. The assessment integrated water availability and environmental flow requirements as a biophysical constraint in the GLOBIOM model at a monthly time-step. Water availability was simulated with the VIC and LPJml model and EFRs were calculated using the VMF method (Pastor et al. 2014). A range of future scenarios were assessed to look at the impacts of future changes in water availability and land use. The simulations included a combination of scenarios based on: biophysical scarcity at spatial resolution of 2 by 2 deg. (driven by water demand and supply), economical scarcity at regional level (driven by water price, determined by elasticity between supply and demand), and climate change scenario (changes in water availability following RCP 2.6). EFRs were set with 2 scenarios: one with a high constraint and one with a low constraint (Table 1). Both EFR scenarios used the VMF method, but the low constraint scenario used 100% of monthly water availability minus EFRs while, the high constraint (EFR - wetlands) used 70% of water availability for maintenance of soil moisture recycling and wetlands minus EFRs (Gerten et al., 2013). Result showed that especially in southern Europe increasing water scarcity will affect future land use. Due to lower reducing dryland agriculture yields there is a push to expand irrigated areas however reducing water availability especially in summer limit this expansion. Especially with high environmental flow requirement there are limited opportunities to expand irrigation.

Task 11.4: Developing guidance and stimulate consistent use of climate change data in climate change impact, vulnerability and adaptation assessments.

Due to improving knowledge of the climate system, model development and updated scenarios new data on climate change are continuously becoming available. This data is used in very different ways
This task reviewed the existing knowledge on using climate change data for impact and adaptation studies and distilled the lessons learned from IMPACT2C as well as other EU projects. The guidance report advances a more consistent use of outputs from GCMs/ESM and RCMs for climate change impact, vulnerability and adaptation assessments. The guidance was formulated from a review and synthesis of the individual guidance documents undertaken as part of IMPACT2C, and drew lessons from the integrated analysis of climate and impact modelling undertaken by the consortium, as well as other documents and guidance. It provides information on the section of climate models, reporting on the approach used within IMPACT2C and other projects, and highlighting the advantages and issues with bias corrections and the use of multi model approaches and the RCP/SSP framework. It also provides examples of good practices and lesson learnt, and ends with recommendation and knowledge gaps.

The final steps of this process – and the document finalisation - were undertaken with a large team from across the IMPACT2C consortium, as part of a special session at the final General Assembly of the project. Following this, the guidance document was further developed and finalised, incorporating inputs from across the consortium involving a large range and variety of experts. The final conclusion of the document and key messages was discussed and agreed during a small workshop at Wageningen University on the 18 September.

**Task 11.5: Synthesis**

This work package has provided policy briefs to synthesis the results of IMPACT2C. These have been published as a series of synthesis documents, for each of the major Conference of the Parties (COP) meetings over the course of the project.

The policy briefs are attached as separate deliverables. The first policy was presented at the Warsaw COP (2013). It was also summarised and published as a paper (Vautard et al, 2014). This summarised the fast track climate analysis. The second policy brief was presented at the Lima COP (2014) and summarised the slow-track detailed EURO-CORDEX results and the biophysical impacts, e.g. sea level rise, hydrological modelling. The third policy brief covers the impact results from global analysis project, and will be published and disseminated at the Paris COP in 2015.

A series of technical deliverables for each of the sub work-packages has been produced.
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6 SYNTHESIS

6.1 Introduction

6.2 References
1 Introduction

There are a wide range of potential impacts from climate change in Europe. These include impacts on the built and the natural environment, which affect many sectors. In Europe, these impacts have been typically assessed using scenario-Based Impact-Assessment. This approach combines climate model outputs with sector impact models (or functional relationships) to estimate physical impacts, which are then valued to estimate welfare costs (see Ciscar et al, 2011; Watkiss et al, 2012).

However, a consequence of this sector based approach is that the potential interaction across sectors is omitted, as are the potential effects of cumulative impacts from sectors acting on a single hot-spot or receptor. Furthermore, the focus on sectors presents information in a way which may not be obviously relevant to all stakeholders. This task aims to address these issues, by taking a cross-sectoral and cross-cutting approach. This is reflected in the objectives of the work package (11) in

i) undertaking cross-sectoral analysis to link the sectoral pan-European analysis from WP6 – 10.

ii) focusing on particularly vulnerable areas in Europe, especially those that are subject to multiple impacts where cumulative effects may arise and

iii) considering cross-cutting themes to address issues in an alternative way to the traditional sector analysis (e.g. water, cities and the built environment).

Alongside this, the task also brings the impacts, vulnerability and cross-sectoral information together in a synthesis, allowing the integration of all the study findings in a consistent way, to provide some of the key statements for policy information, providing succinct overview of the project.

1.1 Outline

The WP consists of five tasks. These are outlined below.

Task 11.1: Integrating the sectoral pan-European assessments into a cross-sectoral analysis

Task 11.2: Vulnerable regions exposed to multiple (cross-sectoral) impacts.

Task 11.3: Cross cutting analysis, and integrated adaptation.

Task 11.4: Developing guidance and stimulate consistent use of climate change data in climate change impact, vulnerability and adaptation assessments.

Task 11.5: Synthesis

A series of technical reports has been produced.

References


2 Integrating the sectoral pan-European assessments into a cross-sectoral analysis

2.1 Outline

One issue in the analysis and economic costing of climate change impacts is the potential interactions across sectors. Existing damage models treat each sector as largely independent. Yet an impact on water resources will cascade through ecosystems, agriculture and tourism, and possibly health and urban planning and design. This task provides a cross-sectoral analysis and integration, including support to ensure consistency among the sector assessments. It maps the impacts and input and output parameters defined for individual sectors in the previous tasks (building on WP5). This task links the different pan-European sectoral studies (WPs 6-8) together and so helps facilitate interactions between teams. It has reviewed the impacts and input and output parameters between sectors in the previous tasks and provided support to the quantification of such links by providing general cross-sectoral support to ensure all analysis (in previous tasks) is consistent and harmonised. This task will also link to cross-sectoral pan-European vulnerability indicators and maps integrating the impacts and risk assessments of WPs 6-10 into other tasks in WP11.

2.2 IMPACT2C modelling environment

The IMPACT2C project has run a large number of impact models. In some cases, the outputs of one model feed in as input to another model. A critical part of the study was therefore to understand these linkages between these models, to ensure the models can harmonise inputs-outputs. In other cases, the project employs different models to look at the same sectors. This was critical in understanding the role of impact model uncertainty (alongside climate model output uncertainty) in the project. To progress this task, a survey covering all impact models was carried out during the project. The list of models is presented below.
# Models within the IMPACT2C project

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Institutions</th>
<th>Sector</th>
<th>Output</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIC</td>
<td>WU</td>
<td>Water and Energy</td>
<td>Grid based (outputs also at basin scale)</td>
<td>Cooling water/hydropower</td>
</tr>
<tr>
<td>LPJml</td>
<td>PIK</td>
<td>Water, Agriculture, Ecosystem services</td>
<td>Grid based</td>
<td></td>
</tr>
<tr>
<td>WBMplus</td>
<td>ENEA</td>
<td>Water</td>
<td>Grid based</td>
<td></td>
</tr>
<tr>
<td>LISFLOOD</td>
<td>JRC</td>
<td>Water</td>
<td>Grid based (outputs also at basin scale)</td>
<td>Floods</td>
</tr>
<tr>
<td>CNRS-WRF</td>
<td>JRC</td>
<td>Energy</td>
<td>Grid based</td>
<td></td>
</tr>
<tr>
<td>Wedda</td>
<td>JRC</td>
<td>Tourism, Energy Demand</td>
<td>Nuts3</td>
<td></td>
</tr>
<tr>
<td>EPC</td>
<td>IIASA</td>
<td>Agriculture</td>
<td>Grid based</td>
<td></td>
</tr>
<tr>
<td>G4M</td>
<td>IIASA</td>
<td>Forestry</td>
<td>Grid based</td>
<td></td>
</tr>
<tr>
<td>Hype</td>
<td>SMHI</td>
<td>Water</td>
<td>Basin scale</td>
<td>Little time in project</td>
</tr>
<tr>
<td>DSSAT</td>
<td></td>
<td>Agriculture</td>
<td>Grid based</td>
<td></td>
</tr>
<tr>
<td>DIVA</td>
<td>Uni Southampton</td>
<td>Coastal</td>
<td>Coastline</td>
<td></td>
</tr>
<tr>
<td>Orchidee</td>
<td></td>
<td>Water/Agriculture</td>
<td>Grid based</td>
<td></td>
</tr>
</tbody>
</table>

To understand the linkages, the landscape of the IMPACT2C project was mapped.

The Figure shows the linkages of models across sectors thus showing the coverage of and degree of integration between sectors across the different Work Packages. Some models are linked or have been part of model inter-comparison (MIP) exercises. However, it was also necessary to make additional connections and to identify the level of spatial detail and other such issues so as to allow the later synthesis bringing together the information in a harmonised analysis for Europe and also for the subsequent step of vulnerable regions.
All models were run the set of essential scenarios five scenarios have been selected from Ensembles and an addition 10 were selected from Cordex (see figure). Five using RCP 2.6 and five using RCP 4.5. It is important that the results of the models are comparable therefore a model inter-comparison protocol was developed. This protocol was used by the different for the model runs of their impact model.

Climate change impacts modelling framework

For the hydrological and water resources assessment, five different models were used for model inter-comparison. Each of these models have partly common output but also each focus on different sector. All model compute primary hydrological variables such as run-off, evaporation and discharge. These variables will be compared and used for model chain uncertainty assessment. Each model also has it particular focus, for example Lisflood will be used for the flood analyses and LPJml for water for irrigation assessments.

For the agricultural and bioenergy analyses the different IIASA models were linked. At the heart of the cluster is the Global Biosphere Management Model (GLOBIOM, www.globiom.org ), a bottom-up, partial equilibrium model balancing demand and supply in the agricultural, forestry and bioenergy sectors. It is based on input information from a suite of biophysical models: the Global Forest Model (G4M), the crop model EPIC and RUMINANT on the coefficients for livestock. GLOBIOM has currently a resolution of 52 regions, with a representation of individual EU countries. GLOBIOM will share the major driver information with the other participating models. In the socio-economic dimension, this will be based on the SSPs, where the main inputs will be GDP and population. For climate data, these will be used indirectly in the form of e.g. crop yields processed by EPIC, which will then be used as input to GLOBIOM. Changes in crop yields will translate into differences in land use, impact on prices and production/consumption and trade flows. More detailed information on the modelling can be found in Havlik et al. (2011).
Impact2C cross sectoral water modeling framework
3 Vulnerable regions exposed to multiple (cross-sectoral) impacts.

Another key issue is that the impacts of climate change will fall disproportionately on certain regions, i.e. where multiple impacts occur, potentially leading to cumulative effects (e.g. Mediterranean region, Alpine region, etc.). This work package has considered these potential effects by combining the information from WPs 6-8 and WPs 9-10 and overlaying these to identify potential hotspots. This has identified multiple vulnerability and potential impacts under 2°C scenarios.

Complementing this, further cross-sectoral analysis was undertaken on water, due to its cross-sectoral dimensions, with a European level and a national case study. These focused on European water use and on Eastern Mediterranean island states, which are particularly vulnerable to multiple issues.

3.1 Hot Spot Mapping

3.1.1 Introduction
The spatial distribution of impacts across Europe under a two degree world is of major interest to European and national policymakers. This task investigates the question whether there are particular parts of Europe that may be exposed to more than one climate impact. The analysis undertaken considers potential negative and positive impacts in a number of different economic sectors, using a number of different climate and impact model simulations. In doing so, this work provides a means of identifying hotspots of potential winners and losers across Europe and sectors, under a two degree world.

3.1.2 Method

Climate models used
In the various different economic sectors, a number of different impact models were used which allows the simulation of potential impacts. These models need to be fed with climate data, and an adequate treatment of uncertainty in the climate models is desired. Consistent with the overall project philosophy, a number of different global climate models (GCMs), and regional climate models (RCMs) were used, for three different emissions scenarios from the Representative Concentration Pathways (RCPs). The details of the various climate simulations that were available are given in table 11.x. Another key aspect that all the different modelling groups in IMPACT2C were faced with was the determination of the two degree warming period, and whether this could be defined on the basis of when the driving GCM reaches 2 degrees, or whether because of resource constraints, a different approach would be necessary. In IMPACT2C, two approaches were pursued, one which was based on transient climate data allowing the two degree period to be defined by the GCM per RCP, and a fixed period per RCP, for models which were too expensive to run with transient data. The various time periods used for each RCM/GCM pair is also detailed in table 11.x, and the actual approach taken in each economic sector, it detailed in table 11.x. All climate data used in the analysis were bias corrected.

Socio-economic data
Where it was necessary to make use of socio-economic data, for example where projections of population were important, then the modelling groups made use of the Shared Socio-Economics
Pathway database from IIASA. In the analysis described here this relates to the attributable fraction of deaths to heat stress in the health sector.

**Sectors and climate impact indicators**

Potential impacts in the water, agriculture, health, and ecosystems sectors were investigated. Details of the various modelling experiments are contained in table 11.x. Because the spatial resolution of the different impact models varies between groups, all impact model data was resampled to a common 0.5 degree resolution for this analysis.

**Identifying hotspots**

When trying to identify areas in Europe that may be exposed to multiple impacts, we need an objective way of determining what constitutes a negative or positive impact. In this analysis, we identify hotspots – areas (grid cells) – that may be particularly affected by climate impacts in the various sectors. Where possible we try and link the impacts and the definition of a hotspot to EU policy thresholds, and where this is not possible, we use physically meaningful thresholds. The criteria used for identifying hotspots in each sector and for each impact metric are summarised in table 11.x. The modelling set-up adopted, making use of multiple climate models, and multiple impact models, permits a more complete treatment of uncertainty when identifying hotspots. We quantified the uncertainty in the identified hotspots by using the level of model agreement. Robust hotspots were identified based on a majority rule, such that most models had to agree that a given grid cell was indeed a hotspot. In practice, this meant a minimum of 3 and 6 models for sectors with 5 and 10 members in the ensemble, respectively.

**Summary of the climate models used**, and the time period during which two degrees Celsius above pre-industrial is reached under each GCM, and RCP scenario.

<table>
<thead>
<tr>
<th>RCM/GCM pair</th>
<th>Time period when GCM reaches 2°C above pre-industrial</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RCP2.6</strong></td>
<td></td>
</tr>
<tr>
<td>SMHI-RCA4 / EC-EARTH-r12</td>
<td>2 degree period not reached (2070-2099 used)</td>
</tr>
<tr>
<td>CSC-REMO / MPI-ESM-LR-r1</td>
<td>2 degree period not reached (2070-2099 used)</td>
</tr>
<tr>
<td><strong>RCP4.5</strong></td>
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<td>SMHI-RCA4 / EC-EARTH-r12</td>
<td>2042-2071</td>
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<tr>
<td>SMHI-RCA4 / HadGEM2-ES-r1</td>
<td>2023-2052</td>
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<tr>
<td>IPSL-INERIS-WRF331F / IPSL-CM5A-MR-r1</td>
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<tr>
<td><strong>RCP8.5</strong></td>
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<td>CSC-REMO / MPI-ESM-LR-r1</td>
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<tr>
<td>SMHI-RCA4 / HadGEM2-ES-r1</td>
<td>2016-2045</td>
</tr>
<tr>
<td>SMHI-RCA4 / EC-EARTH-r12</td>
<td>2027-2056</td>
</tr>
</tbody>
</table>
Ideally we would have a consistent and coherent methodology for all sectors, this has not proven to be the case though, because of differences in the number of impact models used, and whether a fixed or GCM specific time period has been used.

**Summary of the impact metrics available for use in the cross-sectoral hotspot analysis.**

<table>
<thead>
<tr>
<th>Sector</th>
<th>Impact</th>
<th>Impact metric</th>
<th>Impact models</th>
<th>2° period</th>
<th>Simulation details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water</strong></td>
<td>Cooling water</td>
<td>Water temperature</td>
<td>VIC</td>
<td>GCM specific</td>
<td>Five mandatory simulations under RCP4.5.</td>
</tr>
<tr>
<td></td>
<td>Hydrological drought</td>
<td>River discharge (change in the duration and magnitude of low flow, for the 10 and 100 year return period events)</td>
<td>E-Hype, LisFlood</td>
<td>GCM specific</td>
<td>All mandatory and optional simulations for RCP2.6, RCP4.5, and RCP8.5, as listed above, for a total of 22 simulations.</td>
</tr>
<tr>
<td></td>
<td>Floods</td>
<td>River discharge (change in level of the 10 year and 100 year return period events)</td>
<td>E-Hype, LisFlood, VIC</td>
<td>GCM specific</td>
<td>All mandatory and optional simulations for RCP2.6, RCP4.5, and RCP8.5, as listed above, for a total of 33 simulations.</td>
</tr>
<tr>
<td><strong>Agriculture</strong></td>
<td>Crop productivity</td>
<td>Crop yield (rainfed winter wheat and irrigated maize analysed)</td>
<td>EPIC, LPJm</td>
<td>GCM specific</td>
<td>All five mandatory simulations under RCP4.5 were used for EPIC and LPJmL, for a total of 10 simulations.</td>
</tr>
<tr>
<td><strong>Health</strong></td>
<td>Heat stress mortality</td>
<td>Daily attributable fraction</td>
<td>Linear regression model</td>
<td>Fixed</td>
<td>Four GCM/RCM simulations under RCP8.5, and one under RCP4.5. (2036-2064 for 2 degrees RCP4.5 and RCP8.5)</td>
</tr>
<tr>
<td><strong>Ecosystems</strong></td>
<td>Terrestrial ecosystem function</td>
<td>Net primary production (NPP)</td>
<td>CLM4.0-CN, LPJmL</td>
<td>GCM specific</td>
<td>The five RCP4.5 simulations for LPJmL, four RCP4.5, one RCP8.5, and one RCP2.6 simulation for CLM4.0-CN.</td>
</tr>
<tr>
<td></td>
<td>Soil organic carbon (SOC)</td>
<td>CLM4.0-CN, LPJmL</td>
<td>GCM specific</td>
<td></td>
<td>The five RCP4.5 simulations for LPJmL, four RCP4.5, one RCP8.5, and one RCP2.6 simulation for CLM4.0-CN.</td>
</tr>
</tbody>
</table>
### Criteria for identification of hotspots for each impact metric.

<table>
<thead>
<tr>
<th>Impact</th>
<th>'Winner' hotspot criterion</th>
<th>'Loser' hotspot criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cooling water</strong></td>
<td>Grid cells with a greater than 10% relative decrease in the number of days when the 23°C threshold is exceeded.</td>
<td>Grid cells with a greater than 10% relative increase in the number of days when the 23°C threshold is exceeded.</td>
</tr>
<tr>
<td></td>
<td>Number of days when water temperature is above 23°C is of relevance to water extraction for cooling water in the EU (van Vliet et al. 2013).</td>
<td></td>
</tr>
<tr>
<td><strong>Hydrological drought</strong> (low flow level, return period 10 and 100 years)</td>
<td>Grid cells with a greater than 10% relative increase in median response.</td>
<td>Grid cells with a greater than 10% relative decrease in median response.</td>
</tr>
<tr>
<td><strong>Hydrological drought</strong> (length of low flow, return period 10 and 100 years)</td>
<td>Grid cells with a greater than 10% relative decrease in median response.</td>
<td>Grid cells with a greater than 10% relative increase in median response.</td>
</tr>
<tr>
<td><strong>Floods (return period 10 and 100 years)</strong></td>
<td>Grid cells with a greater than 10% relative decrease in median response.</td>
<td>Grid cells with a greater than 10% relative increase in median response.</td>
</tr>
<tr>
<td><strong>Crop yield (winter wheat and irrigated maize)</strong></td>
<td>Areas with a greater than 10% relative increase in crop yield.</td>
<td>Areas with a greater than 10% relative decrease in crop yield.</td>
</tr>
<tr>
<td><strong>Attributable fraction (AF) heat stress mortality</strong></td>
<td>Identification of 'winners' not possible.</td>
<td>Areas with an AF greater than 3 were identified as 'losers'.</td>
</tr>
<tr>
<td><strong>Terrestrial ecosystem function (NPP, SOC)</strong></td>
<td>Increases of greater than 10% in NPP and SOC.</td>
<td>Decreases of greater than 10% in NPP and SOC.</td>
</tr>
</tbody>
</table>

### 3.1.3 Results

**Robust hotspots and multi-sectoral 'winners'**

Robust 'winner' hotspots were identified in every impact metric. These are shown in figures below. Because of the method used to generate the flood, low flow, and length of low flow for the 10 and 100 year return period events, it was not possible to identify robust hotspots according to the definition used in this task. Nevertheless, these data are included here for completeness and to aid understanding and interpretation of the multi-sectoral hotspot winners.
Flood 10 year return period 'winners'.

Flood 100 year return period 'winners'.

11
Length of low flow 10 year return period 'winners'.

Length of low flow 100 year return period 'winners'.
Low flow 10 year return period 'winners'.

Low flow 100 year return period 'winners'.

13
Robust wheat hotspot 'winners'.

Robust irrigated maize hotspot 'winners'.
Robust net primary production (NPP) ‘winners’.

Robust soil organic carbon hotspot ‘winners’. 
Robust multi-sectoral hotspot ‘winners’.

As can be seen, the major winners from a plus two degree world, using the metrics analysed in this study, are located in far northern Europe, with some areas of Norway and Sweden having positive impacts for all metrics considered. There is also a cluster of winners in north-eastern Europe in Poland, eastern Germany, the Czech Republic and the Baltic states. For the most part areas in southern and north-western Europe only show one possible winning sector, and that is NPP, where there are winners all across Europe. As regards the various water resource metrics, these areas do not do well under a plus two degree world.

Robust hotspots and multi-sectoral ‘losers’

The robust hotspot losers are shown below. It is interesting to note that using the method we adopt in this task, that there are no robust hotspots ‘losers’, for net primary production (NPP), and soil organic carbon (SOC).
Flood 10 year return period 'losers'.

Flood 100 year return period 'losers'.
Length of low flow 10 year return period 'losers'.

Length of low flow 100 year return period 'losers'.
Low flow 10 year return period 'losers'.

Low flow 100 year return period 'losers'.

19
Robust wheat hotspot 'losers'.

Robust water temperature 'losers'.

20
The major losers from a plus two degree world, using the metrics analysed in this study, are located in southern Europe, with Spain, France, Bulgaria, Romania, and Greece being the major 'losers'.
There are also large areas of eastern Europe in Hungary and Poland where a number of negative impacts may be expected.

3.1.4 Case studies

Three integrated water management case studies were carried out in this task, in three major southern European river basins: the Guadalquivir, Garonne, and the Po. Impacts that were investigated were relative changes in mean monthly discharge, relative changes in the 10 year return period flood and length of low flow events, and relative changes in the yield of irrigated maize, in a plus two degree world.

For the crop yield and flood and length of low flow events, the data basis was the same as for the multi-sectoral analysis. However, for the monthly mean discharge data the number of hydrological models used, and for which RCP scenario were different. No WBM data were used and only 3 RCP8.5 simulations with the VIC model, with driving GCM MPI-ESM-LR, EC-EARTH, and HadGEM2-ES. This resulted in an ensemble size with 30 members.

![Location of the three river basin integrated water management case studies within Europe.](image)

**Garonne basin**

The annual cycle of relative changes in mean monthly discharge at the 25th, 50th and 75th percentile, is shown below, along with relative change in the 10 year return period flood event, the relative change in the 10 year return period length of low flow event and the relative change in irrigated maize crop yield over the basin.

The figure shows very clearly is that in this analysis the median response of changes in monthly mean discharge is for winter and spring to have an increase in flow, whereas in summer and autumn mean monthly discharge is shown to decrease in a two degree world.
At all percentile levels the 10 year return period flood event is shown to increase across the vast majority of the Garonne basin.

At all percentiles levels the 10 year return period length of low flow event is projected to increase considerably over almost the entire basin.

Almost all areas of the Garonne are projected to have an increase in irrigated maize yield. Given the projected changes in the water resources in the basin, particularly the summer and autumn monthly mean discharge, and the length of the low flow event, these projected changes may need adequate adaptation planning if they were to be realised.

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Annual cycle of relative changes in mean monthly discharge in the Garonne basin, with uncertainty quantified at the 25th, 50th, and 75th percentiles.
Relative change in the 10 year return period flood event in the Garonne basin, with the 25th, 50th, and 75th percentiles shown.
Relative change in the length of the 10 year return period low flow event, with 25th, 50th, and 75th percentiles.
Guadalquivir Basin

The annual cycle of relative changes in mean monthly discharge at the 25th, 50th and 75th percentile, is shown below, along with the relative change in the 10 year return period flood event, the relative change in the 10 year return period length of low flow event and the relative change in irrigated maize crop yield over the basin.

This shows very clearly is that the overwhelming picture is one of a reduction in monthly mean discharge throughout the year. Only at the 75th percentile are there some areas of the basin showing projected increases, and this is particularly marked in the month of November.

At the 50th and 75th percentile levels the 10 year return period flood event is shown to increase across the vast majority of the Guadalquivir basin.
At all percentiles levels the 10 year return period length of low flow event is projected to increase considerably over almost the entire basin.

Almost all areas of the Guadalquivir are projected to have a moderate increase in irrigated maize yield at the 50th percentile level. Given the projected changes in the water resources in the basin, particularly the summer and autumn monthly mean discharge, and the length of the low flow event, these projected changes may need adequate adaptation planning if they were to be realised, since the crop model simulations assume that sufficient irrigation water will be available, which seems questionable in view of these simulations, and is worthy of further investigation.

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</table>

Annual cycle of relative changes in mean monthly discharge in the Guadalquivir basin, with uncertainty quantified at the 25th, 50th, and 75th percentiles.
Relative change in the 10 year return period flood event in the Guadalquivir basin, with the 25th, 50th, and 75th percentiles shown.
Relative change in the length of the 10 year return period low flow event, with 25th, 50th, and 75th percentiles.
Relative change in irrigated maize yield in the Guadalquivir river basin.

**Po Basin**

The annual cycle of relative changes in mean monthly discharge at the 25th, 50th and 75th percentile, is shown below, along with the relative change in the 10 year return period flood event, the relative change in the 10 year return period length of low flow event and the relative change in irrigated maize crop yield over the basin.

This shows very clearly that the overwhelming picture is one of increased seasonality, with an increase in monthly mean discharge in the winter and spring months across the basin, and a reduction in monthly mean discharge in summer months.
On the whole flooding is projected to get worse across almost the entire basin, and at all percentile levels. With respect to the length of the low flow event, hydrological droughts show a split picture between the northern and more southerly areas, with drought increasing in the south, and decreasing in the north. This pattern holds across all percentiles levels.

Almost all areas and under all percentile levels are projected to have a significant increase in irrigated maize yield. Given the changes in water resources in the Po basin, there seems reason to believe that the provision of irrigation water to achieve these yield increases, is not particularly threatened, though this is worthy of further investigation.

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</tbody>
</table>

Annual cycle of relative changes in mean monthly discharge in the Po basin, with uncertainty quantified at the 25th, 50th, and 75th percentiles.
Relative change in the 10 year return period flood event in the Po basin, with the 25th, 50th, and 75th percentiles shown.
Relative change in the length of the 10 year return period low flow event, with 25th, 50th, and 75th percentiles.
Relative change in irrigated maize yield in the Po river basin.
3.2 European Water Case Study

Case study on Water availability - cross-sectoral synthesis of climate change impacts on water availability and European water management multi-sectorial water use.

3.2.1 Introduction

Water is used by different sectors and changes in water availability due to climate changes affect a range of different sectors. For this analyses we selected various water use sectors and present for each sector hydrological indices that are most critical under climate change. The sectors addressed are Risk and Safety (floods and streamflow droughts), Agriculture (streamflow and soil moisture droughts), and Energy (hydropower potential and cooling water availability) and the Environment (water temperature, dissolved oxygen concentrations, nutrient loads). We used the hydrological model, Lisflood, LPJml, Hydrological Predictions for the Environment (HYPE) hydrological model set up for Europe (E-HYPE) and Variable Infiltration Capacity (VIC) land surface scheme linked to the stream temperature model RBM to simulate hydrological changes. All hydrological models were used to produce an ensemble of water resources projections based on climate scenarios developed within the project. The basis for the analyses was the simulations performed within Work Package six but for the case study here we analysed a range of indicators.

3.2.2 Method

For these analyses we used the hydrological model runs done as part of WP6. For more details on the hydrological models and climate input data see Greuell et al. 2015; Roudier et al. 2015 and deliverable 6.1 (Ludwig et al. 2015).

For the analyses a range of different indicators were selected to assess the vulnerability of European water use sectors (Table 1). Indices selected reflect the vulnerability of the following water related sectors to climate change.

- Safety and Risk (floods and streamflow droughts);
- Agriculture (streamflow and soil moisture droughts);
- Energy (hydropower potential and cooling water availability); and
- Environment (water temperature)

The indices selected and the aforementioned sectors are presented in Table 1.

Table 1: Selection of hydrological indices, units and definitions and associated water use sectors

<table>
<thead>
<tr>
<th>Hydrological index</th>
<th>Unit</th>
<th>Definition</th>
<th>Other sectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_{\text{max} \ 1:10\text{yr}} )</td>
<td>m(^3) s(^{-1})</td>
<td>1 in a 10-year flood</td>
<td>agriculture</td>
</tr>
<tr>
<td>( Q_{10} )</td>
<td>m(^3) s(^{-1})</td>
<td>10-percentile streamflow (streamflow drought)</td>
<td>agriculture, energy</td>
</tr>
<tr>
<td>( ndays( Q &lt; Q_{10} ) )</td>
<td>-</td>
<td>number of days per year with streamflow drought (flow less than 10(^{th}) percentile flow)</td>
<td>agriculture, energy</td>
</tr>
</tbody>
</table>
### 3.2.3 Results

Two degree warming has an important impact on the European water cycle (Figure 1). At annual time scale rainfall is reducing in the south and increasing in the North. The higher rainfall and increased temperatures result in higher evaporation in the northern and Eastern parts of the continents. Water availability is especially increasing in the Northern and Eastern parts of Europe while in Mediterranean Europe water availability is reducing especially in summer (Figure 11.2.1). There is a clear North to South gradient for changes in flood magnitude (Figure 11.2.2). There is a strong increase in flood events below the 60°N, except for the southern part of the Iberian Peninsula, Bulgaria, and Poland. Across Europe the increase in 100 year floods (QRP100) is stronger than the 10 year floods (QRP10). Floods are even increasing in areas such as southern Mediterranean where an average discharge is projected to decrease.

Streamflow droughts are especially increasing in southern and Western Europe. Both duration and magnitude of one in 10 year droughts are increasing in especially Portugal, Spain, France, Italy and Greece (Figure 11.2.3). In Northern and Eastern Europe stream flow droughts are reducing. The dryland agricultural sector is especially affected by soil moisture droughts. For these droughts the picture is quite a bit different. These droughts are increasing throughout continent except for the Alps and the Northern parts of Finland, Sweden and Norway (Figure 11.2.5).

When combining the changes in stream flow drought and floods it becomes clear the especially in Southern Europe hydrological extremes will increase while in North-East Europe there is a reduction of extremes (11.2.6).

### Table 1: Meteorological droughts

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sum_{\text{max}} \frac{0, (Q - Q_{10})}{\text{ndays}} )</td>
<td>m³·s⁻¹</td>
<td>mean flow deficit (of the days defined as drought)</td>
</tr>
<tr>
<td>( \frac{Q_{10}}{\text{ndays}} )</td>
<td>mm</td>
<td>10-percentile soil moisture</td>
</tr>
<tr>
<td>( \text{agriculture, energy} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \sum_{\text{max}} \frac{0, (SM - SM_{10})}{\text{ndays}} )</td>
<td>mm</td>
<td>mean soil moisture deficit (of the days defined as drought)</td>
</tr>
<tr>
<td>( \text{agriculture, energy} )</td>
<td></td>
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</tbody>
</table>

### Table 2: Hydrological droughts

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_{\text{avg}} )</td>
<td>m³·s⁻¹</td>
<td>mean streamflow</td>
</tr>
<tr>
<td>( T_{\text{avg}} )</td>
<td>°C</td>
<td>mean water temperature</td>
</tr>
<tr>
<td>( \text{environment} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{energy} )</td>
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</table>

### Table 3: Energy sector

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Description</th>
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<tbody>
<tr>
<td>( \text{Hydropower potential} )</td>
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<tr>
<td>( \text{Hydropower potential} )</td>
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<td>( \text{Cooling water use potential} )</td>
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<td>( \text{thermoelectric power} )</td>
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<td>( \text{Environment} )</td>
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<tr>
<td>( \text{Energy} )</td>
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<tr>
<th></th>
<th>Unit</th>
<th>Description</th>
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<tbody>
<tr>
<td>( \text{Hydropower potential} )</td>
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<td>( \text{Hydropower potential} )</td>
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<tr>
<td>( \text{Cooling water use potential} )</td>
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<tr>
<td>( \text{thermoelectric power} )</td>
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<td>( \text{Environment} )</td>
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<td></td>
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<tr>
<td>( \text{Energy} )</td>
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</table>
Changes in the water resources especially affect the energy sector through an impact on cooling water availability and hydropower production. Climate change even at two degree warming has a large impact on thermos electric power potential (Figure 11.2.8). In most countries the power production potential is reducing due change in cooling water availability. Especially countries in Southern and Western Europe are affected. For hydropower the results are more mixed (Figure 11.2.6). For most countries in Europe the hydropower potential will increase. Only for Portugal, Spain, Italy and Greece a clear reduction is predicted.

**Figure 11.2.1.** Average annual changes in precipitation, run-off, evapotranspiration and discharge at two degree warming. Except for precipitation, results are the average of 55 model runs (5 hydrological models * 11 Regional climate models).
Figure 11.2.2. High flows median relative change, for two different return periods; RP10 (top), and RP100 (bottom). The median is computed over 33 members (3 hydrological model * 11 RCMs). Only significant changes are shown here.

Figure 11.2.3. Changes in future streamflow droughts at 2°C warming. Top panel shows changes in 10 year low flows and top panel shows changes in drought duration. Only significant changes are shown here. When flow is zero for the baseline period, we set the relative change as missing value.
Figure 11.2.4: Changes in occurrence of streamflow deficits (number of days per year with streamflow < 10-percentile streamflow of control period) at 2°C degree warming for the E-hype and Vic model.

Figure 11.2.5. Changes in soil moisture drought at 2°C warming. Left panels show spatial patterns of changes in low (10-percentile) soil moisture content and the right panels show spatial patterns of changes in number of days per year with soil moisture deficits (soil moisture < 10-percentile soil moisture of control period)
Figure 11.2.6. Summary of the impacts on extreme discharge (return period is 10 years) under a 2°C warming. Green area means that flood risks, drought duration and magnitude are all decreasing (i) QRP10 change < -5%, (ii) QRPlow10 change > +5% and (iii) QRPlow10 duration change <-5%). Red indicates an increase of flood and drought. Only pixels are shown when all three changes are statistically significant.

Figure 11.2.7. Relative change in hydropower potential for European countries at 2°C warming using five different hydrological models. Each bar is the average of five regional climate models.
Figure 11.2.8. Relative changes in thermo-electric power potential for European countries at 2°C warming. Each bar is the average of five different regional climate models.

### 3.2.4 Conclusions

In general projected climate change impacts on water use sectors are most extensive in southern Europe. Water availability will reduce and droughts and flood risks will increase. This is likely to have serious impacts on the Energy and Agricultural sector. Changes in water availability will also affect the pressure on the environment, in particular in areas where water is already a limiting factor at the moment. In Northern Europe most of the climate pressures will result in increased risks and reduced safety levels due to higher flood risks. However also in some parts of Northern Europe soil moisture droughts will increase and also water temperatures will be higher in the future. These changes will impact the energy and agricultural sector. Results show that Europe will face significant changes in the water use sector already at two degree warming with potentially large impacts on especially the agricultural and energy sector.
3.3 Mediterranean Case Study

Cross sectoral impacts on water availability at +2°C and +3°C for east Mediterranean island states: the case of Crete

A case study was completed on cross sectoral impacts on water availability at +2°C and +3°C. This case study investigated how impacts will fall disproportionately on certain regions in Europe, looking at south Eastern Europe, which is projected to experience a more intense warming, and for east Mediterranean island states which are particularly vulnerable, looking at the island of Crete.

3.3.1 Introduction

At the regional level of the Mediterranean, the temperature increase from climate change is expected to be larger than the global average (Vautard et al., 2014). By the time that global warming reaches the +2°C relatively to the preindustrial baseline period (1881-1910) it is estimated that the Mediterranean region will experience approximately 0.2°C higher temperatures on average, with even more pronounced summer temperature increase. The higher temperature will increase the evaporation rates from reservoirs and the potential evapotranspiration from the land surface (Bates et al., 2008). Additionally, climate change is also projected to pose changes in the precipitation regime (Hagemann et al., 2013), with climate models depicting that precipitation on average is likely to be less frequent but more intense, while drought events are likely to become more frequent and severe in some regions (Koutoulis et al., 2013; Tsanis et al., 2011). The progressive decline of future water scenarios for Mediterranean will most likely cause short-term unsustainability of many water infrastructures in the Mediterranean basin (García-Ruiz et al., 2011), posing additional pressures to water availability in addition to human induced changes (Grouillet et al., 2015).

Several studies have assessed cross-sectoral climate change impacts at global and continental scale (Arnell et al., 2013; Harrison et al., 2012; Metzger et al., 2005; Piontek et al., 2014; Schewe et al., 2014; Warszawski et al., 2014) but few have done so at local or even regional scale. Furthermore, local climate change impact studies (Cleridou et al., 2014; Fabre et al., 2015; Garrote et al., 2015; Vargas-Amelin and Pindado, 2013) are framed on socioeconomic prospective scenarios and management choices without considering water demand in the form of qualitative/narrative scenarios according to SSPs. Based on recent studies on water availability and stress (Koutoulis et al., 2015, 2013; Tsanis et al., 2011) for the island of Crete, Greece, the issue of future water resources availability is revisited under the latest generation of climate scenarios (RCPs) combined with tailored information on shared socio-economic pathways (SSP). We integrate the major impacts of climate change on the water resources of a Mediterranean insular socioeconomic system by downscaling the socio-economic drivers information such as population and economic development and climate information to the local area. Therefore, the present study is one of the few to date that is considering water use in the context of qualitative/narrative scenarios of SSPs, at local level, following a plausible combination of SSP-RCPs scenarios to examine future water availability under a cross-sectoral climate change impacts framework.

3.3.2 Method

Cross-sectoral framework

The study was built around the scenario-based impact assessment approach (Christensen et al., 2011; Ciscar et al., 2014) focusing on the risks of future climate change. Two different climatic pathways, RCP 4.5 and RCP 8.5 were considered for assessing the future climate relative to the baseline period. Projection periods defined by the level of global warming (+2°C and +3°C) as
simulated by the driving GCMs (described in detail in the dataset section). Three potential associated socio-economic pathways were considered, SSP1, SSP2 and SSP3. The changes in supply and demand were then assessed at two different global warming levels, of +2°C and +3°C. The three SSPs were combined to the hydro-climate projections to incorporate scenarios of alternative futures of water supply and demand under future economic and societal development. The climate scenarios provided the climatic information for the assessment of the hydrological impacts at specific warming levels by modeling the changes in the local terrestrial water cycle. Information on existing and planned water resources infrastructures and management practices were used for the development of realistic local water demand and supply scenarios compatible with the SSPs. The localized scenarios were developed in collaboration with the Directorate of Water, the general water managing authority for the Region of Crete (RoC), exploring the feasibility and the costing adaptation measures, in terms of additional water infrastructures, associated with the set of socioeconomic pathways. Scenarios of future changes in irrigation, tourism, energy, domestic, livestock and industrial water demand were also composed according to the potential socio-economic futures, within a framework of a cross-sectoral water resources analysis. Finally, hydro-climatic and socioeconomic scenarios were associated in the context of plausible RCP-SSP combinations. Five future situations under different local hydro-climatic and socioeconomic conditions were considered to examine the range of potential impacts on water availability at +2°C and +3°C of global warming. This methodological framework is illustrated in Figure 1.

Framework of a cross-sectoral climate change impact study of 2°C and 3°C global warming on Water Resources for the island of Crete

Scenarios

In the context of water resources research the basic information provided by the SSPs and RCPs scenarios. For global population, SSPs trajectories are very close until around 2030s, while by the 2050 a clear differentiation occurs, with the highest (SSP3) and the lowest (SSP1) trajectories spanning 1.5 billion. This difference is further expanding until 2100 with the SSP3 reaching 12.6 billion and SSP1 falling to 6.9 billion, lower than the today’s world total population (KC and Lutz, 2014). Greece belongs to the rich OECD membership countries, with low fertility (average offspring per woman ≤2.9). Under SSP1 which assumes a future that is moving toward a more sustainable path, Greece will experience population stabilization, and from 2060, a decline. Population also falls in other SSPs, though growth is higher compared to SSP1. A critical limitation of SSP scenarios is that they do not provide any qualitative or narrative information on future water use (Naota Hanasaki et
al., 2013) that would be downscaled and adjusted to the needs of a local or regional study. Hence, in collaboration with the local water authorities we developed water use scenarios compatible with the SSPs. The scenarios included information about the future planned large water storage infrastructure.

Projections of global population (upper), population of Greece (mid) and GDP of Greece (lower) according to the three analyzed SSPs. Dots represent the projected mean value of population and GDP for each SSP for the global warming levels of +2°C and +3°C.

Data sets and bias correction

Observed precipitation data from 53 raingauges and 15 temperature stations were used to estimate the basin scale precipitation and temperature for the 130 distinct watersheds of Crete. Regional climate model data from five Euro CORDEX RCMs at 0.11 degrees resolution provided the climate projections according to RCP 4.5 and RCP 8.5.

Three 30 years periods were considered, a reference period between 1971 and 2000 and the future time-slices around +2°C according to RCP4.5 and around +2°C and +3°C under the RCP8.5. The +2°C and +3°C periods were explicitly defined for each model as the period in which each driving GCM reaches this specific level of global warming comparing to the preindustrial baseline period 1881-1910 (Vautard et al., 2014). The 30-year time slice around which the +2°C and +3°C periods are defined for each GCM driving model. The RCM data were downscaled to basin level. The difference in mean and standard deviation of the downscaled timeseries were then adjusted using the basin scale
precipitation and temperature timeseries between 1973 and 2004. The methodology that was used for the adjustment is presented in (Haerter et al., 2011) and was applied on the monthly time-step.

**CORDEX RCMs, their driving GCMs and the timing of +2°C under the RCP4.5 and RCP8.5. GCMs that do not reach the +3°C under RCP 4.5 are indicated with N/R. Not available = N/A.**

<table>
<thead>
<tr>
<th>Driving GCM</th>
<th>RCM</th>
<th>+2°C timeslice</th>
<th>+3°C timeslice</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC-EARTH-r1</td>
<td>KNMI-RACMO22E</td>
<td>2042-2071</td>
<td>2028-2057</td>
</tr>
<tr>
<td>EC-EARTH-r12</td>
<td>SMHI-RCA4</td>
<td>2042-2071</td>
<td>2027-2056</td>
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<tr>
<td>IPSL-CM5A-MR-r1</td>
<td>IPSL-INERIS-WRF331F</td>
<td>2028-2057</td>
<td>N/A</td>
</tr>
<tr>
<td>HadGEM2-ES-r1</td>
<td>SMHI-RCA4</td>
<td>2023-2052</td>
<td>2016-2045</td>
</tr>
<tr>
<td>MPI-ESM-LR-r1</td>
<td>CSC-REMO</td>
<td>2050-2079</td>
<td>2030-2059</td>
</tr>
</tbody>
</table>

Details regarding existing and future water resources infrastructure were provided by the local authority. Existing infrastructure (dams, reservoirs, groundwater abstractions) shapes the current supply potential to 421.40 Mm³/yr. Future exploitation plans include the construction of small – local scale dams and reservoirs, large embankment dams of wider operation range, improvement of existing boreholes, construction of new irrigation networks and other complex water engineering structures. A total number of 68 water engineering projects were defined with a total capacity of 166.8 Mm³ (about 40% additional supply compared to existing, at present climate conditions) and a cumulative construction cost of 893 million EUR (current prices). The feasibility and the implementation maturity of these projects were evaluated in collaboration with the local authority in the context of the SSPs. Information regarding local population, overnight tourism stays, industry, energy and livestock population were retrieved by the Hellenic Statistic Authority. Crop area and water demand by cultivation type were obtained by the study of Papagrigoriou et al., (2001).

**Hydrological modelling**

The hydrological simulations were performed using the calibrated SAC-SMA continuous rainfall–runoff model (Tsanis et al., 2011). The SAC-SMA Sacramento model is a lumped continuous rainfall-runoff model that can estimate stream runoff \( Q \) from precipitation \( P \) and potential evapotranspiration \( \text{PET} \), based on soil moisture accounting (Podger, 2004). Soil moisture storage increases by \( P \) and reduces by actual evapotranspiration \( AET \) and total runoff \( Q \) \((Q_{\text{direct}} + Q_{\text{surface}} + Q_{\text{baseflow}})\) and infiltration \( I \) between the upper and lower zone that discharges at a slower rate \( Q_{\text{slow}} \). The size and relative wetness of the storage determines the depth of \( P \) absorbed, \( AET \), and the amount of water moving vertically or laterally out of the store. These processes are described by 16 parameters that need to be determined by the user or an optimization process using a suitable objective function. Here, SAC-SMA is calibrated using a scheme based on an application of Genetic Algorithms (GAs) in order to eliminate subjective judgement of an expert user in model parameter selection. GAs are adaptive random search algorithms that mimic the principal of selection and evolution of the fittest in a natural system. Given a defined search space, GAs have a globally oriented searching approach and are thus potentially useful in solving complex optimization problems (Wang, 1997).

**3.3.3 Study Area and Context**

Crete is the fifth largest island in Mediterranean Sea and the first and most populous island of Greece. The climate is characterized as Mediterranean – Semiarid featuring long and dry summers
and relatively wet and cold winters (Kottek et al., 2006). The Water District of Crete (GR13) is the southernmost Water District of the country and includes the entire area of the Region of Crete. The RoC consists of four territorial units according to NUTS3 classification: Chania (GR434), Heraklion (GR431), Rethimno (GR433) and Lasithi (GR432). The population of Crete corresponds to 5.4% of the national population, with an increasing trend, since between the censuses of 2001 and 2011 the population increased by 3.65% (to 623,065 inhabitants).

The intense tectonic activity has formed the complex topography of the island with the elevation ranging from sea level to 2450 m, shaping small catchments with ephemeral streams and karst geology (Tsanis et al., 2011). During an average hydrological year, Crete receives about 7.7 billion m$^3$ of precipitating water, of which 68-76% evaporates or transpires, 14-17% infiltrates and 10-15% is lost to the seas as surface runoff (Koutroulis et al., 2013). Total annual surface runoff is about 1,080 Mm$^3$ and half of it discharges through the major rivers of the island. Total subsurface recharge is estimated to 780 Mm$^3$ per year.

The highly rugged terrain of Crete is crucial in terms of the spatial organization, the urban structure, the drivers of development of the productive sectors, the transport system and generally all to date, and future parameters related to human activities on the natural environment. It is estimated that the total water consumption corresponds to the 7% of the total precipitation (Tsagarakis et al., 2004). However, there are often water imbalance issues even that are attributed to the temporal and spatial variations in the precipitation over the island, the increase in water demand during the dry months due to tourism, and the difficulty of transporting water due to the mountainous terrain of the island (Tsagarakis et al., 2004).

The main water consuming sectors in Crete are agriculture that share the 84.5% of the total consumption, while domestic and industrial sectors use the 12% and 3.5% of the water respectively (Chartzoulakis, 2001). Agricultural water is mainly used to grow of vegetable crops, fruit trees and vines. More than 91% of vegetable crops are irrigated, 34.0% for row crops, 36.3% for fruits and 45.1% for vineyards (Chartzoulakis, 2001).

The RoC contributes about 5% (12.854 billion € in 2008) to the Gross Domestic Product (GDP) of the country. Regarding the three major sectors of the economy of Crete, during 2008 the primary sector participated with 5.51%, the secondary (Industry and Construction) contributed 13.84%, while the tertiary sector had the highest share with 80.65%. Before the 2008 crisis and during the period 2000-2008, the most important contribution to the added value of products of Crete was the "Trade and
Tourism sector, as part of the tertiary sector with 4.59 billion €, growing by 85% from 2000 to 2008. The primary sector, in absolute terms, remained stagnant, with a significantly reducing rate of contribution to the regional added value from 10.04% in 2000 to 5.51% in 2008. On the other hand, the "Industry and Energy" sector increased its contribution from 4.96% in 2000 to 7.48% in 2008. Since 2008, the island is facing a prolonged crisis, on par with that of the rest of the country, leading to little overall investments and financial contraction. Nevertheless, tourism is the most dynamically growing sector and the demand has given incentives for significant investment in hotel facilities, resulting in a quantitative and qualitative improvement of the accommodation infrastructure. Overnight stays in Crete in 2010 amounted to 16,449,065, representing 24.6% of all overnight stays in Greece. The intensification of tourism activity has increased the environmental stress (Andriotis, 2003), including the water demand stress.

![Graph of Population of the Region of Crete (RoC) from 1920 to 2011. Source (HSA, 2015); right Real GDP growth rate - volume - Percentage change on previous year for the Euro Area, Greece and Crete (Source: EUROSTAT, 2015; HSA, 2015).]

**3.3.4 Results**

**Hydro-meteorologic projections**

Transient temperature response at local level reveals an increasing temperature trend that is more pronounced in the case of the high-end RCP8.5 scenario. A global temperature increase by 2°C is projected to be milder at local level (Crete), reaching the +1.69°C above the annual average of 16.92°C (median 18.61°C) according to RCP4.5 (2037-2066 on average) and +1.80°C under RCP8.5 (2026-2055 on average). Similarly local temperature is projected to increase by 2.86°C around 2060 on average, at the global warming level of +3°C. Detailed projected changes of the range of the multi-model projections are included in the table. Average annual precipitation (903mm) is projected to decrease by 6% at the global warming level of +2°C nevertheless the concentration pathway (RCP4.5 around 2050s or RCP8.5 around 2040s) and this is an important piece of information that precipitation response to climate change is similar to the cumulative CO₂ concentration (about 70PgC from 2000 to 2050 for RCP4.5 and up to 2040 for RCP8.5), regardless the timing. The dry years (5th percentile) are also expected to be dryer by 7.3% and 11.9% under RCP4.5 and RCP8.5, respectively at a +2°C warmer world. Drought is projected even more pronounced (-17.9% of the 5th percentile of annual precipitation) at the higher warming level of +3°C.

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Transient response of temperature, precipitation and water availability at local scale (Crete) according to RCP4.5 and RCP8.5. The strong dashed line represent local observations, colored line correspond to the multi-model median, the strong shaded envelope to the interquartile range and the light shaded envelope to the 5th to 95th percentile range.

Potential evapotranspiration is also expected to increase by roughly 5% at +2°C and by 8% at +3°C attributed to temperature increase. The combined effect of increasing temperatures and decreasing precipitation foresees a decrease of average annual availability (defined as the sum of runoff and infiltration (Koutroulis et al., 2013; Tsanis et al., 2011)). The availability decrease is more pronounced compared to precipitation. At a +2°C warmer world, according to RCP8.5 the water availability is simulated to decrease roughly by a factor of two (-12.1%) compared to precipitation (-6%). The corresponding availability under RCP4.5 and compared to precipitation change is foreseen to decline by a factor of three (-18%) probably due to the further discharge of groundwater aquifers (RCP4.5 crosses the level of +2°C warming by 10 years later compared to RCP8.5). Dry years (in terms of availability) are expected to be drier by 20% – 25% in the case of +2°C and by over 35% at +3°C. The availability of wet years is projected to slightly decrease for RCP4.5 at +2°C and for RCP8.5 at +3°C and on the other hand, increase by almost 15% under RCP8.5 at +2°C.
Historical and projected local hydrol-meteorological response to different global warming scenarios and levels.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>5th%ile</th>
<th>25th%ile</th>
<th>Median</th>
<th>75th%ile</th>
<th>95th%ile</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature (°C)</td>
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<td>18.46</td>
<td>18.61</td>
<td>18.91</td>
<td>19.15</td>
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<tr>
<td>Precipitation (mm)</td>
<td>766</td>
<td>830</td>
<td>903</td>
<td>981</td>
<td>1054</td>
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<tr>
<td>Availability (mm)</td>
<td>138</td>
<td>172</td>
<td>218</td>
<td>274</td>
<td>330</td>
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<tr>
<td>Potential Evapotranspiration (mm)</td>
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<td>1,452</td>
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<tr>
<td><strong>RCP4.5 @ +2°C</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Temperature change (°C)</td>
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<td>1.69</td>
<td>1.77</td>
<td>1.76</td>
</tr>
<tr>
<td>Precipitation (mm)</td>
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<td>759</td>
<td>846</td>
<td>926</td>
<td>1,063</td>
</tr>
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<td>Precipitation change (%)</td>
<td>-7.3%</td>
<td>-6.9%</td>
<td>-5.9%</td>
<td>-6.0%</td>
<td>-1.5%</td>
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<tr>
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<td>1,529</td>
<td>1,536</td>
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<td>Potential Evapotranspiration (%)</td>
<td>4.8%</td>
<td>5.2%</td>
<td>4.9%</td>
<td>5.0%</td>
<td>5.0%</td>
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<tr>
<td>Availability (mm)</td>
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<td>176</td>
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<td>329</td>
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<td>-18.0%</td>
<td>-10.7%</td>
<td>-5.0%</td>
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<td><strong>RCP8.5 @ +2°C</strong></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Temperature change (°C)</td>
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<td>1.80</td>
<td>1.82</td>
<td>1.79</td>
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<td>849</td>
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<td>1,109</td>
</tr>
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<td>Precipitation change (%)</td>
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<td>-8.9%</td>
<td>-6.0%</td>
<td>-1.3%</td>
<td>5.2%</td>
</tr>
<tr>
<td>Potential Evapotranspiration (mm)</td>
<td>1,520</td>
<td>1,531</td>
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<td>1,551</td>
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</tr>
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<td>Potential Evapotranspiration (%)</td>
<td>5.2%</td>
<td>5.1%</td>
<td>5.2%</td>
<td>5.2%</td>
<td>5.1%</td>
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<td>Availability (mm)</td>
<td>104</td>
<td>142</td>
<td>192</td>
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<td>377</td>
</tr>
<tr>
<td>Availability change (%)</td>
<td>-24.6%</td>
<td>-17.1%</td>
<td>-12.1%</td>
<td>-1.4%</td>
<td>14.3%</td>
</tr>
<tr>
<td><strong>RCP8.5 @ +3°C</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature change (°C)</td>
<td>2.74</td>
<td>2.81</td>
<td>2.86</td>
<td>2.91</td>
<td>2.99</td>
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<tr>
<td>Precipitation (mm)</td>
<td>629</td>
<td>700</td>
<td>787</td>
<td>897</td>
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<td>Precipitation change (%)</td>
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<td>-15.7%</td>
<td>-12.9%</td>
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<td>-3.0%</td>
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<td>Potential Evapotranspiration (mm)</td>
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<td>1,571</td>
<td>1,584</td>
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<td>Potential Evapotranspiration (%)</td>
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<td>7.9%</td>
<td>8.1%</td>
<td>8.2%</td>
<td>8.4%</td>
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<tr>
<td>Availability change (%)</td>
<td>-37.3%</td>
<td>-31.4%</td>
<td>-26.8%</td>
<td>-16.9%</td>
<td>-2.6%</td>
</tr>
</tbody>
</table>

Existing and projected water demand

Domestic water consumption

Current average annual domestic water consumption is estimated based on the historical average consumption of 288 L/day/capita and the latest population census data (623,065 in 2011), resulting to a total of 65.49 Mm³ for the Water District of Crete. Future projections for the RCP-SSP combinations are based on national level projections according to the examined SSP and the corresponding +2°C or +3°C warming level period. The effect of increased temperature on water consumption is also introduced as a factor of 7% increase (or 15 L/day/capita) per degree of warming (Chang et al., 2014). Domestic consumption is projected to increase up to 77.5 Mm³ (+18%) for the +2°C period (2037-2066) according to the RCP4.5 - SSP1 combination. Similarly, a 14% increase is foreseen for the RCP4.5 – SSP2 combination and for the same period while a decrease of -1% is projected following the RCP4.5 – SSP3 scenario mainly due to the projected population decrease for Greece expected under SSP3. A slight increase of 7% in domestic water use could be expected for the
approaching 2026 – 2055 +2°C period of the RCP8.5 – SSP3 pathways, mainly due to the increase of temperature. At the highest warming level of +3°C, despite the intense temperature increase, a decrease of -3% is projected, mainly driven by the population decrease of 18% depicted in SSP3.

Tourism

The highly developed tourism sector in Crete has relatively large water requirements especially during the summer season. For the estimation of the average water demand associated to tourism activities, a consumption rate of 400 L per overnight stay is assumed (Papagrigoriou et al., 2001). For the warmer projection periods, the effect of increased temperature on water consumption, similarly to domestic use, is also taken into consideration. The table contains information on multi-model projections of overnight stays (median, interquartile and 5-95 percentile estimates) for every analyzed period and corresponding RCP-SSP combination, as derived by (Grillakis et al., 2015b). The projection of overnight stays is derived as a combination of the information of projected climate comfort related to tourism activities through the Tourism Climatic Index (TCI) approach (Grillakis et al., 2015a; Mieczkowski, 1985), also described in D6.1 and D9.1 of the project, and projections of global population that drives the tourism demand. The combined effect of increased consumption of 12% due to +2 °C (downscaled to a local +1.7 °C), of 42% due to climate comfort improvement under RCP4.5 for the 2037-2066 period and due to global population under SSP1 results to an overall increase of 59% (from 6.6 to 10.5 Mm³) in water demand for tourism activities. Similar increasing trends are projected for all RCP-SSP storylines, driven by global population increase (from +39% to +74%), increase due to improved climate comfort (from +7.1% to 7.9%) and increase from higher temperature consumption (from +12% to +20%) resulting to higher consumption ranging from +59% (3.9 Mm³) to +116% (7.6 Mm³).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SSP</th>
<th>5th%ile</th>
<th>25th%ile</th>
<th>Median</th>
<th>75th%ile</th>
<th>95th%ile</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1990 - 2011)</td>
<td></td>
<td>11,795,753</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>RCP4.5 @ +2°C</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2037-2066)</td>
<td>SSP1 (stays)</td>
<td>16,805,304</td>
<td>17,126,024</td>
<td>17,956,772</td>
<td>18,531,864</td>
<td>18,564,421</td>
</tr>
<tr>
<td>(%) SSP1</td>
<td>+40%</td>
<td>+41%</td>
<td>+42%</td>
<td>+43%</td>
<td>+43%</td>
<td></td>
</tr>
<tr>
<td>SSP2 (stays)</td>
<td>18,079,139</td>
<td>18,437,829</td>
<td>19,368,333</td>
<td>20,013,632</td>
<td>20,050,190</td>
<td></td>
</tr>
<tr>
<td>(%) SSP2</td>
<td>+51%</td>
<td>+52%</td>
<td>+54%</td>
<td>+55%</td>
<td>+55%</td>
<td></td>
</tr>
<tr>
<td>SSP3 (stays)</td>
<td>19,651,002</td>
<td>20,056,544</td>
<td>21,110,144</td>
<td>21,842,075</td>
<td>21,883,572</td>
<td></td>
</tr>
<tr>
<td>(%) SSP3</td>
<td>+65%</td>
<td>+66%</td>
<td>+68%</td>
<td>+70%</td>
<td>+70%</td>
<td></td>
</tr>
<tr>
<td><strong>RCP8.5 @ +2°C</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2026 - 2055)</td>
<td>SSP3 (stays)</td>
<td>14,977,956</td>
<td>17,308,610</td>
<td>19,680,339</td>
<td>20,410,411</td>
<td>20,647,529</td>
</tr>
<tr>
<td>(%) SSP3</td>
<td>+45%</td>
<td>+50%</td>
<td>+55%</td>
<td>+57%</td>
<td>+57%</td>
<td></td>
</tr>
<tr>
<td><strong>RCP8.5 @ +3°C</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2047 - 2076)</td>
<td>SSP3 (stays)</td>
<td>15,230,057</td>
<td>18,680,506</td>
<td>22,726,221</td>
<td>24,238,586</td>
<td>24,427,615</td>
</tr>
<tr>
<td>(%) SSP3</td>
<td>+60%</td>
<td>+69%</td>
<td>+79%</td>
<td>+83%</td>
<td>+84%</td>
<td></td>
</tr>
</tbody>
</table>

Historical (1990-2011) and projected overnight stays for different RCP-SSP combination and warming levels after Grillakis et al (2015) for the Crete region.

Industry

The secondary sector of Crete is less developed compared to the others. The majority of industries – manufacturing (more than 60%) are concentrated in the regional unit of Heraklion, at the central part of the island. Industrial – manufacturing activities include production of plastics, marble processing and concrete production, clothing and textile, milk products, citrus and vegetable packaging, canneries, metal constructions, etc. Total industrial water consumption is estimated to 4.1 Mm³.
Projections of industrial water needs are adjusted according to industrial water withdrawal scenarios presented by Hanasaki et al. (2013a). According to SSP1, industrial water consumption is expected to remain at current levels (4.1 Mm$^3$) for the period 2037 – 2066 at +2 °C of global warming, mainly due to advances in water saving technologies. For the same period and following SSP2 of medium water saving efficiency, the increase is estimated at +21% (+0.9 Mm$^3$), while for low efficiency and high growth (SSP3), the increase ranges from +14% to +67%.

**Olive mills**

Olive tree cultivation is the primary agricultural activity in the region, occupying 70% of the total agricultural land. Olive oil is produced by 620 olive mill facilities spread over the island, operating annually from November to February. The average water requirement is estimated at 1,500 m$^3$/year for each olive mill (Papagrigoriou et al., 2001) resulting to a total 0.93 Mm$^3$ annually. Future projections of water consumption of olive mills are estimated proportionally to irrigation needs detailed at a later point in this text.

**Energy**

Energy needs of the island are covered by three thermal power stations of total power 950 MW. Average annual water needs for steam production are estimated at 0.2 Mm$^3$. Projections of future water needs for energy are derived proportionally from the total projected water needs of other sector needs (domestic, tourism, industry, olive mills) based on the rationale that they constitute the key energy intensive sectors. The slight increase in SSP1 is associated to the potential introduction of additional renewable energy sources or the connection to the national grid.

**Livestock**

Current water need for livestock is estimated at 8.7 Mm$^3$ annually, based on animal watering need (Papagrigoriou et al., 2001) and the number of animals as listed in the national census. The projections of the corresponding RCP-SSP combinations are based on global population trends for each SSP as a demand driver along with a climatic index of potential evapotranspiration change (increase) according to the livestock watering method. For specific species (mainly caprinae), a decreasing trend is assumed due to decreased production trends affected by low price competitive imports. Projected water demand ranges from 11.4 to 11.7 Mm$^3$ (increase from +31% to +34%), depending on scenario.

**Irrigation**

Total cultivated land in the Region of Crete is 255,359 ha, of which 107,909 ha (42%) are irrigated (Papagrigoriou et al., 2001). A fraction of 70% (178,401 ha) corresponds to olive groves and only 68,949 ha (39%) are irrigated, producing on average 150,000 tons of olive oil annually. Vineyards cover an area of 27,665 ha (11%), arable land 27,236 ha (11%), orchards 7,748 ha (3%), horticulture 10,032 ha (4%), greenhouses 2,286 ha (1%), and the rest of the area is covered by other cultivations.

Crop water requirements per cultivation type have been defined by the local authority in consultation with the research team of Papagrigoriou et al., (2001) that estimated the irrigation demand based on theoretical methods of optimum crop yield. It should be noted that the adopted crop water needs which have arisen from the local-scale research and expert judgment of the local Authority, are typically greater than the total annual consumption reported by the Local Organizations of Land Reclamation (LORL) that are the major irrigation organizations (in many cases fields are not irrigated to full extent, or irrigation restrictions are applied for some resilient
cultivations like olive trees during dry seasons). Moreover, actual water needs are further estimated at local (municipal level) taking into account the losses of individual irrigation networks. Thus, a loss factor of 15% is assumed for organized irrigation networks of irrigation organizations and 25% for municipal networks.

Total irrigation needs including systems losses are estimated to 439.62 Mm$^3$. Realistic future scenarios of irrigation demand are based on local development plans and proposed strategies for expansion of irrigation networks, along with the corresponding information of each SSP for irrigated area and crop intensity presented by several studies (N. Hanasaki et al., 2013; O’Neill et al., 2013). For the sustainability scenario (SSP1) of low growth in irrigated area and crop intensity combined with high water use efficiency, the demand could be shaped to 543.76 Mm$^3$ annually for the period 2037-2066. This increase by 24% is attributed to the extension of irrigation networks along with the application of water saving technologies. For the medium crop intensity growth scenario (SSP2) and medium water use efficiency (which is considered as the business as usual scenario), irrigation water demand is expected to increase by 30% to a total 571.94 Mm$^3$ per year on average for the 2037-2066 period. According to the SSP3 of low water efficiency and high growth in crop intensity, crop water demand is assumed to follow global population trends based as a food demand driven approach (Ignaciuk and Mason-D’Croz, 2014). Total demand is based on the demand of SSP2 plus the proportional increase of the global population of SSP3. The resulting annual crop water demand is shaped to 623.47 Mm$^3$ during 2037 – 2066 and RCP4.5, 576.08 Mm$^3$ during 2026 – 2055 and RCP8.5 and 661.42 Mm$^3$ for the 2047 – 2076 period.

**Total water demand**

Current total water demand is estimated at 525.62 Mm$^3$ with the largest share (84%) corresponding to irrigation. A robust signal of increase is projected for all future scenarios mainly attributed to the increase of irrigation demand. The total demand of the +2°C warmer 2037 – 2066 period according to SSP1 – RCP4.5 combination is shaped to 648.69 Mm$^3$, increased by 29% compared to present situation.

*Current (2010) and projected (RCP-SSP combinations) annual water demand in Mm$^3$.*

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>RCP4.5 @+2C</th>
<th>RCP4.5 @+2C</th>
<th>RCP4.5 @+2C</th>
<th>RCP4.5 @+2C</th>
<th>RCP8.5 @+3C</th>
<th>RCP8.5 @+3C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic</td>
<td>65.49</td>
<td>77.53</td>
<td>74.82</td>
<td>64.61</td>
<td>69.89</td>
<td>63.44</td>
<td></td>
</tr>
<tr>
<td>Tourism</td>
<td>6.58</td>
<td>10.45</td>
<td>11.30</td>
<td>12.37</td>
<td>11.48</td>
<td>14.18</td>
<td></td>
</tr>
<tr>
<td>Industry</td>
<td>4.10</td>
<td>4.11</td>
<td>4.97</td>
<td>5.70</td>
<td>4.68</td>
<td>6.85</td>
<td></td>
</tr>
<tr>
<td>Olive mills</td>
<td>0.93</td>
<td>1.15</td>
<td>1.21</td>
<td>1.32</td>
<td>1.22</td>
<td>1.40</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>0.20</td>
<td>0.24</td>
<td>0.20</td>
<td>0.18</td>
<td>0.21</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>livestock</td>
<td>8.70</td>
<td>11.45</td>
<td>11.47</td>
<td>11.51</td>
<td>11.70</td>
<td>11.38</td>
<td></td>
</tr>
<tr>
<td>Irrigation</td>
<td>439.62</td>
<td>543.76</td>
<td>571.94</td>
<td>623.47</td>
<td>576.08</td>
<td>661.42</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>525.62</td>
<td>648.69</td>
<td>675.91</td>
<td>719.16</td>
<td>675.25</td>
<td>758.87</td>
<td></td>
</tr>
</tbody>
</table>
The estimated irrigation demand of the *business as usual* scenario RCP4.5-SSP2 is estimated at 675.91 Mm$^3$ that is close to the 670.80 Mm$^3$ estimated by Papagrigoriou et al., (2001). For the same level of warming (and period) of RCP4.5 and SSP3, an increase of 37% is estimated. Respectively, for the higher end scenario of RCP8.5 the same level of warming is reached approximately 10 years sooner (2026 – 2055) and combined with SSP3 results to a total demand of 675.25 Mm$^3$ (increase by 28%). For the higher levels of warming (+3 °C) of RCP8.5 that are reached during the period 2047 – 2076 and for the fragmentation – high growth and low efficiency scenario, total demand is shaped at 758.87 Mm$^3$. This increase (44%) is attributed to high population change which in turn generates higher food demand and thus increased irrigation needs (87% of the total needs). The tourism sector is also affected by population increase and tourism water demand likewise.

### Water supply and exploitation potential

The Integrated Water Resources Management study of Crete (Papagrigoriou et al., 2001) includes all existing water infrastructure (dams, reservoirs, abstractions) until 2001. The infrastructure that developed since 2001 in order to support the water supply of the Water District of Crete is described in the recent draft of water resources management (Special Secretariat for Water, 2014). Total water supply in Crete is estimated at 421.40 Mm$^3$/yr and distributed 335.40 Mm$^3$/yr for irrigation (80%), 8.70 Mm$^3$/yr for livestock and 77.3 Mm$^3$/yr for water supply, tourism, energy and industry (18%). It is important to emphasize the heavy reliance to the system to groundwater, as water resources originating from surface bodies account only 8% of the total availability.

Future plans focus on the exploitation of surface water due to the overexploitation of groundwater resources (Daliakopoulos et al., 2005; Varouchakis et al., 2015) in several aquifers of the island and the consequent salt intrusion (Dokou and Karatzas, 2012; Kourgialas and Karatzas, 2015). The table below includes the number of future water resources infrastructure per RCP – SSP combination, the total capacity and the construction cost, projected to the corresponding period according to the projections of the national GDP. This classification was established after consultation with the Directorate of Water of the Decentralized Administration of Crete that serves as an end user for the project. The impact of climate change on water supply for open structures (dams, reservoirs) is associated to the changes in potential evaporation and for groundwater abstractions the output of hydrological modeling regarding changes in subsurface availability are considered. Capacity and surface extend from 5 dams and 8 open reservoirs over Crete were examined to estimate the average water storage area per Mm$^3$ of stored water for the island of Crete.
Impact of climate change on water availability for each type of infrastructure per RCP-SSP combination.

<table>
<thead>
<tr>
<th>Infra-structure type</th>
<th>RCP4.5 +2°C SSP1 (2037-2066)</th>
<th>RCP4.5 +2°C SSP2 (2037-2066)</th>
<th>RCP4.5 +2°C SSP3 (2037-2066)</th>
<th>RCP8.5 +2°C SSP3 (2026 - 2055)</th>
<th>RCP8.5 +3°C SSP3 (2047 - 2076)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dam</td>
<td>-0.57%</td>
<td>-0.57%</td>
<td>-0.57%</td>
<td>-0.60%</td>
<td>-0.94%</td>
</tr>
<tr>
<td>Reservoir</td>
<td>-1.12%</td>
<td>-1.12%</td>
<td>-1.12%</td>
<td>-1.18%</td>
<td>-1.84%</td>
</tr>
<tr>
<td>GW</td>
<td>-18.0%</td>
<td>-18.0%</td>
<td>-18.0%</td>
<td>-12.1%</td>
<td>-26.8%</td>
</tr>
</tbody>
</table>

For the 2037 – 2066 period and the RCP4.5 – SSP1 high efficiency scenario, a total of 39 infrastructure projects are considered feasible, 24 of them further exploiting or optimizing groundwater and 15 harvesting surface runoff. The total capacity of surface projects (64.36 Mm³) is almost four times the groundwater abstractions (16.52 Mm³) and the implementation cost is more than 8 times compared to groundwater exploitation. The increased costs compared to SSP2 scenario, despite the lower capacity, reflects the cost of investing on water saving technologies. The business as usual RCP4.5-SSP2 scenario foresees additional infrastructure (4 groundwater and 8 surface) providing a total of 117.69 Mm³, thus increasing current availability by 28% with a total approximate construction cost of 1.289 billion €. According to the low water efficiency and high growth SSP3 scenario an approximate of 160 Mm³ (ranging from 158.8 Mm³ to 162.5 Mm³ depending on the warming level – reference period of each RCP) could be added to the available water resources. The cost of this “upgrade” is estimated at around 1.3 billion € which is mainly attributed to the construction of surface water resources infrastructure such as dams and reservoirs.

Number of future water resources infrastructure by exploitation type (GW=groundwater or Surf=surface), RCP – SSP combination, total capacity and construction cost.

<table>
<thead>
<tr>
<th>Number</th>
<th>Capacity (Mm³)</th>
<th>Cost (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW</td>
<td>Surf</td>
<td>Tot</td>
</tr>
<tr>
<td>RCP4.5 @ +2°C SSP1</td>
<td>24</td>
<td>15</td>
</tr>
<tr>
<td>RCP4.5 @ +2°C SSP2</td>
<td>28</td>
<td>23</td>
</tr>
<tr>
<td>RCP4.5 @ +2°C SSP3</td>
<td>29</td>
<td>39</td>
</tr>
<tr>
<td>RCP8.5 @ +2°C SSP3</td>
<td>29</td>
<td>39</td>
</tr>
<tr>
<td>RCP8.5 @ +3°C SSP3</td>
<td>29</td>
<td>39</td>
</tr>
</tbody>
</table>

Water resources availability and cost

The impact of climate change on the supply potential of the current infrastructure is projected to decrease by 17% (from 421 Mm³ to 351Mm³ ) and by 11% at +2°C according to RCP4.5 and RCP8.5, respectively. This is attributed mainly to the decline of water groundwater availability that is the major source of the supply system. This decline is foreseen to be more pronounced (-25%) at +3°C of global warming. The implementation of future infrastructure projects will increase the supply.
potential. Ignoring the effect of climate change the additional availability is shaped to 506Mm$^3$ (+20%) according to SSP1, 544Mm$^3$ (+29%) under SSP2 and 588Mm$^3$ (+40%) for SSP3. The corresponding cost of the water engineering projects for the respective RCP-SSP period is included in the tables above. Including the information of climate change impact on current water supply and future exploitation potential, as described in the previous section, the projected supply potential could range from 432Mm$^3$ (+3%) to 537Mm$^3$ (27%) depending on the RCP-SSP combination. It is important to note, for example according to the RCP4.5 at +2°C combined to SSP1, despite the implementation of infrastructure of 80.9Mm$^3$ additional water resources the resulting availability is shaped to 432Mm$^3$ (+3%) compared to current supply. This is due to the impact of climate change on the availability of groundwater resources and thus to the current supply system (that depends mostly). The proposed infrastructure plans is based mainly (80%) on the exploitation of surface water through dams and reservoirs and can substantially alter the timing of water resource availability, compensating the inefficiency of the existing situation.

Water resources demand, supply under existing infrastructure including the effect of climate change, supply potential according to infrastructure implementation for each SSP without the effect of climate change (no CC) and with CC.

The impact of climate change on the hydrology of the region and thus to the supply potential ranges from -51.3Mm$^3$ to -75.4Mm$^3$ under 2°C of global warming, depending on the RCP-SSP formulation. The impact is more pronounced for RCP4.5 (compared to RCP8.5) probably due to the ten years later crossing of the +2°C and the further loss in terms of discharge from groundwater aquifers. The expected deficit under the RCP-SSP formulation ranges from 20% to 37, mainly due to increasing irrigation demand. The least cost effective scenario in terms of investment cost for additional availability per Mm$^3$ is the business as usual RCP4.5-SSP2 scenario (10.95 M€/Mm$^3$). The RCP4.5-SSP1 high sustainability combination, despite the high investment cost due to the increase in GDP, is simulated as the most cost effective option but with a high deficit rate (33%). The second most cost effective option, for the warming level of +2°C is the RCP8.5-SSP3 with the lower projected deficit which, however, assumes rapid adaptation in terms of investments in water resources infrastructure of high cost. Nevertheless, this high end scenario leads to higher deficit rates (37%) at global warming levels around +3°C.
Total water supply per RCP-SSP combination, the effect of climate change on the supply potential, the total demand, the absolute deficit and as percent of demand, the additional availability, the total construction cost and the cost of the additional Mm$^3$ of availability.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Supply Mm$^3$</th>
<th>Supply under CC Mm$^3$</th>
<th>CC effect Mm$^3$</th>
<th>Demand Mm$^3$</th>
<th>Deficit Mm$^3$ (% of demand)</th>
<th>Additional availability Mm$^3$</th>
<th>Construction Cost (M€)</th>
<th>Cost of additional availability per M€/Mm$^3$ (in case of no constructions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCP4.5 @ +2°C</td>
<td>506.2</td>
<td>432.2</td>
<td>-74.1</td>
<td>648.7</td>
<td>-216.5 (-33%)</td>
<td>80.9</td>
<td>612.67</td>
<td>7.57</td>
</tr>
<tr>
<td>SSP1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCP4.5 @ +2°C</td>
<td>544.0</td>
<td>469.0</td>
<td>-75.0</td>
<td>675.9</td>
<td>-206.9 (-31%)</td>
<td>117.7</td>
<td>1289.12</td>
<td>10.95</td>
</tr>
<tr>
<td>SSP2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCP4.5 @ +2°C</td>
<td>588.2</td>
<td>512.7</td>
<td>-75.4</td>
<td>719.2</td>
<td>-206.4 (-29%)</td>
<td>161.5</td>
<td>1357.21</td>
<td>8.41</td>
</tr>
<tr>
<td>SSP3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCP8.5 @ +2°C</td>
<td>588.2</td>
<td>536.9</td>
<td>-51.3</td>
<td>675.3</td>
<td>-138.4 (-20%)</td>
<td>162.5</td>
<td>1285.92</td>
<td>7.91</td>
</tr>
<tr>
<td>(2026 - 2055)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSP3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCP8.5 @ +3°C</td>
<td>588.2</td>
<td>475.5</td>
<td>-112.7</td>
<td>758.9</td>
<td>-283.4 (-37%)</td>
<td>158.5</td>
<td>1381.78</td>
<td>8.72</td>
</tr>
<tr>
<td>(2047 - 2076)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSP3</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

3.3.5 Conclusions

While mitigation and adaptation policies to restore sustainability are usually centrally planned, their success invariably depends on the implementation efficiency at local level where awareness and perception often pose barriers (Betzold, 2015; La Jeunesse et al., 2015). Especially for adaptation, mobilization incentives are highly local and thus mediating the impact of climate change induced threats is challenging (Agrawal, 2010). In this context, communicating relevant and targeted climate change information to stakeholders and decision makers is crucial for converting and gaining commitment. This case study makes a first attempt to translate global scale SSPs to the context of local development scenarios, to provide information directly to local administration and end users. The close collaboration with the local water authority has been a major part of this process, but it is also a major requirement that results on water availability and expected future costs are disseminated to end users.

Similar to all Mediterranean islands, Crete is largely dependent on groundwater resources (MED-EUWI WG on groundwater, 2007). This dependence (50% on average), and the simultaneous scarcity of alternative freshwater sources, may pose grave risks on the water intensive agricultural sector. Despite technological progress and specialization (Daliakopoulos and Tsanis, 2014), and a significant natural comparative advantage, the agricultural sector of Crete faces similar challenges to the agriculture of the southern regions of Greece. The major problem, common to all the prefectures of Crete, is the scarcity of irrigation resources, a factor impairing the restructuring and intensification of cultivation, and often the risk of saltwater intrusion in coastal aquifers.

This work confirms and updates previous findings of a robust signal for water scarcity (Koutroulis et al., 2015, 2013; Tsanis et al., 2011) that is projected to aggravate the current deficit of water resources in the island and increase tensions among sectors and users.
Given the fact that water stress in the island arises due to the spatial and temporal variability of precipitation, infrastructure such as dams and reservoirs can substantially alter the timing of water resource availability, and seem to present a viable solution for the island. On the other hand, the intensification of agricultural production for globalized markets has led to some extent to the loss of self-sufficiency (Daliakopoulos & Tsanis, 2014). For this reason, feasibility studies need to be undertaken to determine the degree to which the costs and risks of proposed infrastructure and agricultural restructure can be sustained by the resulting additional production. For example, the conversion of all olive trees to irrigated (estimated additional demand of over 250 Mm3 per year) may eventually reach the limits of resilience to drought and require capital investment (estimated over 1 billion € ) that is disproportionate to the long term social and financial profits.

It is also possible that high infrastructure costs can be avoided with the use of alternative water resources (such as reuse) for irrigation, and advocating water resource conservation. Such approaches may include deficit or precision irrigation, taking into account the sensitivity of each crop to water stress (e.g. diverting excess irrigation from resilient crops such as olive trees), switching production to more drought tolerant crops or optimizing it to lower risk endogenous cultivations. Nevertheless, these practices require a high level of sophistication and significant dedication and restraint from the end users, as well as tackling irresponsible actions such as illegitimate water use. In this context, the projected water scarcity highlights the important role for development and deployment of water conservation technologies and practices (Hejazi et al., 2014) and the need for strategic resource planning from global to regional and local scale. Eventually, awareness of the practical implications of each SSP in the not so distant future may be the key to shift user perception and preferences towards a more sustainable direction.

References


4 Cross cutting analysis

4.1 Outline

This sub-task considered an alternative framing of impacts, focusing on cross-cutting themes. This considers receptors or themes that have linkages across many sectors, i.e. for multi-functionality in areas such as with water. It also considers where end-user information and adaptation responses could be best tackled through a cross-cutting theme rather than a sector, such as with cities or urban areas. Following a quick review, a number of case studies were undertaken to provide information on these themes. One aim of the case studies was to match emerging policy interest, thus some flexibility was included in the programme.

4.2 Rapid Review

As highlighted earlier in this document, the use of sector based impact assessments often does not adequately capture the linkages between that come together on specific receptors, and they may not resonate with all stakeholders.

This is important for two specific reasons (Defra, 2009). First, the way that climate change risks are identified and grouped will determine their relevance to agents in the public or private sectors which may use the information to determine their adaptation response. Second, a reliance on traditional sectoral analysis does not foster the analysis of cross-sectoral linkages. For these reasons, an alternative grouping to the traditional sectoral approach is interesting and was considered in IMPACT2C. A number of alternatives are possible.

- Around climate effects (SLR, mean temperature, extremes).
- By end-users or typical input-output conventions, households, industrial sectors, etc.
- By cross-sectoral themes, e.g. land-use, etc.
- By geographical location

As highlighted earlier, most European and national studies effectively use a sectoral grouping. Moreover, nearly all the impacts and valuation literature is based around this sectoral approach, and thus quantification is primarily therefore undertaken on a sectoral basis. There are strong practical reasons for this. First, from a government policy perspective it is likely to be most efficient to use a sectoral division that closely reflects the existing central government departmental structure, in order to mainstream impact information and then adaptation consistently with current responsibilities and organisation. Second, research expertise tends to be specialised along sectoral lines; given the time constraints, it is more difficult to re-orientate parts of the research community to reflect other demarcation principles.

This case study approach recognises that there is a need maximise cross-sectoral links. To try and progress the cross-sectoral themes, it is possible to undertake integrated assessment. Progress has been made in this regard (e.g. with CLIMSAVE study, Holman et al, 2013) for impacts as well as for wider economic modelling for macro-economic linkages (e.g. Ciscar et al, 2011).

For IMPACT2C, it was not possible to include a more ambitious restructuring of the IMPACT2C project, because of the strong alignment to sectors in the WPS. Therefore, the cross-cutting task was taken forward using case studies.
The case studies chosen were as follows.

- First, to centre on the end-user and on households as the unit of analysis. This was taken forward with a case study in the UK.

- Second, to think about cross-sectoral themes, with the issue of urban and rural areas. The IMPACT2C study did not have a strong urban planning component, but there was the potential to widen the coastal analysis to look at port cities.

- Third to look at cross-sectoral analysis, with a study on water-food-energy nexus and competition for land and water under future climate change – towards sustainable land allocation strategies

The case studies are summarised in the following sections.

**References**


4.3 UK Case study: Impacts of Climate Change on Households

The first case study considered impacts from the perspective of an end-user/end-receptor, by focusing on households. This was undertaken as a policy case study, working with the UK Committee on Climate Change, as an input to the cross-cutting chapter of the UK’s Second Climate Change Risk Assessment and the Joseph Rowntree Foundation. The case study investigated two major issues. First, it estimated the potential impacts of climate change on the cost of living, as well as the effects on wider welfare, for UK households. Second, it analysed the differences in these impacts for different income groups, comparing the impacts average and the poorest households. A comparison was also made to Italy, using Italian household expenditure data, to explore whether households in different parts of Europe would be affected by climate change.

4.3.1 Introduction

As highlighted above, most studies undertake analysis by sector. For this cross-cutting exercise, the analysis therefore focused on end-user, using, households as the main receptor. This involved gathering information from various sector sources, and investigating what they might mean for the average household overall. This analysis therefore has a different focus compared to most previous studies to date, including the UK Climate Change Risk Assessment (CCRA) (Defra, 2011), which took an aggregated national-scale approach. In addition, there is a large literature—as reported in the IPCC 5th Assessment Report (2014) — that highlights that people who are socially, economically, culturally, politically, institutionally, or otherwise marginalized are especially vulnerable to climate change. This literature primarily concerns the high impacts of climate change that are likely to be arise in developing countries, and the higher relative impact on the poorest within these countries, but it is also likely that there could be strongly distributional differences, especially linked to income and deprivation within European countries. The second aim of the case study was therefore to investigate these distributional patterns. The aim of the case study was therefore to explore how climate change could affect the future costs of living at the household level and the implications for low income households, using the UK as a case study country, but with a comparison with Italy. The specific aims are to understand:

4.3.2 Method

The analysis considered how climate change might affect the cost of living and household budgets, thus it investigates the impacts on the main household expenditure items, considering the distributional patterns across household income deciles. Climate change acts on these items in a variety of direct and indirect mechanisms, including the effects on supply and demand on market-traded goods and services, and in turn on prices (with associated feedbacks). However, climate change will also affect households in other ways that go beyond the cost of living, i.e. the quality of life and well-being (or in economic terms, welfare). Therefore to fully capture the effects of climate change on households, a number of aspects are considered in the study. The study therefore considered a broad range of costs from climate change on households, including:

- Direct expenditures, such as on household energy;
- Indirect cost pathways, as arise from the effects of flooding;
- Indirect cost international, such as from impacts on global agriculture and UK food prices;
- Non-market costs, which affect the quality of life and well-being (welfare).

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3 This case study was co-funded by the Joseph Rowntree Foundation, under the project ‘Climate Change Impacts on the Future Cost of Living’. 
These are shown in Figure 1.

The Household Cost Categories Considered in the Study.

First, the analysis considered the potential direct impacts of climate change on household expenditures, such as from higher temperatures affecting household demand for heating or cooling. Second, the analysis considers the impacts on household costs that arise from more complex pathways. For example, changes in flood risks will affect the number of insurance claims, and the insurance market, which will in turn lead to an increase in (average) premiums and thus household insurance costs, affecting household budgets (or the affordability of insurance). These indirect effects also include more complex transmission mechanisms, where climate change affects production / supply (or demand) and thus changes the market, leading to changes in prices. These effects can occur at the UK scale, but they may also occur at the global scale and feed-back to the UK. As an example, as climate change will affect global agricultural production (yields) and this will alter market conditions, and (via supply chains) lead to changes in food prices in the UK.

In all these cases, climate change may affect potential household costs, which in turn may lead to a change in the demand from these households for these goods and services. It is therefore important to understand how the quantity or demand for a good or services changes with its price (the price elasticity of demand). However, understanding the market response to climate impacts, the price
transmission effects and the demand responses requires more complex economic modelling, which is rarely undertaken in climate impact studies.

Finally, many of the impacts of climate change lead to impacts that are not captured by markets, and thus do not feed through to prices, though these are still important for households in terms of well-being. For example, this includes changes in health resulting from climate change (e.g. increased incidence of health impacts). These impacts can be expressed in monetary terms that capture the economic, social and environmental costs borne by society as a whole (i.e. on societal welfare), in order to make sure they are considered equally alongside financial costs.

Importantly, for these various effects, the study investigates the patterns of impacts and costs of climate change across different households, notably whether they disproportionately affect low income households. To advance this, a number of different evidence lines have been used.

- Review and synthesis of the impact assessment literature. There are existing studies that have assessed the potential impacts and economic costs of climate change in the UK, and these have been used a source of information, which complement the findings of IMPACT2C. This analysis has primarily drawn on a review and update of the economic costs of climate change published in the UK’s 1st Climate Change Risk Assessment (CCRA), which included a mixture of direct, indirect, policy costs and welfare costs, alongside the IMPACT2C findings. The analysis has investigated the economic costs to assess their impact on a) household budgets, estimating the costs per average household from climate change and b) economic welfare, and the impact per average household.

- Review of international effects. UK studies (the CCRA1) focused on the domestic impacts of climate change in the UK. However, this largely omitted the potential effects that could happen internationally from climate change, and their subsequent impact on the UK. This part of the work has therefore undertaken a review and analysis of the international literature on the possible economic costs of climate change and the impact on prices of international goods, notably food, and how these might affect households in the UK. This includes European analysis from IMPACT2C.

- Econometric analysis. This part of the work undertook a new econometric analysis of the observed links between climate and major household expenditure items in the UK. The aim was to identify climate elasticities between climate and key household budget items, i.e. for food, energy, water and other expenditure items in low and average income households.

The information from these various evidence lines was brought together and is presented by risk category, considering effects on household budgets and effects on household prospects.

### 4.3.3 Household Expenditure

In undertaking the analysis, a key issue has been to investigate how climate change affects the average household, but also whether it disproportionately affects low income households. These distributional effects may arise in different ways. Some of the impacts of climate change may fall primarily on certain locations or particular groups in society, e.g. due to their higher exposure. For many households, income is their most important economic resource for meeting everyday living expenses. However, it is the consumption of goods and services (best reflected by expenditure) that is pivotal in meeting a household’s requirements: evidence suggests that income and expenditure together represent a better determinant of economic well-being than income alone (ONS, 2014). However, even when impacts are evenly distributed, the impact of higher costs (or prices) may affect
low income households to a greater extent, because they spend a greater proportion of their income on certain expenditure items such as food or household energy (see table 1, from the 2014 UK Living Costs and Food Survey).

**Table 1. Household expenditure as a % of total expenditure by equivalised disposable income decile group, 2013**

<table>
<thead>
<tr>
<th>Commodity or service</th>
<th>Lowest 10%</th>
<th>Fifth</th>
<th>Highest</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food and non-alcoholic drinks</td>
<td>16.4</td>
<td>12.9</td>
<td>8.0</td>
<td>11.4</td>
</tr>
<tr>
<td>Alcoholic drink, tobacco &amp; narcotics</td>
<td>3.4</td>
<td>2.4</td>
<td>1.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Clothing &amp; footwear</td>
<td>3.8</td>
<td>4.6</td>
<td>4.0</td>
<td>4.4</td>
</tr>
<tr>
<td>Housing (net), fuel &amp; power, of which</td>
<td>25.0</td>
<td>16.0</td>
<td>10.7</td>
<td>14.4</td>
</tr>
<tr>
<td>Less housing benefit, rebates &amp; allowances rec'd</td>
<td>26.5</td>
<td>1.5</td>
<td>[0.0]</td>
<td>3.1</td>
</tr>
<tr>
<td>Gross rent</td>
<td>38.3</td>
<td>8.8</td>
<td>4.0</td>
<td>9.3</td>
</tr>
<tr>
<td>Net rent</td>
<td>11.8</td>
<td>7.2</td>
<td>4.0</td>
<td>6.2</td>
</tr>
<tr>
<td>Second dwelling rent</td>
<td>[0.0]</td>
<td>[0.0]</td>
<td>[0.0]</td>
<td></td>
</tr>
<tr>
<td>Maintenance and repair of dwelling</td>
<td>0.7</td>
<td>1.2</td>
<td>1.9</td>
<td>1.4</td>
</tr>
<tr>
<td>Water supply and miscellaneous services</td>
<td>2.9</td>
<td>1.8</td>
<td>1.2</td>
<td>1.7</td>
</tr>
<tr>
<td>Electricity, gas and other fuels</td>
<td>9.6</td>
<td>5.7</td>
<td>3.6</td>
<td>5.1</td>
</tr>
<tr>
<td>Household goods &amp; services</td>
<td>6.2</td>
<td>6.1</td>
<td>7.4</td>
<td>6.4</td>
</tr>
<tr>
<td>Health</td>
<td>0.7</td>
<td>1.3</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Transport</td>
<td>9.8</td>
<td>13.9</td>
<td>15.3</td>
<td>13.6</td>
</tr>
<tr>
<td>Communication</td>
<td>3.5</td>
<td>3.2</td>
<td>2.0</td>
<td>2.8</td>
</tr>
<tr>
<td>Recreation and Culture</td>
<td>8.7</td>
<td>11.4</td>
<td>14.6</td>
<td>12.4</td>
</tr>
<tr>
<td>Education</td>
<td>2.2</td>
<td>1.3</td>
<td>2.2</td>
<td>1.7</td>
</tr>
<tr>
<td>Restaurant and hotels</td>
<td>5.9</td>
<td>7.3</td>
<td>8.7</td>
<td>7.8</td>
</tr>
<tr>
<td>Miscellaneous goods and services</td>
<td>6.5</td>
<td>7.6</td>
<td>7.8</td>
<td>7.6</td>
</tr>
<tr>
<td>Other expenditure items</td>
<td>7.9</td>
<td>12.1</td>
<td>16.4</td>
<td>14.1</td>
</tr>
</tbody>
</table>

Lines in red are major focus areas for the study for direct and indirect cost pathways. Note that equivalised income takes into account the fact that households with many members are likely to need a higher income to achieve the same standard of living as households with fewer members.

The table shows that all households spend a large proportion of their budget on a small number of major items. Of particular relevance to this study are those areas which are most likely to be affected by climate change (shown in red). This is dominated by food (11% of expenditure) and household energy costs (5% of expenditure) which will be impacted through direct effects. However, the Table also shows how the expenditure of different income groups varies for the same items. For example, for low income households (in the lowest decile), food is 16% of expenditure and household energy costs are almost 10%. Price changes to these items will therefore have a larger impact on low income household budgets (affordability) or will reduce their available budget for other goods or services (depending on the elasticities above and whether they vary with income level).

At the same time, there are a wider set of impacts that also affect households in other ways. These include impacts on well-being or quality of life (economic welfare). They can include, for example, additional health impacts. The study also considers the effects of climate change on these broader quality of life aspects, and again, also looks to see whether these have impact disproportionately on low income households.

Following from this, the results of the study are presented in terms of the potential risks to various household budget and well-being (economic welfare) categories in turn. In each case, the analysis of average effects is followed by an assessment of the distributional effects. For the latter, this includes consideration of how much low income deciles spend compared to the average (Table 1). In presenting the results, it is useful to benchmark impacts against current household costs. The following have been used.
• Negligible: <£1 a week/£50 per household per year

• Minor: £1-£3 a week/£50-£150 /hh/year – up to around 1% of minimum budget (net of
rent/mortgage) of a couple without children.

• Modest: £3-£15 a week/£150-750/hh/year – 1-5% of minimum budget of couple.

• Substantial: higher than £15 a week/£750/hh/year >5% of minimum budget of couple.

Note that even the major costs are small in comparison with normal fluctuations in costs due to
inflation and other factors. However, it is also worth bearing in mind that for certain groups, the
disposable equivalised income will involve higher spend on key household items (e.g. low income
families and their spending on for example food as a % of available income), or lower available
disposable income (e.g. pensioners living alone).

4.3.4 Results by Household/Welfare Item

Food (agriculture)

One of the largest household expenditure items is food, and production (agriculture) is a highly
climate sensitive sector. Climate change therefore has the potential to lead to major effects on the
costs of living for this item. The future effects of climate change on food prices are, however, rather
complicated to assess (See IMPACT2C WP7). First, there are a very large number of effects to
consider. These involve potentially negative effects (e.g. from lower rainfall and/or increasing
variability) but also potentially positive effects (e.g. from CO₂ fertilization and from extended growing
seasons), as well as complex changes from the changing risks of extreme events, the range and
prevalence of pests and disease, etc. These vary strongly with crop type, management practice
(including irrigation), as well as with the exact future changes that arise, notably in relation to the
changes in precipitation and variability. Second, changes in agricultural production involve rather
complex transmission mechanisms through to the changes in prices that households are likely to
experience under climate change. Much of the food purchased in the UK is part of global supply
chains, and thus the consideration of how climate change impacts on these requires analysis of
changes in production globally and the effects on trade.

There is a large literature on the potential effects of climate change on agriculture, which shows a
very large range of potential outcomes (including both positive as well as negative effects), though a
general finding is that significantly negative effects are likely after 2050 or above 2°C of warming
(Porter et al, 2014). However, the key issue for this study relates to how changes in agricultural
production feed through to prices, and the affordability of household expenditure on food. The
econometric analysis undertaken looked at the observed correlation between the climate of the UK
and food prices, finding changes in temperature variability negatively affect agricultural prices. It
also found that bread and cereals have a positive relationship with temperature but negative with
extremes. However, neither of these approaches takes into account the international effects of
current or future climate on UK food prices. For this reason, the analysis here draws on the review of
the effects of climate change on agriculture from the international review. This addressed the
question of how changes in agricultural production feed through to prices (and household
affordability of food in the UK) and how food prices may vary due to the future effects of climate
change. The assessment first reviewed the relationship between current weather shocks and global
food prices. This found an observed pattern between climate change and international food prices.
This was extended to consider the link with UK household expenditures, as reflected by changes in
UK food prices, during periods of higher international prices. The analysis revealed a link between
the global price and UK consumer price of food. The analysis then looked at the potential effects of
climate change on global agriculture. As highlighted above, this is challenging, and results vary strongly with study, assumptions, etc. For this study, the analysis drew on the most recent comprehensive review and synthesis of the literature on the global impacts of climate change on agriculture (Agricultural Model Inter-comparison and Improvement Project (AGMIP) and the main results reported in Nelson et. al. (2013). This focuses on the year 2050 for a high warming scenario (noting that before this, the net effects are likely to modest). The propagation of changes in production through to end prices is complex and requires economic modelling – they also involve a number of intermediate responses, such as changes in management, areas under production, trade, etc. and patterns of positive and negative effects in different regions.

On average, the Nelson et al study reports that prices under climate change increased by 20% by 2050, though with a considerable range (0% to 60%) by 2050. The results of these two elements – the rise in UK food prices under changing international prices – and the implied 20% (average) price rise in global prices under climate change, was used to provide an initial estimate of the potential effect on household food costs. This assumes linear responses (including consumer responses) and a very large number of assumptions thus can only be considered as highly indicative. It also assumes that the modelled food items in Nelsen et al. (2013) apply equally to the full basket of food types consumed in the UK (including foodstuffs, processed food and non-alcoholic drinks). Nonetheless, the results indicate the food bill for an average family could be important, with the results indicating a rise by 9% (with a range of 0%-28%) in 2050 with climate change (assuming all other things being equal, i.e. future climate change on current conditions). The average weekly household expenditure in the UK in 2014 was £517.30, with the amount spent on food and non-alcoholic drinks being £58.80 (11%). This increase therefore equates to an effect of- £275/year (with a range of 0 to -£856), indicating a modest to substantial increase in household expenditures.

Distributional effects. Food is a major household expenditure item and a core human necessity. Importantly, low income households spend a greater proportion of their disposable income on food and non-alcoholic drink (16% for the lowest income decile) than the average household (11%), so the impacts of higher food prices will have a disproportionate impact on these groups. Food is also rather inelastic, i.e. families will still purchase food if prices go up, which in turn reduces their available income for other items. Nonetheless, there is some response in purchase volumes as a result of higher prices. During the price shocks of 2011, low income households bought less food with the bottom ten per cent of households by income purchasing 10 per cent less food by weight (Defra, 2012). Thus, while the average family food bill would increase by 9% (with a range of 0%-28%) with climate change, the bill for the lowest income decile would rise by 13% (with a range of 0%-39%). The percentage of an overall minimum budget in a low income family devoted to food is typically around 23%. This suggests that for a low decile family, the projected climate effect on food prices would add about 3% to overall household costs, with a range from 0 to 5%. This highlights the disproportionate impact of these impacts on the poor, affecting disposal income of other items (although changes in future household income also have to be considered). The econometric analysis also found that expenditure on basic food items (in a panel format) shows that the climate has more significant effects on the poorer members of society, especially the climatic effects relevant to food production.

Energy

The current climate already influences the use of energy in the UK, because of the major influence of temperature on the heating of buildings. The warmer temperatures from climate change will have potentially large effects in reducing household energy costs, therefore reducing heating demand. However, at the same time, there will be higher temperatures in summer, which will increase the
potential need for cooling (or otherwise lead to lower comfort levels from increasing building temperatures and health effects).

The costs of electricity, gas and other fuels are a major component of current household expenditure (5%). A large proportion of this is for winter heating (see WP9). Climate change will lead to warmer winters, which will have benefits in reducing the costs of heating (a private autonomous adaptation). This benefit is large due to the high levels of current energy demand, the high cost of heating in the UK and the large fall in heating demand anticipated. For example, even by the 2030s, there could be an estimated 15-20% reduction in winter heating demand. There is a high confidence in the direction of change (i.e. in this benefit), although considerable variation in exact level of change and the household level benefit. The analysis in CCRA1 estimated the potential costs of the reduction in winter heating demand. These estimates have been updated here using current DECC retail (market) prices for energy costs (2013 values), rather than the values used in CCRA (DECC government appraisal values, which were based on the long-run variable cost of energy supply rather than the costs paid by households). By the 2020s, the reduction in winter heating costs (on average) is estimated at +£87/household/year (with a range from +£38 to +£135), rising to +£135/household/year by the 2050s (with a range from +£58 to +£226) – equivalent to low and high warming scenarios (i.e. 2 and 4°C pathways). This compares to current average expenditure of around £500/household/year. The benefits are modest, but important. However, these changes assume static prices and current socio-economics. Future energy costs to households will change in the future, with low or high price scenarios, low or high growth scenarios, and critically on the implementation of mitigation policy (overall and at the household level). For example, even in the 2030s, prices are around 25% higher under Government (DECC) high price scenario. This highlights that future prices (for the same unit of a good or service) may be very different to today, and that a degree of self-consistency is needed: future prices will be determined by the level of future mitigation, which in turn will affect how large the impacts of climate change are in the future (in the 2050s and beyond). There is also the issue of how much the building stock improves in terms of energy efficiency, and under more aggressive uptake scenarios, this would dominate future reductions in winter heating (reducing the climate benefits).

However, at the same time that winter heating demand increases, there will be higher summer-time temperatures. Because the UK is a temperate country, there are low levels of cooling and air conditioning in place today (cooling of buildings is estimated to be around 4% of electricity demand (Day et al., 2009) and cooling is only fitted in around 3% of houses). Even under future scenarios, the likely increase in demand (cooling degree days and energy for cooling) is likely to be lower than the reduction in winter heating. While the costs of cooling were only considered indicatively in CCRA1, the estimated costs were broadly an order of magnitude lower than the changes in heating demand, and were estimated to be in the range of -£2 to -£32/household/year in the 2050s (for 2 and 4°C pathways), a minor impact, though rising quickly thereafter. However, more recent estimates (compiled as part of the CCRA2 review, Kovats and Osborn, 2015) indicate higher levels of cooling demand are likely, driven by rising temperatures and heat-extremes, and the low cost/marketing of air conditioning. The UK housing stock has not been designed with higher temperatures in mind, and already around 20% of households in the UK experience overheating during relatively cool summers. This is likely to be a growing issue with warmer temperatures and heat extremes, especially for some properties (e.g. high level flats), and in some locations (notably London) due to the urban heat island effect. It is also worth highlighting that the costs of cooling (generally met by air conditioning) is more expensive because it uses electricity (which is more expensive per unit delivered) and involves the incremental purchase of AC units / cooling systems (which are not currently in place, unlike heating systems). Indeed, in some extreme scenarios, where cooling is adopted by all houses, the
costs of cooling could be a similar order of magnitude to the reduction in winter warming by the 2050s, having a modest impact on household budgets.

**Distributional effects.** It is clear that on changes in energy costs will affect households differently. Lower income households spend a higher percentage of their total expenditure on energy relative to the wealthiest households, with the cost of living survey reporting 9.6% of total expenditure for the former (the lowest decile) compared to 3.6% for the latter (the highest). The reduction in winter heating will therefore have disproportionately large benefits for the poorest households, as heating is a necessity (i.e. heating demand is quite inelastic and demand does not change much with higher prices, thus the price elasticity is close to zero), although increasing energy prices can result in lower income households reducing their energy consumption somewhat, decreasing comfort levels. As low income households currently spend a higher proportion of their available income on fuel, as the demand for heating reduces with climate change, this will increase available income. For cooling, the picture is more complex, because the ownership of air conditioning is strongly income dependent (there is a strong correlation between income and AC appliances, Isaac and van Vuuren, 2008), and demand for electricity for cooling is likely to be more elastic. The take up of AC is likely to be extremely low amongst low-income groups, but instead they will experience higher temperatures and impacts on economic welfare (lower comfort levels, and potentially higher health impacts).

There are also some areas of social housing stock / low value houses, which are poorly designed and subject to over-heating, thus there is also a distributional impact from exposure. These heating and cooling patterns will also have a strong geographical pattern across the UK: winter heating demand (and thus benefits) will be greatest in Scotland and the North, while summer cooling demand will be greatest in the South and particularly in London.

**Housing (flooding and insurance, maintenance and repair)**

There are a number of potential effects of climate change on housing and indeed, this include some of the largest impacts among any considered. However, the patterns through which the impacts of climate change cascade through to household costs are complex. The primary effect here is from flooding (from coastal, river and flash floods). However, it also includes other aspects where climate is a factor, such as wind-storms and subsidence.

Floods are among the important weather-related loss events in the UK currently and can have large economic consequences. Climate change has the potential to increase the potential risks of these events, and the estimated economic costs are large, as identified in CCRA1. These events directly affect households, but the costs that are experienced involve more complex pathways, as in practice, most of the flooding cost will be borne by insurance companies. The pathway to cost increases to households is therefore rather complex, feeding through to higher insurance payouts, and in turn to changes in risk that are then captured through higher insurance premiums. Note that there are also economic welfare effects from flooding (captured in the health section).

The estimated costs of flooding (at the aggregate national level) was estimated in CCRA1 and updated by the CCC (ASC, 2014) and mostly recently for CCRA1 (Sayers et al, 2015). These values were used in preference to the IMPACT2C results, because they involve more disaggregated modelling. The CCRA2 results are similar to CCRA1 – but with a very high increase for the high ++ scenario. The estimated national costs of flooding in the UK are equivalent to an increase (above baseline) of £1 to £8 per household per year by the 2020s (for a 2 and 4°C scenarios) with an upper value (High ++) of £14, increasing to £6 to £28 per household per year by the 2050s (2 and 4°C) but with a high++ estimate of £87/household/yr (note these are slightly lower than the IMPACT2C numbers, reflecting the more detailed analysis). These increases are additional to the current risk
levels, which equate to around £13/household/year. These indicate a minor to modest increase in impacts (if passed through) to household budgets. However, there is the likelihood that more substantial insurance premiums will be passed through to those most at risk. This is particularly important as flooding is the climate effect most likely to have a large impact on a small minority of households, i.e. for those house affected (see distributional effects below).

There is also a smaller cost on households from the increase in subsidence. The pathway for this impact will be similar to floods (via insurance), but the overall impact is much lower. The average costs would fall into the negligible category £50 a year. There is the potential for other effects on housing costs, notably if there are changes in wind-storms under climate change: however, the current evidence base is not robust enough to estimate the potential change in risks.

**Distributional effects.** There are a number of distributional aspects with respect to flooding. First, there are differential patterns of exposure, from risk patterns or differences in protection (as found in CCRA1). These appear clearly for coastal flooding, where there is a high correlation with socio-economic profile and the index of multiple deprivation (i.e. poorer communities are at higher risk). There is not the same correlation for river flooding, due to the higher proportion of higher income households in these locations. At the national level, the CCRA1 found that some of the areas that are at particularly risk of flooding, in Yorkshire, The Humber and East Midlands, are areas that have (relatively) high levels of deprivation/lower average incomes. There are also differentiated patterns of protection in place. As highlighted by the CCRA1, London has a higher standard of protection than elsewhere in the UK (annual probability of flooding of 0.1%, or 1 in 1000 years). It is also likely that low income groups may be more adversely affected by flooding in relation to the post-flooding events and responses (see CCRA2).

The CCRA2 analysis (Sayers et al, 2015) estimates there are currently 230,000 people in deprived areas at a 1 in 75 (year) risk of flooding, relative to the UK total risk (1 in 75) of 1,300,000 people. The increased risk of flooding for deprived areas by 2050 (current population) under climate change increase by 80%, 190% and 260% (for the 2°C, 4°C and High ++ scenarios respectively), which is a higher relative increase than for the overall population (52%, 140% and 200%). This equates to between an extra 184,000 to 598,000 people at risk in deprived areas by 2050.

There is also the issue of how the costs that arise from flooding affect low income households, notably around insurance cost. The LCF shows that insurance represents less than 1% of total expenditure for the lowest decile group (0.8%) as well as for the highest (0.9%). However, ABI (2010) reports that almost 40% of people in the lowest decile did not have insurance at all in 2010, compared to 2% in the highest decile group. Low income households are also unlikely to invest in the costs of household measures to reduce flood impacts, as while the benefits of these are high, they involve high up-front costs (Grant et al. 2011). This is especially important given the high individual costs of a flood event on a household. In the event of flooding, the impact of an event on an uninsured individual household will be extremely large, both in terms of direct costs and economic welfare (well-being). The cost of a flood event depends on height, length and velocity of the flood as well as property type, but the average insurance claim per domestic property is between £23k and £30k. The combination of low insurance cover amongst the poorest households, and the large (life-changing) impact of an uninsured flood, has the potential for very dramatic impacts on households in relation to the 4Ps (even if households borrowed to offset the costs, this would fall into a substantial reduction in household expenditure).

Combining the estimates of the number of properties in deprived areas at risk of flooding (Sayers et al, 2015), and assuming current level of uninsured properties among this socio-economic group (ABI,
2010), the number of low income households that could be affected dramatically from future climate induced flooding could be very significant, i.e. there could be an additional 70 000 (2C) to 240 000 (high ++) people in low income households at additional risk of flooding and with no insurance cover by the 2050s (note this is a risk level, not an annual number flooded).

The implications of these effects will be determined by how the UK household insurance market evolves, and the policies introduced by Government. Currently, the proposed Flood Re scheme (a collaboration between the insurance industry and the Government) will cap the cost of insurance to households in flood prone areas with a banded system with premiums increasing with council tax band to provide affordable cover (though note houses built since 2009 are excluded to prevent building in high flood risk areas). However, as this may support a transition to market prices which reflect risk, this could have very important implications for future cover. There are also issues with the nature of the insurance agreement and the planned level of Government investment in flood protection, which could alter the future landscape. Although the eligibility for Government flood finance takes account of the Index of Multiple deprivation, it is seeking to leverage other source of funds (partnerships) to meet the necessary flood protection investment levels. Analysis in a recent JRF report (Targeting flood investment and policy to minimise flood disadvantage: JR, 2015) highlights that in practice, there is not such a strong link for funds being directed to areas with higher IMD and higher flood risk.

There will be similar insurance related issues with subsidence. The unit values in the CCRA1 for a case of subsidence used a value of £10,000, though ABI reports the average cost of dealing with subsidence is running at £6,900. Irrespective of the exact value, the potential for large costs, especially due to lower insurance cover levels, will lead to disproportionately high incomes on low (owner occupier) households.

**Water supply**

Climate change is projected to have a significant impact on water cycles. This will potentially lead to a number of changes in risks. This includes more frequent and/or intense floods (covered in the previous section on household costs), and changes to the water supply-demand balance including potential water deficits and water quality.

Water charges are around 2% of average household expenditure currently. However, while climate change may have potentially important impacts on the supply availability of water, the regulated nature of the UK’s water sector means that any impacts on household costs are indirect. The CCRA1 looked at estimates on the amount of water available for abstraction – and compared this with demand forecasts to estimate when resources zones might fall into deficit. The resulting water deficits were valued using supply-side cost data, as a proxy for the economic welfare value of water. These were estimated at-£9/household/year by the 2050s (with a range from -£3 to -£14, for 2 and 4°C pathways), thus the changes are negligible when compared to current household expenditure. Assuming the current structure of the sector, the increases in supply side costs from measures taken by the water companies (under most scenarios), which would be passed on in the form of water charges to customers. Note that for households with water meters, there would be the potential for changes in demand as a result. The costs above would then translate to additional direct costs to households. It is highlighted that this was one area where the uncertainty is large. There are also geographical patterns of risk across the UK, with the south more potentially at risk.

CCRA2 has updated the water demand-supply deficit. The pattern of projected supply-demand deficits is approximately the same between the original CCRA analysis, with the greatest deficits in
England, particularly London and the north east. Such deficits are projected to become more acute and widespread in the 2080s and would present significant challenges in most parts of the UK but particularly across England. There some differences are in the volumes of deficit calculated, with CCRA2 projecting slightly less severe deficits than the first CCRA analysis, but in terms of costs, the overall results are broadly similar.

**Distributional effects.** The lowest income decile of household spends 2.9% of their budget in water supply services compared to 1.2% of the highest decile, and 1.7% of the average UK household. The increases in costs associated with additional supply side measures would therefore impact more strongly on these low income households. In cases where the structure of the industry changed, or even if there was more water metering, this might have stronger distributional impacts.

**Health**

The major impacts from climate change on well-being (or economic welfare costs) arise from the potential effects on health (although this reflects the ease of valuation for this non-market category compared to say ecosystems). These costs are estimated from the perspective of social welfare, and capture the wider costs and benefits to society as a whole. They consider three components which capture different components of this cost. These are the resource costs i.e. medical treatment costs; the opportunity costs, in terms of lost productivity; and dis-utility i.e. pain or suffering, concern and inconvenience to family and others. However, as health care costs are largely covered by service providers (e.g. NHS and health facilities), these do not feed through to changes in household expenditure.

The main effect of climate change and health – at least in economic terms – is the changes in temperature related mortality (see WP8). Higher temperatures increase the number of fatalities, an effect which is heightened during prolonged heat-waves (as already observed in the European 2003 summer). However, in a temperate climate such as the UK, there are also additional fatalities during colder periods. CCRA1 reported a large direct benefit from warmer winters in reducing cold related mortality and morbidity, but also an impact from increased summer temperatures and heat extremes. The CCRA reported that the cold-related effects (and costs) outweighed the heat related costs by some margin, though the difference narrows in the longer-term.

The temperature related mortality health estimates were updated as part of the ASC (2014) report, and these health impacts – when monetised using the same unit values as the CCRA analysis – indicate the differential is lower. The UK values are used, because they include both heat and cold related effects. The increase in heat related mortality is equivalent to an average household cost (noting this is a social welfare cost, not one borne by the household) of -£0.4/household/year in the 2020s rising to -£1.4/household/year in the 2050s. This is still lower than the benefits from decreased winter mortality (+£1.2/household/year in the 2020s rising to +£3.6/household/year in the 2050s, central projection). More recent assessments present similar changes (Hajat et al. 2014) seem to indicate a lower reduction in cold related deaths (partly driven by an aging population). Irrespective of this, when the other health costs (from CCRA1) are added, this effectively closes the gap, and there are net health impacts (in economic terms) from climate change. These include flood related deaths (which equated to a further -£0.9 and -£1.9/household/year as a societal welfare cost per average household in the 2020s and 2050, flood related injuries (which was of a similar order), ozone related deaths (which were an order of magnitude lower), skin cancer cases and mental stress from flooding (which were also low compared to temperature related mortality). Nevertheless, aggregate health (societal welfare) costs are likely to be low compared to the other categories. They
do, however, have a very large impact on the individuals affected, especially where this leads to higher fatalities (obviously).

**Distributional effects.** Direct health costs are not a large direct expenditure item, and indeed high income households spend more on health than low income deciles (presumably due to private health care). Indeed this might mean that some of the additional health impacts might affect high income households more (in the form of higher taxes, or higher health insurance). The health impacts do, however, have distributional impacts with some larger impacts on low income households, though these will include beneficial as well as detrimental effects. First, vulnerability to health impacts, particularly heat and cold-related mortality, is higher for certain population groups, notably the elderly, those with existing health conditions and those with access to low levels of social care. There are strong correlations with these groups and income levels. This is a particular concern as it means major life changing impacts (including death) are more likely in lower income or vulnerable groups. However, while there will be greater impacts from heat related mortality on low income households, there will be greater benefits for similar groups from reduced cold-related mortality. For morbidity, where costs arise, such as the lost time at work, it may have greater impacts on low income households due to temporary work contracts.

**Other effects (wider economic and the 4Ps)**

As well as the impacts of climate change of direct relevance to households, there are a number of impacts that will affect business, industry and the wider economy. These include domestic impacts and from International effects and supply chains. These have the potential to affect households indirectly, either by increasing the costs of goods or services, or in affecting the prospects in relation to employment, etc.

As part of the econometric analysis the analysis found a number of current relationships exist between the macro-economy and climate variables. These relationships indicate that future climate and associated macro-economic sensitivities will have implications for households at the micro-economic scale. There is strong evidence that increased precipitation reduces prices, whilst an increase in the difference between the minimum and maximum temperature produces a significant rise in prices. However both effects are relatively small with a 1% rise in precipitation producing a 0.002% fall in inflation. An explanation for the first of these findings is that as precipitation increases water availability for agriculture and industry, this enables added productivity across the economy. In relation to the second finding, as the temperature becomes more variable, it is likely that prices rise and so it becomes more uncertain what the weather is likely to do and more difficult to plan ahead, reducing production and increasing prices across the economy. There was also found to be an effect of precipitation on recreation which is significant: clearly as it rains more, there is less demand for recreation, so there is a fall - or less of an increase - in prices.

In addition to these effects, review of the future effects of climate change was used to look at other effects. There are a large number of small additional impacts (and costs) which will add to the major categories above. There are also a set of much larger and more important impacts of climate change on non-household categories (e.g. non-residential flooding). The most important of these for the UK, as identified in CCRA1 (and updated in CCRA2) – is the costs of flooding on non-residential buildings and on various sector activities, i.e. flooding of energy infrastructure, transport infrastructure, agriculture, etc. The estimated annual costs of flooding on non-residential properties are very large, i.e. of the same order of magnitude as the costs of flooding for residential properties above. However, it is unclear quite how these various costs will pass through to households, i.e. whether
this will be in the form of higher prices for goods and services, or changes in employment or pay. Further work on these transmission mechanisms is needed.

Finally, as well as the health effects there are number of other non-market costs that could have potentially important effects on households through more complex pathways. The most important is in relation to the effects on biodiversity and ecosystem services, and in turn how this could affect household (economic) welfare, but this remains a major gap in the knowledge base.

It is more difficult to assess how these effects will translate through to different income or societal groups. In cases where they increase the costs of goods and services, they may have a higher impact on low income groups (due to their lower levels of disposable income).

4.3.5 Household Expenditure and Household Impacts in Italy

Similar to the UK, there is a national Household Expenditure Survey 2014 (ISTAT). Findings are divided by five geographical regions (North-West, North-East, Centre, South, and Islands), 20 regional administrations and type of family (by composition, occupation of head of the household etc.). The Survey reveals that the average household monthly expenditure in Italy in 2014 was €2489 with significant geographical variations: it was the lowest in the Islands (€1871) followed by the South (€2003), and the highest in the North West of the country (€2799). The data show that over the past 7 years there has been a decrease in Italian households spending: in 2014 expenditure was lower with respect to 2008 by 6%.

**Median and average expenditure by expenditure items in 5 geographical areas in 2014, € per month in Italy**

<table>
<thead>
<tr>
<th>MEDIAN Household Expenditure per month</th>
<th>2110</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVERAGE Household Expenditure per month</td>
<td>2489</td>
</tr>
<tr>
<td>1) Food &amp; non-alcoholic drinks</td>
<td>18% 436</td>
</tr>
<tr>
<td>2) Non-food expenditure</td>
<td>82% 2052</td>
</tr>
<tr>
<td>Sub categories of 2):</td>
<td></td>
</tr>
<tr>
<td>Alcoholic drink, tobacco &amp; narcotics</td>
<td>2% 43.31</td>
</tr>
<tr>
<td>Clothing and footwear</td>
<td>5% 114</td>
</tr>
<tr>
<td>Housing, fuel and power, of which:</td>
<td></td>
</tr>
<tr>
<td>(Excluding a and b)</td>
<td>37% 913</td>
</tr>
<tr>
<td>(12%)</td>
<td>(287)</td>
</tr>
<tr>
<td>a) Extraordinary maintenance works</td>
<td>1% 34</td>
</tr>
<tr>
<td>b) Imputed rents</td>
<td>24% 592</td>
</tr>
<tr>
<td>Transport</td>
<td>10% 257</td>
</tr>
<tr>
<td>Recreation and culture</td>
<td>5% 121</td>
</tr>
<tr>
<td>Miscellaneous goods and services</td>
<td>8% 202</td>
</tr>
</tbody>
</table>

The analysis of potential impacts of climate change on these household costs is assessed below, primarily drawing on IMPACT2C results.

**Food**

Italian families’ monthly expenditure on food and non-alcoholic drinks represent 18% of their total expenditure. We assume a similar profile to the UK, as a result of changes in International Food
prices. As with the UK, these impacts would also affect low income households more. There is also a
greater level of domestic food sourced in Italy, which has been affected by recent extremes. The
Italian MoE reports a decline in productivity during 2003, when a heat wave hit the Mediterranean
including Italy and the National Federation of Farmes (Coldiretti) estimated that in 2012 10% of
agriculture production was lost due to droughts and extremes. Looking forward, climate change is
likely to have a stronger influence on Italian production. Work Package 7 does indicate that the
biophysical impacts on crop yield are more severe in lower latitude European regions, which might
translate into higher domestic impacts (or higher use of irrigation, noting water constraints below).
This is also important because a large number of people (around 1 million) are employed in the
agriculture sector.

Energy

Work Package 9 reported the econometric analysis of electricity demand in Italy (figure 5 of D9.1).
This considered the electricity demand with temperature and found a very strong and distinct cooling
effect, i.e. as temperatures rise, there is a strong additional demand for electricity for cooling. While
there was also a winter heating effect, a decrease of the heating effect for degrees lower than 5°C
was observable: in contrast, the cooling effect increases continuously and showed no decrease for
higher degrees. The IMPACT2C also found that with climate change, there was a large increase in
electricity demand (the net of cooling over heating). This result contrasts (rather obviously) with the
UK, which is more temperature. As a consequence, there will be a strong increase in household costs
for energy under climate change in Italy, due to additional cooling.

Household costs (including flooding and water)

Floods are already a major hazard in Italy. The Italian MfE reports that between 2002 and 2012
extreme events caused 290 deaths, 128 due to floods and 165 to landslides. There are two sets of
flood related damages of relevance for Italy where quantified information is available from other
work packages in IMPACT2C. The first is river flooding and the second is coastal flooding (Work
Package 7). For river flooding, the results of the LISFLOOD model (for the 8 model ensemble for 2°C
of warming, from the RCP4.5 and 8.5 simulations), the household costs for Italy are estimated at Euro
24.5 per household/year in the baseline (2007 Euro), rising to Euro 133/household/year at 2C (no
socio-economic change) or Euro 196/household/year under SSP2 (population and growth). These
values are higher than the UK (i.e. when UK LISFLOOD numbers are compared). The second is the
coastal flooding (noting this includes a wider set of costs, discussed in Work Package 6). The costs of
coastal flooding for Italy are lower than river flooding, with a baseline cost of Euro
0.5/household/year. The projected costs (for the 2060s) vary strongly with the RCP scenario and low
and high sea-level scenarios, from Euro 0.3/household/year to Euro 45/household/year (SSP2). The
value for RCP4.5 (medium SLR) is Euro 3.6/household/year. These costs are therefore much lower
than for river flooding. In Italy, insurance companies are also reluctant to provide cover to residential
properties for catastrophic risk that includes floods and landslide events.

It is more difficult to assess the potential changes in water charges in Italy under climate change,
although the hydrological analysis (see IMPACT2C WP6) finds a projected decrease in mean annual
river flow in many parts of the Mediterranean, although there are complex patterns in summer, due
to the reduction in summer snow melt in mountain regions. There are also potential changes in
drought intensity and duration, in terms of low flows in rivers (streamflow drought) and soil moisture
levels (agricultural drought). Low flow (streamflow drought) periods are projected to become more
intense and last longer in the Mediterranean, and there are projected decreases in soil moisture
levels as well. These combined changes indicate potential increases in water deficits for a number of
water-dependent sectors in Southern Europe. This would indicate a likely increase in public water supply costs, although there are no valuation estimates available. Given the pressing need for infrastructure investment anyway in Italy, and the increasing scarcity of water due to climate change, tariffs in Italy are expected to increase significantly over the next few decades.

Health

The analysis of health impacts – and in particular heat related mortality – were assessed in WP8 (D8.1). This quantified the heat attributable deaths under 2°C of warming. These estimates were then valued (in the work package). Using the value of a life year lost, the equivalent welfare cost for Italy is an average of Euro 46/household/year at 2°C (with a range from the climate models of 18 to 74). This is an order of magnitude higher than the UK. The welfare costs per household in Italy rise to an average of Euro 126/household/year at 3°C, a significant increase. Cold related mortality was not assessed in IMPACT2C, but it would be expected that the increase in heat-related deaths is much larger than cold-related deaths, given the baseline climate.

Other

As with the UK, there are a large number of other possible effects from climate change, which will affect the economy, employment, etc. For Italy, this includes important issues in relation to summer (beach) and winter tourism (see WP9) – noting around 1 million people are employed in the sector. For both of these, there are indications that Italy may experience dis-benefits under climate change, though it is more difficult to assess how these might pass through to household costs, wider effects and broader welfare. Bosello et al. (2010) estimated the macroeconomic impacts of climate change on the Italian economy from changes in tourism, estimating that in 2050 foreigner tourists would decrease by 15%, and while this would be partly counterbalanced by an increase in domestic tourists a CGE model estimated that this would have an impact on GDP of -0.25% in 2050. A similar exercise was carried out as part of the EU adaptation strategy, which estimated the impacts (using CGE model) of -0.35% and -1.05% of GDP in 2050.

Overall

The combined impacts across the categories above reveal interesting results compared to the UK. With the exception of coastal flooding, the impacts are generally found to be much higher, in terms of the potential costs to households in Italy. This arises from the strong cooling demand signal, the higher costs of riverine flooding. There are also higher welfare costs due to the stronger heat related mortality signal. When the costs to households for Italy from climate change are added together, it is clear that the impacts could have substantial impacts on household budgets by 2050 (noting the need to consider future socio-economic trends and changes in incomes over time), and potentially very major effects under higher warming scenarios.

4.3.6 Conclusions

Overall, the case study concludes that there are likely to be relatively modest impacts on the costs of living and household budgets in the UK from climate change up to the middle of the century, especially under pathways of 2°C of warming. There was also found to be a difference between 2 and 4°C pathways, even by the 2050s, with potentially large increases and significant impacts thereafter under higher warming scenarios.
The early impacts on households from climate change in the UK are likely to be dominated by a small number of major effects (each with a modest impact of up to 5% of the current average household budget), with negative effects from food prices, flood related housing costs and cooling demand, but positive effects from reduced heating demand. The total effects will be negative in aggregate. There are also net negative (societal welfare costs) from increased health impacts. It is stressed that the actual effects borne by household will be determined by future socio-economic changes (notably income levels), and are subject to high uncertainty, and thus some care should be taken in interpreting individual and especially aggregate figures.

Perhaps more importantly, a clear and consistent finding is that low income households will be most affected by these climate change impacts, though they will also benefit most from the positives. In all areas, there are large and disproportionate impacts on low income households, either because of the reduction in disposable income (e.g. from rising food prices), the reduction in quality of life (e.g. from relative higher negative health outcomes) or because of differentiated patterns of risks (e.g. higher flood vulnerability), though low income households will also benefit most from reduced winter heating (increasing disposable income). The overall negative effects of these changes will have important impacts for low income households, even with the relatively modest changes expected in future decades, and could be substantial for the higher warming scenarios later in the century (noting the underlying socio-economic situation will be very different to today).

Moreover, for some impacts, there are very large individual costs which are more likely to affect low-income households, notably from the risks of uninsured flood losses. These will have major (life-changing) consequences for those affected. Such shocks have the potential to increase the number of people in poverty and the fact that they fall disproportionately on the most vulnerable groups in society are a particular concern.

The analysis of the potential impacts of climate change on households in Italy leads to different results. In contrast to the UK, the analysis on Italian households shows much stronger impacts on average, due to the strong negative signals from cooling demand and potentially also water supply costs as well as high levels of (river) flooding. There are also higher welfare costs due to the stronger heat related mortality signal. When the costs to households for Italy from climate change are added together, it is clear that the impacts could have substantial impacts on household budgets by 2050 (noting the need to consider future socio-economic trends and changes in incomes over time), and potentially very major effects under higher warming scenarios. These impacts would be exacerbated for low income households.

Given these findings, a key issue is for the distributional impacts of climate change to be considered in national, regional and local assessments, and for these issues to be reflected when designing adaptation policy.

References


4.4 Port city case study

POPULATION EXPOSURE TO 1:100 YEAR STORM FOR THE WORLDS LARGE COASTAL PORT CITIES UNDER FUTURE CLIMATE CHANGE, WITH REFERENCE TO A 2°C CHANGE IN GLOBAL TEMPERATURE

4.4.1 Introduction

A global warming of 2 °C relative to pre-industrial climate has been considered as a threshold which society should endeavour to remain below in order to limit the dangerous effects of anthropogenic climate change. For the world’s coastal cities this is particularly important as changes in sea level are one of the more certain and long-term consequences of any rise in the global temperature and higher sea levels can lead to increased storm surges, resulting in episodic or permanent inundation. The financial and social investment in port cities means that they are unlikely to relocate despite the effects of major events (e.g. Hurricanes Sandy and Katrina in the USA) especially as the historical reasons for their existence, e.g. natural harbours, are still valid. Port cities, important nodes in the international transport system, need to safeguard both their infrastructure and workforce into the future resulting in adaptation strategies to future storm events becoming a key focus for planning and policy makers. Successful adaptation planning initially requires an appreciation of the magnitude of potential impacts (Cooper and Lemckert, 2012). This report therefore investigates the population exposure (the worst case scenario) for 136 of the world’s large port cities to a 1:100 year storm event over this century focussing on exposure when the 2°C global mean temperature is reached and the benefits of stabilising any temperature change around this level. While this exposure does not necessarily translate into risk (Aven and Renn, 2010), it discloses, to a large extent, the hazard faced in each city and exposure levels which need to be considered for adaptation planning. The consequences of not considering these potential exposures are shown in New Orleans and New York where local impacts have had, and continue to have, ramifications regionally, nationally and internationally.

4.4.2 Method

The methodology for this investigation follows that described in Nicholls et al. (2008). Global data has been used to estimate population by elevation for each identified city and storm surge levels from which exposure is calculated. The use of global data sets mean that results are indicative rather than precise but they can disclose those cities where potential exposure levels are high and illustrate any benefit of climate mitigation and stabilisation.

City selection was limited to recognised port cities with populations greater than one million in 2005, which includes the fastest growing urban agglomerations (medium-sized cities of 1-5 million people) (UN, 2014). Topographic data from the Shuttle Radar Topography Mission (SRTM4) and city population based on Landscan 20025 data were used to a generate population by elevation distribution to form the baseline for the analysis (for full description please see Appendix 1 in Nicholls et al., 2008). The height of the 1:100 year storm surge is used to represent extreme events which have been experienced around the world. Current and future population exposure is calculated at 5 year intervals over the century for the 1:100 year coastal flood event by combining the following information:

- City Population (assuming no growth in city extent)

4 http://srtm.usgs.gov/index.php
5 http://web.ornl.gov/sci/landscan/
Future country populations (SSP2 projections) 
Urban population (UN urbanisation rates (UN, 2014))

- Water levels (DIVA model)
  - 1:100 year storm surge (with storm factor (Nicholls et al., 2008))
  - Vertical land movement (localised subsidence/uplift)
  - Global (and regional) sea-level rise

The 1:100 year storm surge level and projected relative sea-level change are taken from the DIVA model. The DIVA model spatially distributes the thermal expansion of the ocean, ice melt contribution and vertical land movement to create localised relative sea-level projections for each port city under Representative Concentration Pathways (RCPs) scenarios 2.4, 4.5 and 8.5 (based on the HadGEM2-ES climate model); three ice melt scenarios are also used to account for the variable contribution to sea-level rise from this source; high, medium and low (see Hinkel et al., 2014 for a full description of sea-level scenarios). The height of the 1:100 year storm surge is increased in line with the relative sea-level projections (Nicholls, 2014 #12) and an enhancement factor addressing potential increases and track movement is used for those ports based on the individual tropical and extra-tropical cyclone ratings for each city.

4.4.3 Analysis

Future scenario projections

The distribution of the 136 ports included in the study is shown in Figure 1. Their elevations and locations indicate many are affected by extreme water levels today (e.g. 37 are known to be subject to subsidence either partially or fully and 72 to potential changes in storminess) and are therefore likely be affected by sea-level rise in the future (cf. Munich Re, 2004).

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6 IIASA’s AMPERE Public Database: https://secure.iiasa.ac.at/web-apps/ene/AMPEREDB/dsd?Action=htmlpage&page=about#ampere
Under the RCP scenarios global-mean sea level continues to rise even if the temperature change is stabilised at 2°C (RCP2.6) although the rates of change are significantly different (IMPACT2C, 2015). This ‘commitment to sea-level rise’ (Wigley and Raper, 1993) occurs as oceans can take many decades to absorb the additional atmospheric warming (Schaeffer et al., 2012). Using the HadGEM-ES climate model, the global mean temperature increase for all RCP emissions scenarios reaches 2°C between 2035 and 2040 (with reference to pre-industrial period). 2040 was therefore used to represent the time that a 2°C increase in global mean temperature is reached. Post 2040, comparison between the RCP emissions scenarios can be used to show the benefits of climate mitigation to stabilise global temperature. Comparing the date at which the 2°C threshold is reached (2040), there is a maximum difference in global-mean relative sea-level rise of 10cm (largely related to ice melt) between all the sea-level projections; by 2100 this has increased eightfold to 80 cm.

The SSP2 global population projection shows growth followed by a gradual decline towards the end of the century. There are significant regional differences with Africa showing a continuous increase in population while more developed regions such as Europe showing a gradual decline post 2070. Individual countries also show a variety of patterns; for example Germany shows a gradual decline over the century, China’s population peaks in 2025 and Nigeria’s population increases constantly to 2100.

**Population exposure**

In 2015, approximately 61 million people are exposed to the 1:100 year storm event across all the 136 port cities. By 2040, when the global-mean temperature increase has reached 2°C this has increased by over 13million to between 74.65 to 77.63 million. During this period, exposure varies between the relative sea-level projections with a maximum difference of 3 million occurring in 2035 (see Table 1). This maximum difference in exposure represents an average of 20,000 people per port. Post 2040 the population exposure continues to increase over this century. Under the RCP 8.5 emissions scenarios, the global population exposed to the 1:100 year storm event reaches a maximum of 106.5 million in 2100 under the high ice melt relative sea-level projection. Although the global-mean temperature continues to rise, exposure begins to stabilise towards the end of the century under the low and medium ice melt projections for RCP 4.5 and 2.6; a continuous rise occurs
under the high ice melt projection for both RCP scenarios. As sea levels continue under all RCP emissions scenarios, this stabilisation reflects the SSP2 projected populations which decline both globally and for individual countries toward the end of the century.

Table 1. Exposure totals for all port cities at the 2°C threshold (2040); all RCP scenarios

<table>
<thead>
<tr>
<th>Relative sea-level projections</th>
<th>All cities: total exposure (millions) in 2040</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year</td>
</tr>
<tr>
<td></td>
<td>2020</td>
</tr>
<tr>
<td>RCP 8.5: high ice sheet melt</td>
<td>65.51</td>
</tr>
<tr>
<td>RCP 8.5: medium ice sheet melt</td>
<td>64.37</td>
</tr>
<tr>
<td>RCP 8.5: low ice sheet melt</td>
<td>63.87</td>
</tr>
<tr>
<td>Had 4.5: high ice sheet melt</td>
<td>65.00</td>
</tr>
<tr>
<td>Had 4.5: medium ice sheet melt</td>
<td>64.46</td>
</tr>
<tr>
<td>Had 4.5: low ice sheet melt</td>
<td>64.30</td>
</tr>
<tr>
<td>RCP 2.6: high ice sheet melt</td>
<td>65.18</td>
</tr>
<tr>
<td>RCP 2.6: medium ice sheet melt</td>
<td>64.34</td>
</tr>
<tr>
<td>RCP 2.6: low ice sheet melt</td>
<td>63.91</td>
</tr>
<tr>
<td>max</td>
<td>65.51</td>
</tr>
<tr>
<td>min</td>
<td>63.87</td>
</tr>
<tr>
<td>range</td>
<td>1.63</td>
</tr>
</tbody>
</table>

The global distribution of population exposure shows a concentration in Asia for all relative sea-level projections. Comparing the highest projected relative sea levels (RCP 8.5 with high ice melt) with the lowest (RCP 2.6 with low ice melt) when the 2°C threshold is reached (2040), over 60% of the 75-78 million people exposed to the 1:100 year storm event are located in the 49 Asian ports. Australasia and Central America show the lowest exposure, due to both the number of ports considered and the population growth patterns for individual countries in these regions (the majority show a small increase to this date). This distribution pattern is maintained under all relative sea-level projections. Within Asia, China has the highest individual share of the exposure in a total of 14 ports although the combined exposure of the 10 ports on the Indian sub-continent (India, Pakistan, Bangladesh) is greater by 1-3 million. The two ports in Vietnam show relatively high exposure due to their location in the delta of the Hong (Red) River, where any increase in temperature-related sea level rise is augmented by the subsidence experienced in these environments. Asian countries (China, India, Vietnam, Bangladesh) are also among those with the highest exposure globally, being joined by the United States of America in the top 5. Collectively, these countries represent over 60% of the global exposure in 30% of the total number of ports over time and across RCP scenarios. It is notable that Central America and Australasia, despite the slow growth followed by decline in country level populations post 2050, still shows a significant percentage increase in exposure. This occurs due to continual rise in the urban population percentage associated with these regions. Individually, the port cities considered here are significantly influenced by their location with 4 of the Top 5 cities for population exposure located in deltas (see Table 2) where additional subsidence due to the nature of the delta processes and human activities occur (Ericson et al., 2006). The same cities are included in the Top 20 both over time and across relative sea-level projections although there are some slight variations in table position. These Top 20 cities also account for a large proportion of the total exposure.
Table 2. Port cities with the highest exposure to the 1:100 year storm event at the 2°C threshold (2040) across the relative sea-level projections considered (millions)

<table>
<thead>
<tr>
<th>Port city</th>
<th>Subsiding areas (D)</th>
<th>RCP 8.5 Ice sheet melt</th>
<th>RCP 4.5 Ice sheet melt</th>
<th>RCP 2.6 Ice sheet melt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>high</td>
<td>med</td>
<td>low</td>
</tr>
<tr>
<td>Mumbai (Bombay), INDIA</td>
<td></td>
<td>5.95</td>
<td>5.81</td>
<td>5.81</td>
</tr>
<tr>
<td>Kolkata (Calcutta), INDIA</td>
<td>D</td>
<td>5.32</td>
<td>5.32</td>
<td>5.32</td>
</tr>
<tr>
<td>Shanghai, CHINA</td>
<td>D</td>
<td>5.29</td>
<td>4.98</td>
<td>4.98</td>
</tr>
<tr>
<td>Guangzhou_Guangdong, CHINA</td>
<td>D</td>
<td>5.05</td>
<td>4.98</td>
<td>4.98</td>
</tr>
</tbody>
</table>

However, potentially of more importance is the largest percentage growth in exposure found in Africa where the increase in population exposure is in excess of 50% between 2015 and 2040 for even the lowest of the relative sea-level projections. Some port cities show particularly high percentage increases; under the RCP8.5 high ice melt sea-level projection, 64 port cities show an increase of over 100% in their exposure levels in 2100 and 5 have increases of over 500% (Tel Aviv (Israel), Dar-es-Salaam (Tanzania), Mogadishu (Somalia), Luanda (Angola) and Lagos (Nigeria)). The majority of these correspond with the medium sized cities (1-5 million populations) which are expected to exhibit the most rapid growth over this century, particularly in Africa (UN, 2014). Conversely, some port cities show a persistent decline in population exposure over the century and across relative sea-level projections. Sixteen ports including most of the ports in Japan, Hamburg (Germany), Porto (Portugal) and Odessa (Ukraine) form this group. Many of the ports in China also show a decline post 2050 in line with the SSP2 country populations.

European ports

There are 19 ports within Europe in the data set and, collectively, the exposed population shows the same pattern as the global exposure; under the lower RCP scenarios and ice melt projections the exposed population clearly stabilises or declines towards the end of the century, reflecting the population projections, while there is a continuous rise under RCP8.5 and all high ice melt projections despite the lower population. The lowest levels of ‘worst case’ exposure are seen in Helsinki (Finland) and Stockholm (Sweden), where the rise in sea levels associated with thermal expansion of the oceans is offset by eustatic uplift in the land surface; cities where elevation rises relatively steeply (e.g. Porto, Naples) also show low increases in exposure. The majority of the European exposure is concentrated in 2 port cities, Amsterdam and Rotterdam, which consistently have over 1 million people exposed to the 1:100 year storm event. Recognition of these levels of exposure have led to the use of substantial risk reduction measures but stabilisation of global temperature at 2°C would still have significant benefits for adaptation planning towards the latter part of the century.

4.4.4 Benefits of climate mitigation

With a potential range in sea levels of 80cm by 2100 between the sea-levels projected for RCP8.5 and RCP2.6, the reduction in population exposure by stabilising the global-mean temperature at 2°C can
only increase over the century. Any reduction in exposure becomes particularly noticeable during the latter half of this century when over 28 million globally (Table 3) are no longer living below the height of the 1:100 year storm event. The greatest benefit of mitigation in terms of population exposure can be found in Asia (almost 19 million) followed by, although a significantly lower reduction, Africa and North America.

Table 3. Maximum reduction in population exposure by 2100 achieved by stabilising global-mean temperature increase at 2°C (RCP 2.6 compared with RCP 8.5)

<table>
<thead>
<tr>
<th>Year</th>
<th>Region</th>
<th>AFRICA</th>
<th>ASIA</th>
<th>AUSTRAL-ASIA</th>
<th>C. AMERICA</th>
<th>EUROPE</th>
<th>MIDDLE EAST</th>
<th>N. AMERICA</th>
<th>S. AMERICA</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2100</td>
<td></td>
<td>4.22</td>
<td>18.94</td>
<td>0.09</td>
<td>0.07</td>
<td>0.64</td>
<td>0.31</td>
<td>3.10</td>
<td>0.80</td>
<td>28.18</td>
</tr>
</tbody>
</table>

For individual ports, those which benefit the most from climate mitigation are also found in Asia and those located largely in deltas with the notable exceptions of Lagos (Nigeria), Mumbai (India) and Miami (USA). For Lagos, the reduction in exposure is also related to the rapid rise in the urban population; with the increasing density of the city, the lowering of the 1:100 year storm surge height has a greater effect.

4.4.5 Conclusion

Coastal cities will face significant challenges in managing the significant growth in exposure that will come about from both population growth and climate change in the form of changes in sea level. The long-term nature of sea-level rise means that these cities will continue to be exposed to increased extreme sea levels over this century even if the 2°C temperature stabilisation is achieved. Given the attractions of port cities for people due to their role in local, national and international economies, failure to develop effective adaptation strategies to minimise impacts for the local population could have large national economic consequences.

European port cities with high potential exposure, driven by flooding experience and economic influences (Rotterdam, Amsterdam and Hamburg being among the busiest ports in Europe and regularly appear towards the top of the annual world port rankings), have already addressed this hazard with well-developed long-term strategies for minimising impacts. Other cities, particularly the rapidly expanding cities in Africa and Asia shown here, may not be so well prepared. For these cities, global climate mitigation can slow and limit the exacerbating effects of climate change on coastal flood risk, but does not eliminate the need for putting similar long-term adaptation measures in place. In addition, close to half of the world’s urban dwellers currently reside in relatively small settlements of less than 500,000 inhabitants (UN, 2014). This study therefore probably excludes a number of port cities which may experience significant population growth over this century (e.g. Colombo in Sri Lanka).

In conclusion, this study shows that while the 2°C threshold is to some degree irrelevant when considering the implications of changing sea levels for coastal cities, stabilisation of this temperature over the century will gradually reduce population exposure to extreme sea levels. However, with recent publications suggesting that sea levels are accelerating even more than the RCP projections (s.e. Watson et al., 2015) future exposure may be even greater than the levels suggested here and the benefits of climate mitigation even more pronounced.
References


4.5 Water-Food-Energy nexus competition for land and water under future climate change – towards sustainable land allocation strategies

4.5.1 Introduction

One of the main challenges of the 21st century is to manage natural resources so that human needs can be satisfied without harming the environment. In terms of the global water cycle this means to manage the system in such a way that enough water is available for both food and energy production, human consumption and for environmental needs. In Europe agriculture and energy are by far the largest users of water resources and the competition for water increases between food and energy production. The push for sustainable energy production increases the water demand. For example for both hydropower and biofuels water is needed. The move towards increasing biofuels also increases the competition for land between food and energy production.

Two of the largest sources of uncertainty in future water use are probably land use change and changes in water availability caused by a changing climate. Especially the expansion of irrigated areas can potentially have a large impact on future water use (Fischer et al., 2007; Heistermann, 2006). At the same time, climate change will affect water availability through changes in runoff patterns; and plant water demand through changes in evapotranspiration and elevated CO2 concentrations. Until now there are hardly any studies which look at the combined impact of land use change and climate changes on future water use. Most studies looking at the impact of climate change on future water availability and use are conducted separately from land use change analyses. Visa versa studies on future land use change usually ignore water availability. Especially for the expansion of irrigated areas it is essential to take future water availability into account.

Not all water available can be used for food production. To define how much and where (more) water is available for food and energy production it is necessary to better define and predict how much water is needed by the environment to sustain ecosystem services and maintain biodiversity. Currently often simple and static environmental flow rules are used (Arthington et al. 2006). In many large scale studies a certain percentage of annual water availability is allocated to environment. However many ecosystems do not only need a minimum amount of water they also need certain peak flows to maintain all services and diversity. In order to better define the planetary boundaries on water use it is essential to define the water needed by the environment much more explicitly both in time and space.

The case study focuses on studying how the interaction between land use change and climate change will affect future agricultural water use. To do this we integrated water availability and environmental flow requirements as a biophysical constraint in the GLOBIOM model (Havlík et al., 2014) at a monthly time-step. Water availability was simulated with the VIC and LPJml model (Gerten et al., 2004) and EFRs were calculated suing the VMF method described in detail in Pastor et al. (2013).
4.5.2 Methods

Data and model description

In this study, a combination of model outputs were assembled to feed the GLOBIOM model and project future changes in land-use patterns and, more specifically, new repartition of rainfed and irrigated areas (Figure 11.3.1). GLOBIOM is a partial equilibrium model which allocates agricultural crops and commodities with an endogenous price balance between demand and supply. It is provided with an agriculture, a bioenergy and a forest module to optimize land-use allocation (Havlík et al., 2014; Havlík et al., 2011). The baseline year is 2000 and is recursively dynamic (10 year time-step). The basic spatial unit for supply is 5 by 5 minutes of arc pixel and the demand is defined at the level of 30 world regions. In this study, the supply side was aggregated to the LUID spatial resolution of 2 by 2 deg.

Water availability was simulated by VIC and LPJml for the two degree warming period at a spatial resolution of 0.5 by 0.5 deg using the result of Work Package 6. The overall runoff was re-distributed according to the average discharge rates in each river basin and aggregated to the LUID unit.

Crop irrigation demand was computed with the EPIC model which calculates the potential yield of 18 major crops globally and also calculates the amount of water required to attain those potential crop yields (Williams et al., 1989; Liu et al., 2007). Water withdrawal from household, industries and hydropower was obtained from the WaterGAP model with the socio-economic scenario SSP2, or middle of road scenarios for the time-series 2000-2100 (Flörke et al., 2013; Kriegler et al., 2012; Hanasaki et al., 2012). Environmental flow requirements (EFRs) were calculated with the Variable Monthly Flow method (Pastor et al., 2013) and EFRs represent between 30 to 60% of the mean monthly water availability.
GLOBIOM model was adjusted from an annual to a monthly water balance accounting in order to reflect the seasonality of water availability and demand, an essential factor in water management that is often neglected in global water assessments. The irrigated area maps of LPJml and GLOBIOM models were matching at 85% (Figure 11.3.2).

Monthly water withdrawal was obtained by using a coefficient of seasonal irrigation (CSI) calculated with the LPJml model at the spatial resolution of 0.5 by 0.5 deg. at a monthly time-step. The GLOBIOM model was run with a 10 year recursive time-step.

**Scenarios analysed**

The simulations included a combination of scenarios based on: biophysical scarcity at spatial resolution of 2 by 2 deg. (driven by water demand and supply), economical scarcity at regional level (driven by water price, determined by elasticity between supply and demand), and climate change scenario (changes in water availability following RCP 2.6). EFRs were set with 2 scenarios: one with a high constraint and one with a low constraint. Both EFR scenarios used the VMF method, but the low constraint scenario used 100% of monthly water availability minus EFRs while, the high constraint (EFR - wetlands) used 70% of water availability for maintenance of soil moisture recycling and wetlands minus EFRs (Gerten et al., 2013). The list of scenarios is as described below:

1. **IRRI_BIOPH_2000**: Baseline scenario at year 2000 with current biophysical restrictions at 2*2° grid scale.
2. **IRRI_BIOPH_ANTRO**: Scenario including water demand in 2050 with biophysical restriction 2*2° grid scale.
3. **IRRI_BIOPH_ANTROCLIM**: Scenario including water demand and climate change in 2050 with biophysical restriction at 2*2° grid scale.
4. **IRRI_BIOPH_ANTROCLIM_WET**: Scenario including water demand, climate change and high restriction on EFRs in 2050 with biophysical restriction at 2*2° grid scale.
6. **IRRI_ECON_ANTRO**: Scenario including water demand in 2050 with economical and biophysical restrictions at regional level.
7. **IRRI_ECON_ANTROCLIM**: Scenario including water demand and climate change in 2050 with economical and biophysical restrictions at regional level.
8. **IRRI_ECONBIOPH_ANTRO**: Scenario including water demand in 2050 with economical restriction at regional level and biophysical restriction at 2 by 2 deg.
9. **IRRI_ECONBIOPH_ANTROCLIM**: Scenario including water demand and climate change in 2050 with economical restriction at regional level and biophysical restriction at 2 by 2 deg.
10. **IRRI_ECONBIOPH_ANTROCLIM_WET**: Scenario including water demand, climate change and high restrictions on EFRs in 2050 with economical restriction at regional level and biophysical restriction at 2 by 2 deg.

For each of the scenarios the water stress indicator (WSI) was estimated using the following equation:
WSI = \frac{\text{Water demand}}{\text{Water Availability}} (1)

with water demand representing the total annual water withdrawals from irrigation and other sectors and water availability representing the sum of runoff minus environmental flow requirements.

### 4.5.3 Results

Climate change increases water availability in Northern Europe but decreases water availability in Southern Europe. Especially in summer water availability is reducing in Southern Europe. This is also the time of year when irrigated water demands are higher. Due to increased future water demand the water stress indicator will increase in the future in both Southern and Northern Europe. However in Northern Europe the water demand is still much lower than the water availability and less than 10% of the available water is used. In southern Europe this is completely different. Even at annual scale the Water Scarcity Index is increasing in the future due to a combination of climate change and increased future water demands.

Water scarcity index for the Baseline situation (2000) and six future scenarios for Northern and Southern Europe. The numbers in parentheses indicate the number of the scenario as described in the methods section. CC indicates climate change and EFR environmental Flow requirements.

Future changes in land use have an important impact on future water demand. Especially expansion or reduction in irrigated land have a large impact on future water use. If there are no or limited environmental restrictions on future water use for the crop production reduction due to lower
rainfall in southern Europe could be compensated with increases in irrigated land. To analyse this we simulated future irrigated land expansion with high and low environmental flow requirements.

Future expansion or reduction of irrigated area under two degree warming in 2050 for high and low environmental flow requirements. Countries which are not shown have a change in irrigated area of less than two percent.

Result show that in many European countries the irrigated area is reducing due to lower water availability in summer. This is especially the case under high environmental flow requirements. For Portugal and Spain the irrigated area could increase if limited water is used for the environment. Under the high environmental flow restriction scenario the area under irrigation reduces for both countries of the Iberian Peninsula.

4.5.4 Conclusions

This case study integrates climate change, changes in water availability and water demand at monthly-time step such as international trade and socio-economic adaptation by 2050. This new integration allows for a more complete assessment of future repartition of irrigated and rainfed land. The innovation of including water availability, environmental flow requirements and water withdrawals at monthly time-step improves large-scale land use assessments. Our study shows that future reductions in crop production in Southern Europe cannot be compensated for by the expansion irrigation land due to due to biophysical and environmental limitations. Those limitations come from different drivers: climate change, high restriction on EFRs and increase in water demand from households, industries and hydropower. Different previous studies have suggested that
irrigation could be an adaptation strategy to limited negative impacts of climate change on agricultural production. Previous large scale water and land use studies ignored environmental flow requirements and tended to allocate too much water to irrigation. However our results show that at country scale expansion of irrigation is not a proper adaptation strategy in Southern Europe. In addition, the results show that further expansion of irrigation in southern Europe is likely to come at the expense of other sectors and/or the environment so from a sustainable development point of view further expansion of irrigation is not a good strategy.
5 Developing guidance and stimulate consistent use of climate change data in climate change impact, vulnerability and adaptation assessments

Due to improving knowledge of the climate system, continuous model development and updated scenarios new data on climate change are continuously becoming available. This data is used in very different ways in the various impact, vulnerability and adaptation assessments. For example different bias correction methods are used, some impact studies only use the outcome of one Climate model were others use more than 20. This task brought together the lessons learned from IMPACT2C and initiated the development of a consistent manner on how to use outputs from GCMs/ESM and RCMs for climate change impact, vulnerability and adaptation assessments. It developed initial guidelines and recommendations on how many RCM and or GCM should be used, if and which bias correction could be used, how to deal with different emission scenarios and how to present climate change impact in a consistent and objective way.

5.1 Introduction

Due to improving knowledge of the climate system, continuous model development and updated scenarios new data on climate change are continuously becoming available. This data is used in very different ways in the various impact, vulnerability and adaptation assessments. For example different bias correction methods are used, some impact studies only use the outcome of one Climate model were others use more than 20. Also comparison with control periods to estimate the impacts are done in very different ways. This report review the existing knowledge on using climate change data for impact and adaptation studies and distils the lessons learned from IMPACT2C other EU projects. The aim of this report is to initiate a more consistent use of outputs from GCMs/ESM and RCMs for climate change impact, vulnerability and adaptation assessments.

From the start of the impact2c project 4 years ago until now several guidance documents have been developed. To acknowledge this we start this document with a review of the existing guidance. Then we review the methods developed on selecting climate models within Impact2C and other projects, advantages and problems with bias corrections the use of multi model approaches and the RCP/SSP framework. We end the document with a discussion on Good practices, lesson learnt, recommendation and knowledge gaps.

The aim of this document is not to be a static new guideline but to make it a living document.

5.2 Review of Existing Guidance

A large variety of guidance tools have been established for the use of climate change data and information in support to mitigation and adaptation. Here, we compile selected existing generic guidance documents and web resources, on which we can build our further guidance on the use of climate change data in climate change impact, vulnerability and adaptation assessments, including good practise and lessons learnt from Impact2C.

5.2.1 Using and interpreting multi model ensemble climate projections

Climate models are used to study the impact of anthropogenic emissions on the climate system and project potential future climate evolutions over the coming century and beyond. The climate evolution over the 21st century will depend on external forcing and internal climate variability. Multi-
model ensemble experiments are a common method to assess the ranges of potential future climate evolutions, including modelling uncertainties (e.g. Tebaldi et al., 2007; Stott and Forest, 2007). The interpretation of results from ensemble climate experiments pose numerous challenges on climate change assessments (e.g. Knutti et al., 2010a, Tebaldi et al., 2011; Knutti and Sedlacek, 2013).

Climate change projections based on multi-model ensemble need a coordinated experiment setup in order to be inter-comparable. Since 1990, the first model inter-comparison projects (MIPs) opened a new era in climate modelling. They provide a standard experiment protocol and a world-wide community-based infrastructure in support of model simulations, evaluation, inter-comparison, documentation and data access. There are coupled model inter-comparison projects (CMIP) initiated by the World Climate Research Program (WCRP) and supported by the program for climate model diagnosis and inter-comparison (PCMDI).


In phase 3 of CMIP (Meehl et al., 2007), a set of coordinated climate projections with coupled atmosphere-ocean general circulation models (AOGCMs) had been established, based on emission scenarios from SRES. Within CMIPS (Taylor et al., 2012), a new set of coordinated experiments of AOGCMs and Earth System Models (ESMs) has been established, based on the new RCPs. The data are available via the earth system grid federation (ESGF) which can be accessed from several nodes world-wide, e.g. http://esgf-data.dkrz.de/esgf-web-fe/. The ESGF user guide contains instructions on how to use the ESGF system in order to find, download, visualize and analyse data across the federation:


Knutti et al. (2010b) provide a good practice guidance paper on assessing and combining multi model climate projections:

IPCC: Good Practice Guidance Paper on Assessing and Combining Multi Model Climate Projections


Mastrandrea et al. (2010) give a guidance note on consistent treatment of uncertainties in support to a common approach across the IPCC AR5 working groups:

IPCC AR5 guidance note on consistent treatment of uncertainties: A common approach across the working groups

The World Meteorological Organization (WMO) provides a general guide to best practices in climatology, including references to other technical guidance and information sources:

WMO Guide to Climatological Practices


5.2.2 Regional Downscaling

Global climate projections can be downscaled with dynamical models, i.e. Regional Climate Models (RCMs), or with statistical methods, in order to relate large-scale climate changes to regional and local impacts. Dynamical and statistical downscaling methods are used to bridge the spatial and temporal resolution gaps between global climate models and impact models.

Mearns et al. (2003) provide guidelines for the use of climate projections from regional climate model experiments:

Guidelines for Use of Climate Scenarios Developed from Regional Climate Model Experiments

Mearns, L. O., F. Giorgi, P. Whetton, D. Pabon, M. Hulme, M. Lal, 2003: Guidelines for Use of Climate Scenarios Developed from Regional Climate Model Experiments, Final Version - 10/30/03, DDC of IPCC TGCIA


Wilby et al. (2004) provide guidelines for the use of climate information from statistical downscaling methods:

Guidelines for Use of Climate Scenarios Developed from Statistical Downscaling Methods


In order to represent the range of simulated large-scale climate changes in the regional projections, all or at least a representative set of simulations from the global model ensemble needs to be downscaled.

Within the world wide coordinated downscaling experiments CORDEX, initiative by the World Climate Research Program WCRP, a sample of the global climate simulations of CMIP5 are downscaled for most continental regions of the globe (Giorgi et al., 2009). The CORDEX datasets are available via the ESGF, e.g. http://esgf-data.dkrz.de/esgf-web-fe/. Some datasets are already accessible, others will follow successively. General information about experiment setups, data access
and publications are provided by the WCRP CORDEX website: http://www.cordex.org/. The CORDEX model domains are specified in: http://wcrp-cordex.ipsl.jussieu.fr/images/pdf/cordex_regions.pdf.

The technical aspects of the CORDEX ESGF archive files and data formats are specified in Christensen et al. (2014):

CORDEX Archive Design


Within the EURO-CORDEX initiative, a unique set of high resolution climate change simulations for Europe on 0.11° horizontal resolution has been established (Jacob et al. 2014). Around 26 dynamical downscaling experiments have been conducted, mainly for the scenarios RCP4.5 and RCP8.5 and some selected for RCP2.6. The status of the simulations can be tracked on ↑http://www.euro-cordex.net/EURO-CORDEX-Simulations.1868.0.html. Datasets are also available via the ESGF: http://esgf-data.dkrz.de/esgf-web-fe.

A guidance on the use of climate projections data from EURO-CORDEX is currently developed:

Guidance for EURO-CORDEX climate projections data use is currently developed by the EURO-CORDEX Community will be provided e.g. via:

http://www.euro-cordex.net

5.2.3 Bias Correction

Modelling uncertainties can lead to biases in the simulated compared to the observed climate. For some impact models or other applications these biases mean difficulties if the impact or application is sensitive to non-linearities in the system such as absolute threshold effects. Statistical methods have been developed to adjust model biases to observed climate data sets (e.g. Piani et al., 2010, 2012). Major disadvantages are that bias adjustment may remove physical consistency between climate variables and may impact the simulated climate change signal. In the frame of EURO-CORDEX, this has been analysed by Themeßl et al. (2012) and Wilcke et al. (2013).

Evans and Argüeso (2014) provide guidance on the use of bias corrected data in the frame of the Regional Climate Modelling Project NARCliM:

Guidance on the use of bias corrected data.


5.2.4 Guidance specific for climate impact and adaptation assessment

In 1997, the Task Group on Data and Scenario Support for Impact and Climate Assessment (TGICA) had been established by the IPCC. Its role is to facilitate the use of climate data and information to enable climate change research and sharing information across the three IPCC working groups. Part
of this initiative is the development of guidelines on the interpretation and application of scenario data in impact and adaptation assessment (IPCC-TGICA, 2007):

General Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment


There is an increasing use of climate impact model ensembles for making future climate impact assessments. A number of model inter-comparison programmes (MIPs) with coordinated impact model ensemble experiments have been established, including the Water MIP (WaterMIP, Haddeland et al., 2011), the Agricultural MIP (AgMIP, Rosenzweig et al., 2013), and the Inter-Sectoral Impacts MIP (ISI-MIP, Warszawski et al., 2013). Falloon et al. (2014) highlight challenges in using ensembles to assess uncertainties in future climate impacts and identify priorities for making further progress. Challinor et al. (2014) explore the implications for the design and coordination of future studies.

The Inter-Sectoral Impact Model Intercomparison Project ISI-MIP (Warszawski et al., 2013) is a community-driven modelling effort bringing together impact models across sectors and scales to create consistent and comprehensive projections of the impacts at different levels of global warming. The global impact assessments are based on the Representative Concentration Pathways (RCPs) and Shared Socio-Economic Pathways (SSPs) scenarios. Coordinated by a team at the Potsdam Institute for Climate impact research, with support from the International Institute for Applied Systems Analysis IIASA and backing from the IPCC Working Groups II and III, the ISI-MIP Fast Track provided outcomes for the IPCC’s Fifth Assessment Report (AR5).

With ISI-MIP2 launched in May 2013, the aim is to establish a longer-term coordinated impact assessment effort driven by the entire impact community. The ISI-MIP2 modelling protocol was developed as a collaboration between the ISI-MIP coordination team and the sectoral coordinators and is available for download:

Inter-Sectoral Impact Model Intercomparison Project ISI-MIP Phase 2:

ISI-MIP2 Simulation Protocol


The Agricultural Model Intercomparison and Improvement Project (AgMIP) is a major international effort linking the climate, crop, and economic modeling communities to produce improved crop and economic models and the next generation of climate impact projections for the agricultural sector (Rosenzweig et al., 2013). The AgMIP team developed a handbook with guidelines for regional integrated assessments of agricultural systems under future climate, bio-physical and socio-economic conditions:

AgMIP Guide for Regional Integrated Assessments


Harris et al. (2014) provide a nice overview on the use and interpretation of climate projections for ecological studies:

Climate projections for ecologists


The “Compendium on methods and tools to evaluate impacts of, and vulnerability and adaptation to, climate change”, was established in 1999 by the United Nations Framework Convention on Climate Change UNFCCC, adopted by the Nairobi Work Programme. It assists users in selecting methodologies for assessments of impacts, vulnerability and adaptation to climate change.

Compendium on Methods and Tools to Evaluate Impacts of, and Vulnerability and Adaptation to, Climate Change

UNFCCC (2008) Compendium on Methods and Tools to Evaluate Impacts of, and Vulnerability and Adaptation to, Climate Change. with the services of: Pinto E, Kay RC and Travers A, Stratus Consulting Inc.

http://unfccc.int/files/adaptation/nairobi_workprogramme/compendium_on_methods_tools/application/pdf/20080307_compendium_m_t_complete.pdf

The online version is available here:


A compendium on statistical methods for climate data analyses applied in projects and institutions dealing with climate change impact and adaptation has been established by the Climate Service Center Germany:

Statistical methods for the analysis of simulated and observed climate data, applied in projects and institutions dealing with climate change impact and adaptation

Hennemuth, B., Bender, S., Bülow, K., Dreier, N., Keup-Thiel, E., Krüger, O., Mudersbach, C., Radermacher, C., Schoetter, R. (2013): Statistical methods for the analysis of simulated and observed climate data, applied in projects and institutions dealing with climate change impact and adaptation. CSC Report 13, Climate Service Center, Germany

In the EU FP7 project COMPLEX, a methodological framework had been developed for quantifying the uncertainty in climate projections by means of multi-model ensembles from GCM, RCM and impact models, described in the COMPLEX D2.5 report:

Quantifying uncertainty in climate projections using multimodel multimember ensembles from GCMs, RCMs and impact models

Renard B (2014) Quantifying uncertainty in climate projections using multimodel multimember ensembles. Report D2.5, EU FP7 COMPLEX


In the frame of the EU FP7 project ECLISE - Enabling CLimate Information Services for Europe, a nice user guide on dealing with uncertainties in climate change projection and the relevance for decision making in adaptation had been developed by Pelt and Ludwig:

ECLISE user guide on uncertainties: Dealing with uncertainties in climate scenarios for adaptation

Pelt S and Ludwig F: Dealing with uncertainties in climate scenarios for adaptation. ECLISE user guide on uncertainties, ECLISE Report D1.2

http://www.eclise-project.eu/content/mm_files/do_824/D%201.2-User%20guide%20on%20uncertainties.pdf

5.2.5 Selected Climate Information Portals

Here, we present selected climate information portals which provide services on the use of climate information, including numerous guidance tools.

WMO Climate Services

Presents information gathered, managed and analysed under the coordination of the World Meteorological Organisation WMO by the National Meteorological and Hydrological Services, in collaboration with other regional and international organizations and programmes.

https://www.wmo.int/pages/themes/climate/index_en.php

KNMI climate explorer climate change atlas

Easy access to monthly climate data from CMIP5 by the KNMI climate explorer climate change atlas:

http://climexp.knmi.nl/plot_atlas_form.py

Guide on the use of the KNMI climate explorer climate change atlas is currently established at the Climate Service Center by Paul Bowyer, will be available soon.

NCAR/UCAR Climate Data Guide

Search and access 176 data sets covering the Atmosphere, Ocean, Land and more. Explore climate indices, reanalyses and satellite data and understand their application to climate model metrics. This data portal combines data discovery, metadata, figures and expertise on the strengths, limitations and applications of climate data.
### IS-ENES climate4impact portal

Guidance on how to use climate scenarios, documentation on the climate system, frequently asked questions and examples in several impact and adaptation themes are presented and described, along with the steps required to go from GCM data to impact model input data.

http://climate4impact.eu/impactportal/general/index.jsp

### Climate Adapt European Climate Adaptation Platform

The European Climate Adaptation Platform (Climate-ADAPT) aims to support Europe in adapting to climate change. It is an initiative of the European Commission and helps users to access and share information on: Expected climate change in Europe. Current and future vulnerability of regions and sectors. National and transnational adaptation strategies. Adaptation case studies and potential adaptation options. Tools that support adaptation planning.

http://climate-adapt.eea.europa.eu

Among others, Climate-ADAPT provides uncertainty guidance. This guidance aims to help decision makers in understanding the sources of uncertainty in climate information that are most relevant for adaptation planning. It also provides suggestions for dealing with uncertainty in adaptation planning and for the communication of uncertainty.


### The CLIPC project is currently developing a pre-operational information portal for the Copernicus Climate Change Service (C3S)

CLIPC will provide access to climate datasets, and software and information to assess indicators for climate impact.

http://www.clipc.eu/home

### Copernicus Climate Change Service (C3S)

The Copernicus Climate Change Service (C3S) will combine observations of the climate system with the latest science to develop authoritative, quality-assured information about the past, current and future states of the climate in Europe and worldwide.

http://www.copernicus-climate.eu

### 5.2.6 Glossaries from IPCC AR5

A fundamental basis for integrated assessments in climate research is a common understanding of terms used by the involved disciplines. Here, we list the glossaries which had been established by the three Working Groups in the 5th IPCC Assessment Report.
5.3 Uncertainty and Robustness

Several guidance documents and many paper and reports have been written about climate change and uncertainty. There is no aim to repeat here what is written in other documents. Here we focus on how the use and selection of climate models and emission scenarios affects uncertainty and can facilitate robust decision making.

In general, uncertainty in climate change information originates from two main sources. The first main source natural climate variability which inherent in the climate system. In some years or seasons rainfall or temperatures is much higher or lower than the long term average. So even if there is a drying or warming trend there can still be cold or wet years. The second main source of uncertainty is caused by our limited ability to model and understand the climate system. The climate system is complex and chaotic, and there is no complete understanding of how all the different components of atmosphere, oceans and land surface interact. In addition it is difficult to translate the climate system in mathematical equations that interact in such a way that the “real” climate is simulated (Climate adapt, Van Pelt and Ludwig 2014).

Many different types of uncertainty have been described in the literature. Here we distinguish between three different types of uncertainty as described in Dassia and Hulme (2004) and Van Pelt.

When selecting climate model runs to be used for impact, vulnerability or adaptation assessment it is import to acknowledge the different sources of uncertainty (Figure 5.1). Which uncertainty is more important or prominent depends also on the timescale (see figure 5.2). At short time scale especially natural variability is important. After 20 to 30 years model uncertainty becomes more important after 30 to 50 years also the scenario uncertainty becomes important.

In addition to timescale, it is important to acknowledge what the aim is of the assessment in which the climate model are used. If the goal is to inform about mitigation policies it makes sense to include different emission scenarios. If the main aim is to inform about adaptation measures, strategies or policies at relatively short timescales it might not be necessary to use different emission scenarios.

![Figure 5.1](image)

**Figure 5.1** Different types of uncertainty in climate models and scenarios. The scenario uncertainty can be assessed by comparing the results of different emission scenarios. Model uncertainty stems from the different types of climate models that exist. Natural variability uncertainty can be assessed by using ‘initial condition ensembles’, which are created by running one model multiple times with different initial states of the atmosphere. (Source: Van Pelt and Ludwig 2014)

**From uncertainty to Robustness**

While assessing and acknowledging uncertainty in climate change impact, vulnerability and adaptation assessment is important, it hardly ever results in improve decision making. In general policy and decision makers do not like uncertainty and too much focus on uncertainty can often slow down the decision making process. This does not mean that uncertainty from climate models should be eliminated but it is probably necessary to change the focus from uncertainty to robust decision making. The aim of analysing and showing the uncertainty is to make scientist, policy maker, businesses and individuals aware of the possible range of future climate and it potentials impacts so
they can include this in their adaptation and mitigation decisions. Therefore the selection of climate models should not aim at addressing all uncertainty possible but should focus on robust decision making. To be robust future strategies should function well under a range of future scenarios. So climate models and scenarios should be selected in such a way that they can be used to assess robustness. So the climate models selected should cover the range of future for which the decisions are vulnerable. In this approach not the outcome of the climate models is leading in the selection process but the decision to be made or strategy to be developed is leading.

**Recommendation:**

In selecting the climate and impacts models not representing all uncertainty should be leading the decision or strategy making process should be leading in deciding which climate model and scenarios are used. Uncertainty assessment are necessary to guarantee the there is no over, under of wrong investments and to avoid “unpleasant surprises”.

![Figure 5.2](image)

**Figure 5.2.** The relative importance of each source of uncertainty in decadal mean surface air temperature (Hawkens and Sutton)

### 5.4 Selection of Climate Models

When large ensembles of climate change data are available, it is often necessary to select a limited number of representative climate models to be used for impact studies (Whetton et al, 2012). Desirable properties of such a selected sub-ensemble would be:
To ensure good model performance in order to avoid models with known severe deficiencies.

To capture the climate model uncertainty spread for parameters of interest properly.

To provide climate models which are mutually as independent as possible to ensure maximum diversity.

In practice, also other more practical reasons are used to select a model, for example the availability of output data for the needed variable and/or spatial and temporal resolution.

In practice, models are often selected based on their historical performance. In this approach the historical climate of the models is compared to observed climate characteristics as mean values, variability and extremes. This selection method assumes that models with a good performance on simulating the historical climate will give the most reliable future climate projection (Pitman and Perkins, Smith and Chandler 2010). However still no generally accepted method for the skill of climate models is available and the skill often depends on the variable and region assessed. In addition correlation between past performance and future climate change signals are known to be very weak (Knutti, 2010a), which means that there is no clear indication that the best performing models in the past are most realistic with regard to climate change signal. Therefore it seems reasonable that model performance in the past should rather be used to detect and remove few severely unrealistic models which cannot be trusted in their future projections for some clearly argued reasons, but not to select a few “best performing” models, since there is no indication that they are more realistic in their future projections than other reasonably performing models.

This leads to a further model selection criterion, namely the conservation of statistical properties of the climate change signals -the sub-sample of the selected simulations should properly represent uncertainty. In recent years, methods have been published based on this idea, partly combined with some pre-selection based on model performance (e.g. McSweeney et al, 2012; Bishop and Abramowitz, 2012). The IPCC guidelines for climate scenarios (IPCC-TGIC, 2007) suggests to select models based on model performance in the past and their representativeness (picking simulations from the high and low end of the range of climate change signals of temperature and precipitation) to obtain a representative sub-sample. Such a selection of GCMs has been applied by e.g. Murdock and Spittlehouse (2011) with focus on the region of British Columbia, by analyzing the models based on the spread of change in temperature and precipitation.

The good practice guide on assessing multi model climate projections (Knutti et al, 2010b) gives some more recent recommendations for model selection, also addressing the issue of model dependence. They argue that agreement between models may arise due to the fact that models use similar simplifications and may feature similar errors and as a result. Therefore models do not represent independent information and should be down-weighted in order to avoid biases in the statistical analysis of the ensemble. In a recent study Evans et al (2013) presented a selection method taking into account model performance and independence in climate change signals. This method selects models which are most independent from the rest of the entire model ensemble.

The methods discussed so far focused only on a couple of variables which are important for impact studies (mainly temperature and precipitation change). For bigger projects, as in IMPACT2C or ISI-MIP, often several impact models of completely different nature need consistent input from climate models. In the case of IMPACT2C we identified 8 key variables (Tmax, Tmin, Precipitation, relative humidity, global radiation, wind speed, surface upward sensible heat flux) being of major interest.
Furthermore, the impact models were supposed to be analysed in several regions across Europe. This made the model selection process a (highly) multivariate problem.

Within the IMPACT2C project a method was developed to allow climate model selection for an arbitrary amount of climate parameters and indicators which can be freely defined according to the aim of the study (Mendlik and Gobiet, submitted). Those changes of parameters can also be regarded at several locations and different seasons simultaneously. The method reduces this multidimensional and highly-correlated space of climate change signals to a set of independent patterns of climate change by merging together similarly behaving parameters. Based on these spatio-temporal climate change signal patterns, the method detects model similarities using clustering techniques, which ensures that the selected models are as independent from each other as possible. The authors reason that if models project similar multivariate patterns of climate change, the underlying processes will be implemented similarly, therefore the models being more dependent. Out of each such group of dependent simulations, one representative climate model is selected in such a way that the uncertainty spread of the entire multi-model ensemble is captured.

Recommendations:

In every climate impact research it is important to select at least a couple of climate models, to represent the uncertainty spread of the entire multi-model ensemble to capture a broad range of possible climate impacts. If the focus of your study is in a compact region and only few meteorological parameters are needed to force your impact model, then simple methods as suggested in the IPCC guidelines for climate scenarios (IPCC-TGIC, 2007) might suffice. For example, if your primary driving data were temperature and precipitation, then depicting the models in a 2D scatterplot (temperature change vs. precipitation change) will be helpful.

In order to have physically meaningful input to the impact model, prior exclusion of unrealistic climate models is recommended. The easiest way is to screen the literature on performance of the members within the desired ensemble.

To help deciding on which model to select, it is helpful to perform some sort of clustering (e.g. hierarchical clustering or some divisive clustering) based on model similarity, to obtain a more representative sample (Whetton et al, 2012).

If the input for your impact model is more complex, being either dependent on a multitude of meteorological parameters, or the research is performed on several distinct locations, then such simple methods might not suffice. In that case, dimension reduction of the meteorological parameters will ease the analysis. This can be done for example with a Principal Component Analysis. After such a dimension reduction, the same type of analysis can be applied as discussed above (Mendlik and Gobiet, submitted).

5.5 Time Slice versus Threshold approach

Especially with Impact studies there are two separate approaches used to estimate climate change impacts on different indicators and sectors. The first approach is based on time slices were usually 20 or 30 years in the future is compared with a historic period. The second approach is based on a threshold usually temperature. For example a world under 2 degree warming is compared to a world without global warming (or a historic period).

Time slice approach
In this approach the climate change impacts are analysed by comparing a set future period with historical period. In most studies either a period at mid-century around 2050 and or a period at the end of century are selected. This is then compared to a historic period usually of the same time length. For example the agricultural production for the time period 2040-2070 is compared to agricultural production for the period 1971-2000. In this approach different SRES scenarios or RCPs can be easily compared. Usually for a low emission scenarios the differences between future and current period are smaller than for high emission scenarios.

**Threshold approach**

In this approach impacts of climate change are analysed based on particular threshold. In almost all cases a temperature threshold is used. For example what are the impacts of climate under 2, 3 or 4 degree warming. This approach has become more popular in recognition of the need to inform policy objectives to limit global warming to two degree warming. The typical approach is to assess the year at which two degree global average warming is reached. The climate change impact are then analysed for the 15 years before and the 15 year after the two degree warming are analysed. The 30 year climate model output is than used to analyse the climate change impact at two degree warming.

The standard practice for considering impacts, e.g. in previous European projects, has been to use one time period when the average of various climate models hit the threshold i.e. 2°C. This approach is used because it aligns to a specific emission trajectory, that is also time dependent, i.e. a future emission pathway is considering which has a 50% chance of hitting the target, and the results reported for the period when the threshold is exceed. This can provide a policy maker with key information, i.e. it provides them with a guide to the likely impacts (or avoided impacts) of limiting warming to 2°C, but also communicates the uncertainty from the climate models in relation to climate sensitivity, i.e. it is still possible to exceed the target, if climate sensitivity turns out to be higher

In IMPACT2C a different approach was used. This took account of the fact that each global climate model has a different climate sensitivity, and hits 2°C at a different time, thus different time periods were used from different climate models. (ADD TABLE time periods two degree warming). So the period which is analysed depends on both the emissions scenarios and the climate model. This provides a new and unique approach to the threshold analysis.

The advantage of the IMPACT2C threshold approach is that it reduces the uncertainty from climate model related to climate sensitivity, although it does this by omitting one key variable. The threshold approach facilitates the communication of biophysical impacts because they are less dependent on the emission scenarios used. This is extremely useful in allowing comparison of how the models simulate other variables (e.g. associated with precipitation) for a defined amount of warming.

The disadvantage of this approach is, however, the link with socio-economics, i.e. most impact studies combine future climate and future socio-economics to assess future impacts. This recognises that in the future not only the climate will change but there also changes in population, land use and economic development, and these future values are time specific (i.e. the population of 2040 will be very different to 2100). This means that impacts will differ for alternative future years, even if the change in the climate signal is the same. By using different time periods, as in IMPACT2C, it is no longer possible to compare impacts directly, because the socio-economic influence in different years will change the size of impacts. The use of different time periods also does not work for adaptation, which is also time dependent, and actually needs to consider uncertainty to decide on the most appropriate response.
For these reasons, while the climate and biophysical analysis was undertaken using the period when the individual global model hit 2°C, for the analysis of impacts in the IMPACT2C project (i.e. for flood damages, coastal impacts, agriculture trade) one single fixed time period for each RCP was used (e.g. 2036-2065 for RCP 4.5), to allow consistent socio-economic data and analysis, and to provide information that aligned to specific emission trajectories and time periods, and for informing adaptation.

**Recommendations:**

Climate change impacts are analysed to inform both mitigation and adaptation policies. It addresses mitigation policies by showing which impacts can be avoided if emissions are reduced. It informs adaptation policies by showing for which changes adaptation is necessary to reduce the vulnerability to future climate change impacts, within a framework of decision making under uncertainty. From a scientific perspective, it is extremely interesting to use the approach adopted in IMPACT2C, which assesses the time period when the individual (global) model hits a threshold. However, for informing defined mitigation policy, where emission trajectories are fixed in time, it is preferable to keep a consistent single period, to provide information to policy makers on what the impacts (or avoided impacts) of reducing emissions to try to achieve this target might be, as well as the uncertainty associated with climate sensitivity. This is particularly important where socio-economic drivers influence future impacts, as these are time specific. Similarly, if the main aim is to inform adaptation policies or measures, then specific time periods must be used, in recognition that adaptation involves time-specific decisions that consider socio-economic aspects, and need to consider uncertainty. If the main aim is to develop adaptation measures under a 2°C warming, the threshold approach can also be useful for some adaptation planning.

5.6 Multi-Model ensemble approach and the selection of impacts models

To inform adaptation planning and decision making, policymakers need information relating to potential climate impacts in a range of different economic sectors. In order for this information to be actionable, it needs to be salient, credible, and legitimate; credibility, in this sense relates to the “...scientific adequacy of the technical evidence and arguments” [1]. The sources of uncertainty in climate modelling stem chiefly from natural variability, model response, and scenario uncertainty (see also chapter on uncertainty). These sources of uncertainty are of course of equal importance in designing impact model analyses. In this section, we will focus on the issue of model response, as the issues relating to natural variability and scenario uncertainty have already broadly been dealt with i.e. the same arguments apply. If we are to deliver credible information, clearly we need to be able to quantify uncertainty about the model response. What are our options for doing so? We can run simulations which explore a large range of variation in the model input parameters for a given impact model, and/or we can construct a multi-model ensemble which quantifies some of the structural uncertainty that originates from the way in which different models are structured e.g. different processes, and routines. Having quantified some of the uncertainty in the model response (as represented by the model spread), our task is then to be able to convey this information to policymakers in a clear, understandable, but scientifically rigorous way, ensuring that the uncertainty in the information is carefully represented. This requires the application of careful model evaluation and visualisation of results.

5.6.1 Design of experiments for climate impact modelling

IMPACT2C, faced with the question of quantifying projected impacts under 2°C warming for a range of different sectors, took the approach, wherever possible, of using multiple impact models in each sector, to generate a multi-model ensemble (MME) of climate and impact models. Where multiple
impact models were not available, simulations were at least run with multiple GCM/RCM combinations. The exact constitution of the different climate impact model ensembles is summarised in table 1.

The approach taken in IMPACT2C is similar to that of the ISI-MIP project [2], in that, where possible a consistent and coherent approach was taken to the design and implementation of the modelling experiments, thus ensuring inter-comparability between sectors, which enables a clearer understanding of the sources of uncertainty across sectors.

While adopting a MME approach permits a quantification of the uncertainty arising from structural differences between models, it does not permit a quantification of uncertainty arising from unknown or incomplete understanding of process parameterisation within the impact models.

When designing climate impact model analyses, there are a number of other issues of importance, which may have implications for the way in which the results may be analysed and presented to policymakers. These include:

Model complexity versus accuracy for a particular problem. The suitability of a given impact model in terms of the process representation and accuracy for application in a given area, e.g. whether a given model works particularly well in temperate, but less well in tropical environments.

In the context of risk management and adaptation planning, consideration should be given to being able to quantify the relative contribution to the uncertainty represented by the model spread, to different sources, e.g. the GCM/RCM pair, the impact model, any land use change assumptions, and any relevant socio-economic factors [3]. This has been done in IMPACT2C by running simulations with fixed socio-economics and fixed climate i.e. variation in one source of uncertainty is explored while others are held constant, thus enabling the isolation of the different components.

Whether or not potential adaptation measures can or should be simulated in the impact model. Clearly, if our aim is to inform on potential adaptation responses then this is a desirable feature in modelling studies.

<table>
<thead>
<tr>
<th>Impact model sector</th>
<th>Models used in the impact ensemble</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>E-Hype, LisFlood, LPJmL, VIC, WBM</td>
</tr>
<tr>
<td>Agriculture</td>
<td>EPIC, LPJmL, DSSAT/SALUS</td>
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<tr>
<td>Ecosystems/Forestry</td>
<td>CLM4.0-CN, G4M, LPJmL</td>
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<tr>
<td>Tourism</td>
<td>TCI</td>
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<tr>
<td>Coastal</td>
<td>DIVA</td>
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<tr>
<td>Health (air quality)</td>
<td>CHIMERE, EMEP-MSC-W, MATCH, MOCAGE</td>
</tr>
</tbody>
</table>
5.6.2 Model evaluation, quality assessment and visualisation

Having carried out a modelling experiment, the way in which the model results are evaluated, analysed and visualised is of key importance in learning about the uncertainty, and helping to guide adaptation strategies, or research questions related to model performance, and model differences.

• **How to evaluate models?** Ideally, the suitability of a given model for a given problem should be known *a priori*. This means that there are existing studies which report on the validation of a given model in respect to past performance, where observations are used to assess model performance. However, it also desirable to be able to test the performance of a given model under the conditions of the current experiment. This testing can be carried out for example, by running the impact models with reanalysis data, and comparing to observations. It is important also to state that the performance of a model in hindcast studies, does not necessarily mean that it will perform well in the future. Clearly, the main benefit of using a MME, is being able to inter-compare models, and to summarise the differences, and possible try to understand the reasons for differences. In IMPACT2C, the water sector provided some analysis of the performance of the different models with respect to the past. They did so using different variables and measures. Figure 5.3 shows the results of the MME when run with E-OBS observations over the period 1979-2000, and assessed in relation to annual mean discharge for a number of different rivers. These results show a large range in the bias of the different models, from -117 to +23 (mm/yr). This is however, only one way in which to assess the relative model performance. If a different measure is used, a different picture may be established as to the inter-model performance. When the interannual variation in discharge is used as the performance measure quantified using the centred RMSE metric, a different picture does indeed emerge, and this is shown in figure 5.4. Now, the difference in performance between the models is reduced considerably, as shown by the CRMSE values.

• **Can we say which model is best?** There may be a variety of reasons for wanting to use only one model in a climate risk analysis to inform an adaptation decision, however, there are good reasons for not doing so. Firstly, as figures illustrate, the answer to the question is very much dependent on the way in which the analysis is carried out. Ideally, the assessment of this question would be carried out over a range of different variables and using a number of different metrics. If it is the case that there are stable results, in the sense that one model comes out top in all criteria, then there may be a case to be made to use a particular model. For example in the hydrological assessments within impact2C. However, there may be other reasons to want to exclude a particular model, if for example it is known that some of the relevant processes are not modelled, or modelled too simplistically. Moreover, there is good evidence from a number of studies that using the multi-model mean provides the closest correspondence to observations. In addition, when thinking of informing adaptation decisions, there is much value to be obtained by considering as wide a range of uncertainty as possible, and testing the adaptation options over this range. This would then be of assistance in selecting options that performed satisfactorily across a wide range of options rather than perhaps performing well across a more limited range. Given our limited ability to accurately predict the future the case for using only one model from an MME at this time seems limited. Clearly, in practice, research groups use their own individual model but that is a different question.

• **Summarising and visualising MME results.** In IMPACT2C, the various different work packages have used slightly different approaches to summarising the results of MMEs, as some sectors have more scope for using different measures than others, depending on the number of simulations they have. Nevertheless, the overall approach taken has been to try and
summarise the results such that they can be presented as being robust or not, where robustness is assessed with respect to model agreement on the sign and/or size of a change, and, in some cases, statistical tests have been used, to assess whether any changes are statistically significant. In addition, simpler approaches, such as comparing the size of the change to the standard deviation in the MME, have been used as a measure of the robustness of the changes. Regardless, this attempt to try and present results in terms of their robustness is a worthwhile exercise, limitations of sample size notwithstanding.

![VALIDATION MEAN ALL MODELS](image)

**Figure 5.3.** Inter-comparison of the different hydrological models in simulating annual mean discharge, and the associated summary statistics (Source: Greuell et al. 2015).
VALIDATION INTERANNUAL VARIATION
WITH EOBS AND WFDEI

Figure 5.4. Inter-comparison of the different hydrological models in simulating interannual variation in mean discharge, and the associated summary statistics (Source: Greuell et al. 2015).

Recommendations

While a MME does provide a quantification of the uncertainty of the response as represented by the model spread, it is likely a conservative estimate of the true uncertainty which we cannot of course know. Consequently, it is desirable that in addition to the uncertainty quantified in a modelling exercise, that there is perhaps equal effort devoted to carrying out a certainty assessment. This certainty assessment should inform on the various limitations of the modelling exercise, and can be accompanied by statements of the level of confidence one may have in the modelling results. These confidence statements should be based on the results of many studies (where possible), and not just the results of the analysis in hand. These statements would help greatly in enhancing the credibility of the information provided and also provide guidance as to areas where more research is necessary.

5.7 RCP-SSP Framework

In the assessment of the future impacts of climate change, assumptions have to be made about future conditions. Historically, the emission scenarios of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (the SRES, Nakicenovic et al. 2000) were used.

These defined a set of future self-consistent and harmonised socio-economic conditions and emission futures that, in turn, were used to assess potential changes in climate through the use of global and regional climate models. As an example, the underlying emissions profile and socio-economic scenario (e.g. an A1B world) was run in a climate model, and then combined with socio-economic data for the A1B world when calculating impacts.
In terms of socio-economic data these IPCC SRES scenarios were characterised by quantitative socio-economic data on:

- Population: total
- GDP: US Dollars (1990 prices)
- Land Use: Croplands, grasslands, energy biomass, forest, other.
- Energy Use: Final and primary energy use by fuel; cumulative resource use.

More recently, the SRES scenarios have been replaced by the Representative Concentration Pathways (RCPs), with four RCPs. The four RCPs together span the range of year 2100 radiative forcing values found in the open literature, i.e. from 2.6 to 8.5W/m²: the high RCP8.5 (cf. Riahi et al. 2011), the medium-high RCP6, the medium-low RCP4.5 and the low RCP2.6. The scenarios cover the range from high emission futures to scenarios consistent with the 2°C target (van Vuuren et al, 2011).

However, the RCPs are different to the SRES in that they break the explicit link between socio-economic scenarios, emissions, and impacts. The RCPs have not been designed as a new, fully integrated set of scenarios; the focus in the development process has been on providing a consistent set of projections for components of radiative forcing (emissions and land use) by using scenarios available from the literature. Further, the socio-economic scenarios underlying each RCP should not be considered unique.

For the socio-economic component, a new approach is now proposed, known as the Shared Socio-economic Pathways (SSPs) (van Vuuren et al, 2012: Kriegler et al., 2012). There are five SSPs that have been produced, which represent future paths, e.g. towards more or less sustainable worlds, or greater or lesser degrees of inequality and co-operation. This involves a new set of socio-economic data, but also the potential for a change in the way the data are used, in matching up climate and socio-economic data, i.e. the RCPs and the SSPs have not been designed as a new, fully integrated set of scenarios, but rather offer the potential to mix and match alternative combinations.

While this provides some key advantages in the ability to combine future worlds, it leads to a major problem in terms of the multiplication of possible future combinations. The combination of four...
RCPs ad five SSPs can rapidly lead to a very large number of possible runs, which is then expanded further when climate uncertainty (and multiple climate simulations) are run. Indeed, it is very easy to end up with potentially hundreds of possible combinations.

In theory, this can be reduced by considering a subset of possible combinations of the RCPs and SSP based on the feasibility. In the figure below (based on van Vuuren 2012), each column describes the implications of increasing levels of climate change, or decreasing levels of mitigation effort, for a given set of socio-economic conditions. It might not be necessary to cover all cells of the matrix, however. For example, an SSP with rapid renewable energies deployment, low population growth and environmental orientation would probably not result in 6 degree warming, even without climate policy.

The problem is that even this approach does not significantly limit the number of combinations.

At the current time, there is no new guidance or informal consensus on how best to tackle this problem, and to sample across the RCP/SSP and climate model envelope. Moreover, due to the varying complexity and run time of different models for different impacts, there is a large difference in the capacity to do multiple runs between teams.

In the IMPACT2C, a pragmatic approach was used, which aimed to build up a picture of relevance for policy impacts and adaptation, by sampling across the RCPs, the climate models, and the SSPs.

Therefore, a number of climate model simulations were taken for each RCP (see earlier) and this was combined with a number of SSPs to allow analysis of the influence of socio-economic data on the results. A matrix was compiled for this, recognising that different teams would be able to run more or less simulations.

<table>
<thead>
<tr>
<th></th>
<th>SSP1</th>
<th>SSP2</th>
<th>SSP3</th>
<th>SSP4</th>
<th>SSP5</th>
</tr>
</thead>
<tbody>
<tr>
<td>No climate No LUC</td>
<td>XX</td>
<td>XXX</td>
<td>XX</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>No climate With LUC</td>
<td>XX</td>
<td>XXX</td>
<td>XX</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>RCP 2.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 (low temp)</td>
<td>2</td>
<td>3 (mid)</td>
<td>4</td>
<td>5 (high temp)</td>
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<tr>
<td>RCP 4.5</td>
<td>x</td>
<td>x</td>
<td>XXX</td>
<td>XXX</td>
<td>xx</td>
</tr>
<tr>
<td>RCP 8.5</td>
<td>x</td>
<td>x</td>
<td>XXX</td>
<td>XXX</td>
<td>x</td>
</tr>
</tbody>
</table>

Key: **XXX** Mandatory, xx if possible preferred, x if possible

### 5.8 Recommendations and Knowledge Gaps

Scientists, consultant and policy makers are still struggling with using climate models for climate change impacts, vulnerability and adaptation assessments. The main reason is the large amount of data available, the number of models and the biases and uncertainties in the climate model output. The help with the struggle a number of guidance and data-portals have been developed to facilitate the use of climate models.

Almost all guidelines agree that for any assessment of impacts, vulnerability and adaptation it is necessary to use more than one climate models. The selected models should be representative of the uncertainty spread of the entire multi-model assessment. To improve your sample exclusion of unrealistic climate models is recommended. This can be done for example through a screen of the literature on performance of the members within the desired ensemble. To assist in the process of reducing the number of models to use a second step could do a hierarchical or divisive clustering. What remains still unclear is about how many models should be used. There is a need to develop clear recommendation and more guidance on the number of climate models to be used for different analyses.

For many impact and adaptation analyses a one way coupling of climate and impact models is used. Climate model output is used to drive the impact models. Very often the climate model output has been processed to downscale and/or bias correct the data. The problem with kind of analyses is that they do not capture feedbacks between climate and impacts. To resolve this more integrated approaches are needed, for example by integration of impacts in Earth System Models.
Especially for the water sector not only multiple climate models were used but also multiple hydrological models. There is a need to use also multiple impact models because different model respond differently to climate change. For example the way evaporation is estimated in the model has a large impact on the response to changes in climate. To improve impacts assessments better and more assessments need to be done to study the effect of “impact model” choice climate change impacts. There is a need for a more systematic evaluation of simulated spread from impact models and the relative contribution from the spread of climate model input and the spread resulting from the use of different impact models / and / or from different parameter settings in one impact model.

Climate change impacts and vulnerability assessments are used to inform both mitigation and adaptation policies. It addresses mitigation policies by showing which impacts can be avoided if emissions are reduced. It informs adaptation policies by showing for which changes adaptation is necessary to reduce the vulnerability to future climate change impacts, within a framework of decision making under uncertainty.

In response to policy needs to define better the climate change Impacts under two degree global warming, IMPACT2C developed an approach to assesses the time period when the individual (global) model hits this a threshold. This is very interesting from a scientific approach but has some limitation for policy implications.

In most previous cases, the threshold approach was used to assess the climate change impacts at the period when the average of the global models hit 2 degree warming, i.e. to use one consistent period, which aligns to a specific emission time profile. The IMPACT2C approach is very useful for climate modelling analysis, but is problematic for impact and especially vulnerability and adaptation assessments because it assumes time independence. Comparing different time periods is problematic when both climate and socio-economic information are used for impact analysis, because the socio-economic data, such as for example land use, varies with time, thus it is inconsistent to compare impacts in one period with impacts in another.

Different approaches have been developed and used within Impact2C to assess and visualise uncertainties in climate and biophysical changes such as agricultural production, water availability and biodiversity. For assessing the impacts of socio-economic uncertainties much more limited work has been done. There is need for better evaluation of the relative importance of the biophysical impacts compared to socio-economic factors. This specifically needed for adaptation planning at different scales.

5.9 References


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6 Synthesis

6.1 Introduction

This work package has provided policy briefs to synthesis the work of IMPACT2C. These have been published as a series of synthesis documents, for each of the major Conference of the Parties (COP) meetings over the course of the project.

The policy briefs are attached as separate sub-deliverables.

The first policy was presented at the Warsaw COP (2013). It was also summarised and published as a paper (Vautard et al, 2014). This summarised the fast track climate analysis.

The second policy brief was presented at the Lima COP (2014) and summarised the slow-track detailed EURO-CORDEX results and the biophysical impacts, e.g. sea level rise, hydrological modelling. The briefing note was then updated and used for the IMPACT2C session at the Copenhagen European Climate Change Adaptation Conference in May 2015 (Session Quantifying impacts of +2°C global warming for Europe) and a parallel session: "Multi-sectoral analysis of risks to climate change (hot spots) at 2 °C warming" at the Paris Our Common Futures conference in Paris, July 2015. The summary information was also used to provide the key input for a Pan –European Network Publication on: Climate change impacts and adaptation: What does 2°C mean for Europe? An academic paper was also produced summarising some of the key overarching lessons on mitigation and adaptation (Watkiss et al, 2015). Finally, a synthesis of the IMPACT2C project was produced for the European Environment Agency, for the section on projected economic costs of climate change, as part of the forthcoming 2016 EEA Climate Change Report. The third policy brief was published for the Paris COP. This summarised the global impact results.
6.2 References
