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Preliminary Global Assessment of Economic Impacts of Climate Change at 4°C global warming

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1 Introduction

Work Package 5 of the HELIX project is making a comprehensive global assessment of economic impacts due to climate change. The analysis has two phases. As a first phase, this report (Deliverable D5.2, June 2016) presents a global preliminary assessment, made with the existing fast track ISI-MIP impact results and other results. In the second phase, a comprehensive global assessment will be made running the HELIX climate scenarios with the HELIX biophysical impact models (Deliverable D5.6, due in month 45, July 2017),

The Phase 1 of the activity uses existing information on climate impacts regarding crop productivity, coastal impacts and river floods to obtain a first preliminary global assessment of economic impacts at 4^{o}C global warming. The ISI-MIP project only considered the RCP8.5, with five climate models, with four of them reaching the 4^{o}C level before 2100, the end of the simulation period in ISI-MIP.

The objective of the Phase 1 activities is to test the methodology, showing its possibilities, potential and limitations. It also provides initial results available for discussion ahead of the more comprehensive impact analysis to be done in Phase 2 of Work Package 5 with the climate simulations from WP3 introduced in the biophysical impacts of WP4 and WP5.

Clearly, the three impacts covered in this report do not exhaust all the possible interaction channels between the climate change and economy and at this stage (Phase 1) the presented global economic implications do not aspire to be a comprehensive economic assessment of the 4^{o}C warming, but rather estimation of economic implications of specific impacts evaluated at 4^{o}C warming level.

This assessment is to be understood in the context of the last 21st Conference of Parties (COP21 in Paris 2015)[1] of the UNFCCC, which agreed to undertake steps consistent with "holding the increase in the global average temperature to well below 2^{o}C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5^{o}C".

The economic model used to integrate the biophysical impacts, the computable general equilibrium (CGE) GEM-E3 model, has been extensively used in similar applications in Europe, in the context of the PESETA projects (e.g. Ciscar et al, 2011, 2012). A similar CGE model was used in the USA Risky Business project exploring the climate risks in USA (Houser et al. 2015). Another CGE model forms part of the integrated assessment model FUND (climate Framework for Uncertainty, Negotiation and Distribution), which has previously been used to assess global economic impacts of climate change over the 21st century (Tol, 2013). This provides an opportunity to compare and contrast the

[1] http://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf

different approaches to using a CGE to assessing global economic impacts at approximately 4°c global warming. To this end, this report includes a top-level comparison using the example of impacts on global agriculture. This example is important in the context of HELIX as it highlights the impacts of assumptions made about the relative impact of carbon dioxide fertilization and radiatively-forced climate change, a topic which is a key focus elsewhere in HELIX.

The report is structured around the three main sections describing the global economic consequences of the three climate impacts: agricultural crops productivity (Section 3), coastal impacts (Section 4) and river floods (Section 5). Each section provides an overview of the impact-specific methodology, while section 2 provides a detailed explanation of the general methodology, and particularly the main features of the economic GEM-E3 model. Section 3 additionally includes a comparison between GEM-E3 and FUND results for agriculture. Section 6 concludes with a discussion of the next steps, towards phase 2 of Work Package 5. The appendices at the end of the report supply more detailed and additional information and results.

2 Methodology

The fast track ISI-MIP project made projections of impacts for five GCMs, based on the RCP8.5 scenario. The assessment of agriculture impacts, based on the AgMIP project data, is rather broad as it covers all the ISI-MIP crop models (seven) and the global circulation models (GCMs) (five). It therefore captures the variability due to the use of various climate models and biophysical agriculture crop models. The coastal impact assessment focuses on one coastal impact model and one specific sea level rise, compatible with the 4^{o}C climate change scenario. It is based on the results from the ClimateCost project, which used the same coastal model as in ISI-MIP. The river flood analysis is based on the results of the ISI-MIP runs. ISI-MIP considered ten different hydrological models and five GCMs, generating runoff projections at the global scale for each of the 50 runs. PIK has produced inundation maps based on the ISI-MIP runoffs results. JRC has estimated the economic effects of the simulated water levels from the inundated maps, using a global database of depth-damage functions.

It is important to note that not all the results in this report come from the same family of climate scenarios. While the agriculture and river floods assessments come from the RCP8.5, the coastal impacts come from the A1B SRES scenario, which might not be strictly comparable.

Computable general equilibrium models (e.g. Shoven and Whalley, 1992) combine a high resolution dataset of the economy (the Social Account Matrix, SAM) with standard microeconomic theory. CGE models are multi-agent, multi-sector and multi-country, features which make them ideal for considering how the overall economy (all agents and markets) would adjust to an external shock like climate change, considering the second and higher order round effects of the primary climate shock. A CGE model is in equilibrium when all agents are at their optimum and all factor, goods and services markets are simultaneously cleared (i.e. Walras' Law is holding). The market adjustments captured by a CGE model can be interpreted as market or price-driven adaptation (e.g. OECD, 2015).

The two main agents of the economy are households and firms, whose endogenous behaviour is simulated, assuming they optimize their objective function (utility or welfare for households and profits for firms) subject to a set of constraints (e.g. technology, costs, prices). The modelling setting also considers the public sector (usually exogenous) and the external sector (modelling trade as a function of relative prices).

The multi-sector perspective is a distinctive feature of CGE models. CGE models focus on the overall reallocation of resources in the economy. Thus CGE models consider both the direct effect of a climate shock for instance within the agriculture sector and the indirect effects in the rest of the economy, associated with cross-sectoral transactions, as captured by the underlying input-output tables in the model. Therefore, a clear advantage of this methodology is its comprehensive optic, at the expense of the need to rely on a sound specification and calibration of the non-agriculture sectors of the economic system. The CGE economic model simulates how production (gross domestic product, GDP, a measure of the overall production of a country) and household welfare (an indicator of satisfaction or utility of the households) could be affected by climate change. The welfare change is computed using the concept of equivalent variation.

The model employed for this analysis, CAGE-GEME3[2], is a static multi-country, multi-sector computable general equilibrium model of the world economy linking the economies through endogenous bilateral trade. The CAGE database is mainly based on the Global Trade Analysis Project (GTAP) database, version 8 (Narayanan et al., 2012)3.

The GTAP database provides input-output tables for a large set of countries/regions and commodity categories. The CAGE-GEME3 model has 19 sectors and 25 regions[4]. The major individual countries in the climate negotiations have been included separately (Brazil, Canada, China, India, Indonesia, Japan, Korea, Mexico, Russia, South Africa and the USA). The European Union is split into five regions: UK and Ireland, Northern Europe, Central Europe North, Central Europe South and Southern Europe. The remaining regions are Australasia, Rest of South Asia, Rest of sub-Saharan Africa, Rest of Europe[5], Rest of South-East Asia, Rest of Former Soviet Union, Middle East & North Africa, Central America & Caribbean and South America.

The CGE analysis of climate impacts follows a static comparative approach (as in e.g. Aaheim et al., 2012; Hertel et al. 2010; and Ciscar et al. 2012), estimating the counterfactual of future climate change (reaching the 4^{o}C) occurring under the current socioeconomic conditions. Therefore, the climate shock-induced changes would occur in the economy as of today.

The implications of that choice are widely discussed in Ciscar et al. (2012). In contrast, a 'dynamic' approach would account for changes that the economy and society will undergo until the end of the century, and apply the climate shocks to the version of economy as in the year reaching the 4^{o}C level. Climate impacts might become larger as they would affect a bigger economy. Considerations

[2] See Appendix A. The full model description and mathematical model statement is provided in the Annex of Pycroft et al. (2015).
[3] https://www.gtap.agecon.purdue.edu/
[4] The CAGE sectors and regions are detailed in Appendix A
[5] The Rest of Europe region includes the following countries: Albania, Bosnia and Herzegovina, Macedonia, Montenegro, Norway, Serbia, and Switzerland

of how adaptation might be in the future would need to be made. Development of such representation of future economy, however, would require numerous assumptions about factors shaping the societal and economic development. The assumptions would be required to envisage impact of demography, technology (existing and new), degree of adaptation to climate change (both planned and autonomous), societal preferences and more. All these assumptions would bear a (high) degree of uncertainty and would further complicate the interpretation and validity of the final results.

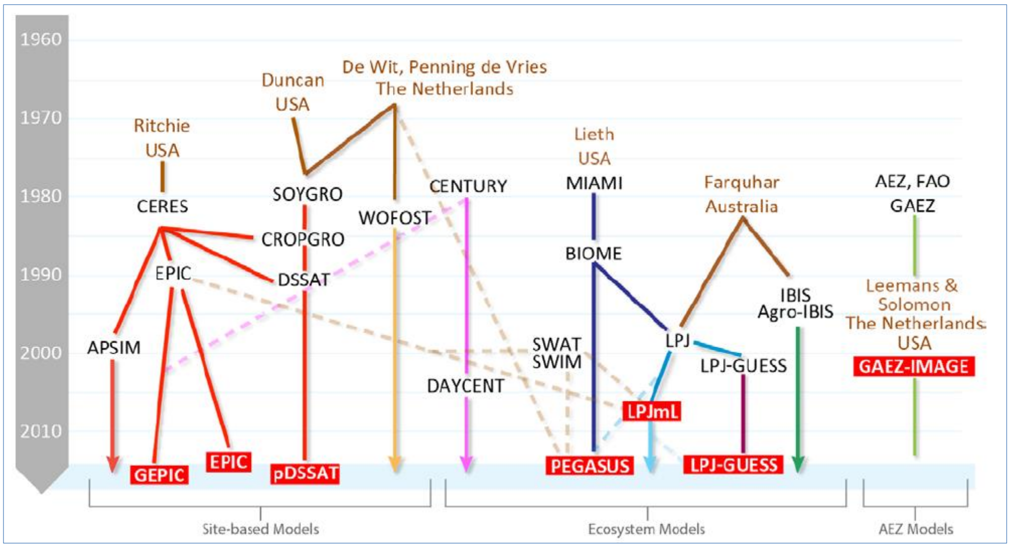
3 Economic assessment of climate impacts

1.1 Crop productivity

This section analyses the economic consequences of agricultural crops productivity changes resulting from future climate change. The future yield changes provided by the Agricultural Model Intercomparison and Improvement Project (AgMIP) together with the Inter-Sectoral Impact Model Intercomparison project (ISI-MIP) are used as an input to the global, multi-country, multi-sector CGE model (CAGE-GEME3) in order to assess macroeconomic implications of the 4°C climate impacts.

The AgMIP project has conducted multi-model simulations with harmonised data on future yield changes. The simulations build on 5 Climate (GCM) Models (HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M, and NorESM1-M)[6] and 7 Global Gridded Crop Models (EPIC, GEPIC, IMAGE, LPJmL, LPJ-GUESS, pDSSAT, and PEGASUS)[7]. The specific combinations of climate and crop models are detailed in Appendix B. A major source of uncertainties in projected yield changes derives from variations in assumptions, approaches and structures embedded in the Global Gridded Crop Models (GGCM): Rosenzweig *et al*. (2014) groups the models into three types. The first type is site-based models (EPIC, GEPIC and pDSSAT) which were developed to simulate processes at the field scale, while the second type, the agro-ecosystem models (LPJ-GUESS, LPJmL, and PEGASUS), were developed to simulate CO_2 and N dynamics, and energy and soil-water balances. The last type, agro-ecological zone model (GAEZ-IMAGE), was made for assessment of agricultural resources and potential at regional and global scales.

Figure 1: Crop model genealogy (adopted from Rosenzweig *et al.*, 2014)



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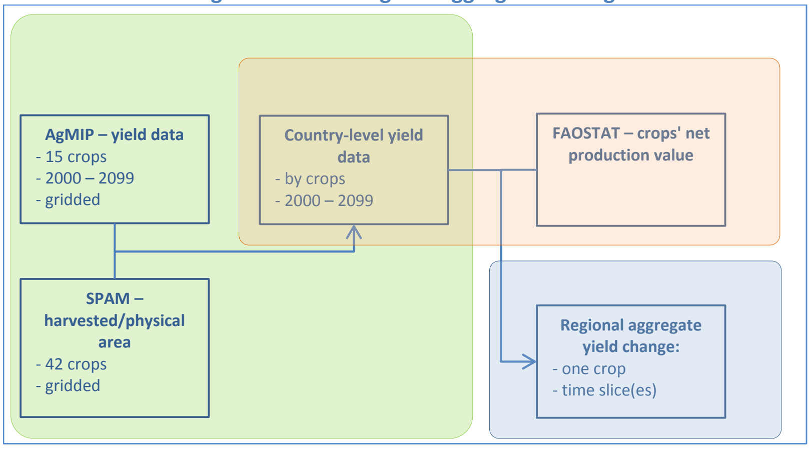
[6] For details see CMIP5 info at: http://cmip-pcmdi.llnl.gov/cmip5/availability.html

[7] Excellent discussion provided in Rosenzweig *et al*., 2014.

1.1.1 The agriculture shock

The grid-level crop yield data from the AgMIP project is processed and aggregated along three dimensions: geographically, across crops and across time using auxiliary data on the actual harvested area (SPAM[8]) and on the individual crop production (FAO[9]). Figure 2 provides an overview of the aggregation process, which is described in detailed in Appendix B.

Figure 2: Processing and aggregation of AgMIP data



The GCMs reach the 4°C warming level at different times. The procedure for choosing for each GCM the specific timing reaching the 4°C warming above the pre-industrial levels follows the method of Schleussner et al. (2016). In the approach, a 20-year average is computed so it reflects 3.4°C warming above the reference period (1986-2005), which is 0.6°C warmer than the pre-industrial levels, 1850–1900 (IPCC, 2013).

The respective time-slices for each GCM are collected in Table**Error! Reference source not found.**.

Table 1: Time to reach 4°C for different GCMs

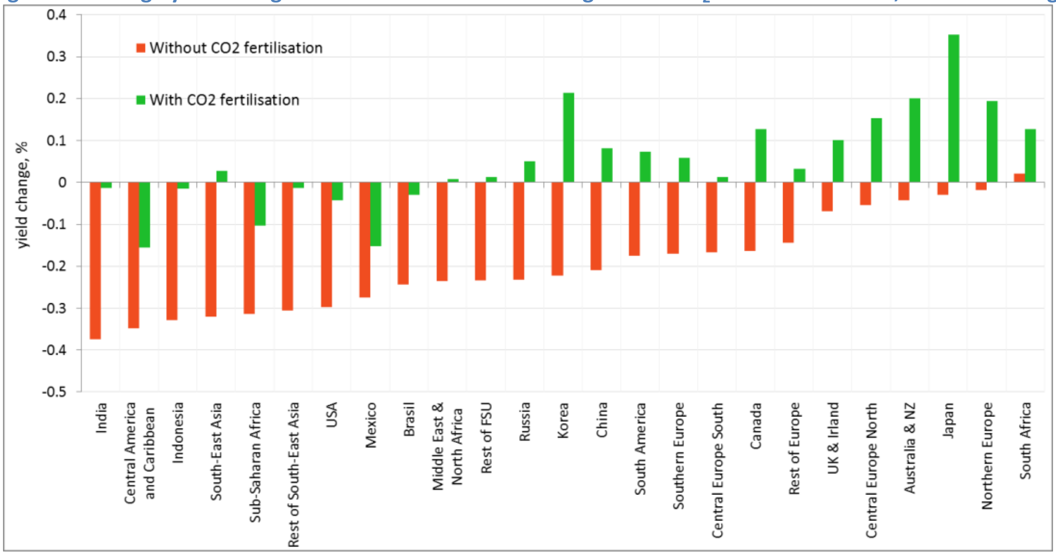
GCM	***Year reaching 4°C***	***time-windows with 4°C average reached***
HadGEM2-ES	2068	2058-2078
IPSL-CM5A-LR	2072	2062-2082
MIROC-ESM-CHEM	2068	2058-2078
NorESM1-M	2095	2090-2100

The above periods refer to a running mean window of 21 years (except of the NorESM1-M model which uses an 11-year window because the AgMIP data are computed up to the 2100 year). The GFDL-ESM2M does not reach the 4°C in the 21 century at all and is excluded from further analysis.

[8] Spatial Production Allocation Model: http://mapspam.info/
[9] FAOSTAT: http://faostat3.fao.org/home/E

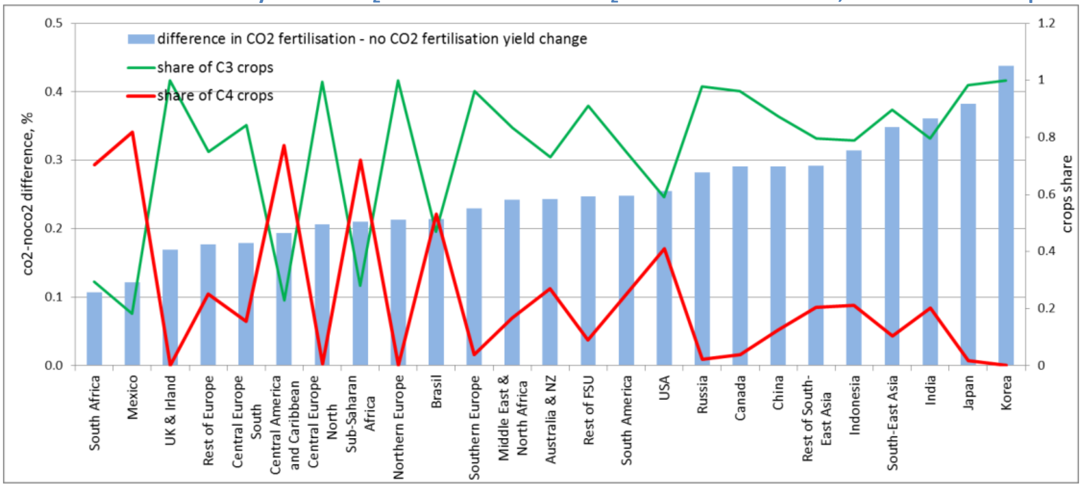
Such computed yield changes of one representative crop for all the combinations of the four climate runs (which can reach the 4°C) and seven GGCMs are introduced to the CGE model as a change in total factor productivity of the agricultural crops sector. Figure 3 represents the average change in yields for both scenarios: with the CO_2 fertilisation effect allowed, and with the CO_2 levels kept constant. The full matrix of all the yield changers reflecting all the GCM x GGCM combinations is provided in Table 14 in Appendix B.

Figure 3: Average yield change with- and without accounting for the CO_2 fertilisation effect, at 4°C warming.



The pattern of yield changes with- and without the CO_2 fertilisation effect presented on Figure 3 (sorted by decreasing yield change) suggests that regions with large reductions predicted for yields in the no CO_2 fertilisation scenario are still facing crop productivity reduction even with the CO_2 fertilisation effect allowed (eg India, Indonesia, South-East Asia, the USA). At the other side of the spectrum, regions which small yield decreases in the no CO_2 scenario may experience a positive crop productivity shock when allowed for the CO_2 fertilisation effect (eg Korea, Canada, Japan, South Africa). This change in yield between the CO_2 scenarios is further explored in Figure 4 which presents the difference for each region.

Figure 4: Difference between yields in CO_2 fertilisation and no CO_2 fertilisation scenarios, and C3 and C4 crops shares



The two additional lines on Figure 4 represent share of C3 and C4 crops[10] in total regional output[11]. Such comparison is motivated by the fact that C3 plants typically respond more to atmospheric CO_2 enrichment than do C4 plants in terms of increasing their rates of photosynthesis and biomass production. Indeed, an overall picture suggests that the regions benefiting the most from the increasing atmospheric CO_2 level are those which mainly grow C3 crops (Korea, Japan, India). For regions where the benefit is smaller (mainly the European regions) the difference in shares of C3 and C4 pants is less conclusive.

1.1.2 Results

The average percentage changes in GDP and welfare resulting from the series of simulations are presented in Table 2. The effect of 4°C global warming can be measured by 1.2% loss of global GDP or 2.1% loss in global welfare. If the positive effect of higher atmospheric CO2 concentrations on biomass growth is taken into account, the GDP loss is reduced to 0.02%, and the welfare loss is by 0.03% only. In term of the monetary values of these changes, the global GDP loss is 634 bn US$ (constant CO_2) and 9 bn US$ (CO_2 fertilisation), while the welfare loss value is 648 bn US$ (no CO_2 fertilisation) and 10 bn US$ with the CO_2 effect.

Considering climate change alone, with no CO_2 fertilozation, the area most affected by the 4°C warming is Asia with most regions recording significant reductions in GDP and welfare. India, Indonesia and South Asia lose 7.8%, 4,9% and 4.8% of their GDP, respectively, with the EV change being even more pronounced: 14%, 9% and 9%. Accounting for the CO_2 fertilisation effect alleviates most of the damage, although for India and Indonesia the GDP loss remains above 1%.

[10] C3 crops: rice, wheat, sugar beet, rapeseed, barley, boy, green peas, sunflower seed, ground nuts; C4 crops: cassava, sugarcane, maize, sorghum, millet.
[11] Shares calculated from FAOSTAT crop data (http://faostat3.fao.org/download/Q/QV/E)

On the American continent, when considering climate change alone, Central America and Caribbean, Brazil and Mexico are most affected with their respective GDPs dropping by almost 3.5%, 2.1% and 1.3%. The CO_2 fertilisation eases the reduction with only Central America and the Caribbean GDP remaining above 1% at 1.7%.

Table 2: Average percentage change in GDP and welfare (EV) at 4°C warming

	with CO2 fertilisation		without CO2 fertilisation	
	GDP %	EV %	GDP %	EV %
China	0.47	1.40	-2.43	-6.39
Japan	0.50	0.75	-0.07	-0.42
Korea	0.40	0.30	-1.28	-3.21
Indonesia	-1.22	-1.97	-4.87	-9.12
India	-1.63	-2.96	-7.77	-14.83
Australasia	0.25	0.78	-0.39	0.08
South Asia	-0.19	-0.48	-4.80	-9.31
Rest of South-East Asia	-0.42	-0.70	-2.53	-4.94
Canada	0.12	0.52	-0.16	0.29
USA	-0.11	-0.21	-0.53	-0.87
Mexico	-0.63	-0.97	-1.27	-2.25
Brazil	-0.48	-0.93	-2.08	-3.50
Central America and Caribbean	-1.62	-2.62	-3.48	-5.52
Rest of South America	0.45	1.03	-0.97	-1.02
Middle East and North Africa	-0.06	-0.04	-2.02	-4.71
Sub-Saharan Africa	-3.35	-6.17	-9.24	-16.65
South Africa	0.11	0.51	-0.45	0.40
Northern Europe	0.28	0.72	-0.20	0.03
UK & Ireland	0.06	0.12	-0.24	-0.61
Central Europe North	0.25	0.55	-0.35	-0.51
Central Europe South	-0.02	0.02	-0.76	-1.16
Southern Europe	0.10	0.20	-0.67	-1.04
Rest of Europe	0.05	0.13	-0.45	-1.17
Russia	0.24	0.47	-2.01	-4.47
Rest of former USSR	0.06	0.11	-3.05	-5.83
World	-0.02	-0.03	-1.15	-2.12

In Africa and, in fact, world-wide, Sub-Saharan Africa is the most affected region by the agricultural crops yield shock. When climate change alone is considered, GDP is reduced by 9.2% and its welfare by 16.6%. This large effects steam form both large yield productivity shock and a relatively large agricultural sector in this region; this is discussed further in this section. With the CO_2 fertilization effect included, the region's GDP and welfare impacts are reduced, but at 3.4% and 6.17% respectively, these negative impacts remain larger than in other regions.

Table 3: Average change (bn US$) in GDP and welfare (EV) at 4°C warming

	with CO2 fertilisation		without CO2 fertilisation	
	GDP bn US$	EV bn US$	GDP bn US$	EV bn US$
China	17	18	-85	-82
Japan	21	17	-3	-10
Korea	4	2	-13	-16
Indonesia	-5	-5	-21	-22
India	-19	-20	-91	-98
Australasia	3	4	-4	0
South Asia	-1	-2	-25	-29
Rest of South-East Asia	-5	-4	-31	-30
Canada	2	4	-2	2
USA	-15	-19	-74	-78
Mexico	-6	-6	-13	-14
Brazil	-6	-7	-28	-26
Central America and Caribbean	-6	-7	-13	-14
Rest of South America	5	6	-10	-6
Middle East and North Africa	-1	0	-44	-51
Sub-Saharian Africa	-19	-22	-53	-59
South Africa	0	1	-1	1
Northern Europe	3	4	-2	0
UK & Ireland	2	2	-7	-11
Central Europe North	13	15	-18	-14
Central Europe South	-1	0	-28	-23
Southern Europe	4	5	-28	-25
Rest of Europe	0	1	-4	-6
Russia	3	3	-24	-27
Rest of former USSR	0	0	-11	-11
World	-9	-10	-634	-648

In Europe the effects of changing crop productivity are mild with GDP loss ranging between 0.2% in the Northern EU regions to 0.8% in Southern EU regions. Russia and former Soviet Union states face higher GDP loss of 2% and 3% respectively.

Subsequent Figure 5 and Figure 6 provide a more in-depth insight into distribution of impacts from different GCM x GGCM combination and on the driving factors of GDP and welfare changes. The first Figure shows results from scenarios including CO_2 fertilisation effect, while the second Figure shows results from scenarios with climate change alone, omitting the CO_2 fertilisation effect (CO_2 concentrations constant at 330-380ppm level). Additionally, the Figures present an indication of the size of the agricultural crops sector (top of the Figure) and an average of the yield change (bottom of the Figure).

The GDP change resulting from yield change with the CO_2 fertilisation effect are in Figure 5. The Sub-Saharan Africa is estimated to face reduction of about 3.3% of its GDP – about a third compared to the no-CO_2 simulations. Many of the regions would experience, in fact, an increase in crop productivity of as much as 35% in Japan – although the GDP effect is rather modest (0.5%) due to the relatively small size of the crop sector.

Figure 5: Average GDP effect by crop model; share of the Crops' sector output in total regional output (red top); size of the average (by crop models and GCMs) crop productivity shock (green bottom); with CO_2 fertilisation

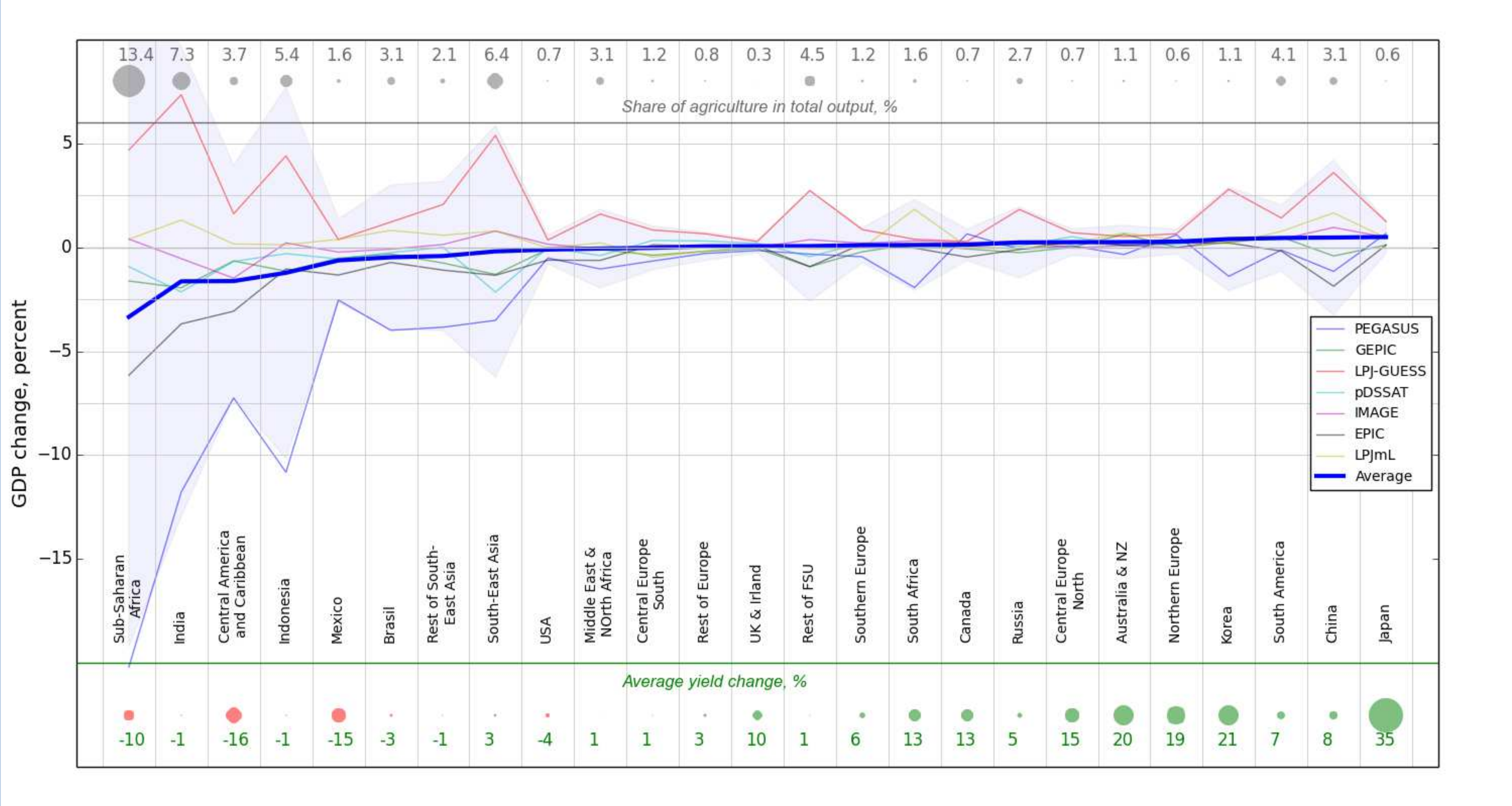
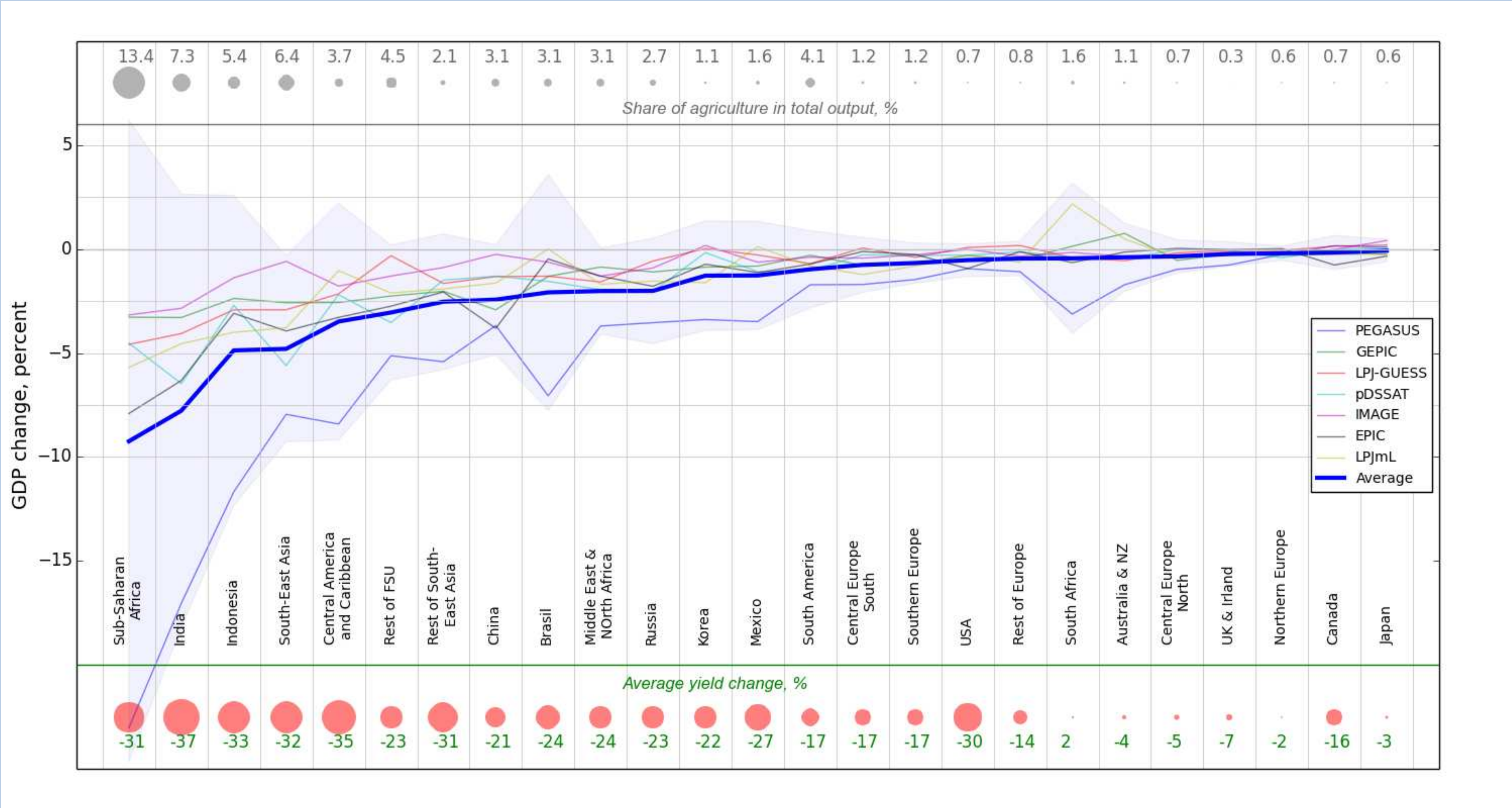


Figure 6: Average GDP effect by crop model; share of the Crops' sector output in total regional output (red top); size of the average (by crop models and GCMs) crop productivity shock (green bottom); without CO_2 fertilisation



The results for the no CO_2 fertilisation case (Figure 6) suggest that the largest economic impact is undergone by regions that experience a negative yield change and have a large agricultural crops sector. This combination is particularly unfavourable to the Sub-Saharan Africa region (with a share of agriculture over GDP of 13% and facing a 31% crops productivity loss shock), with a simulated GDP reduction of 9.2%. In India, climate change alone causes an even greater crop productivity reduction (37%) but a lower GDP loss (7.6%) partially because of a much smaller share of GDP being generated by agriculture (7.8%). A different example is the USA; climate change with no CO_2 fertilization leads to a 0.5% GDP reduction, in spite of a relatively large crop productivity loss (30%) mitigated by the very small share of total output coming from agriculture activities (0.7%).

The GGCM specific results suggest that the agro-ecosystem models (LPJ-GUESS, LPjmL and PEGASUS) are particularly optimistic about the impact of the CO_2 fertilization effect on yields, which can be due to the treatment of N-CO_2 dynamics not present in other crop models.

The variability in the results arising from the different GCM models used are depicted in Figure 7 and Figure 8. In addition to the average GDP change presented with the solid blue line, there are seven smaller vertical lines which present the spread of results from seven crops models (GGCM), each utilising data from the four climate models (GCM). There are four or less markers at each vertical line which indicate the result point (less than four markers indicate that the specific GCM was not applied to the GGCM – see Table 12 and Table 13 in Appendix B for data availability).

Comparing results from GGCMs with the data available from all the four GCMs, it appears that the widest spread of results derives from the PEGASUS crop model. The results based on the EPIC model data have lower variability, while the LPjmL model provides for the smallest variability in the results of the economic model.

Figure 7: GDP change (%), for 7 crop models (colours) applied to 5 GCM models (points on the lines), with CO_2 fertilisation effect. The vertical lines show the range of results from each crop model due to different GCMs.

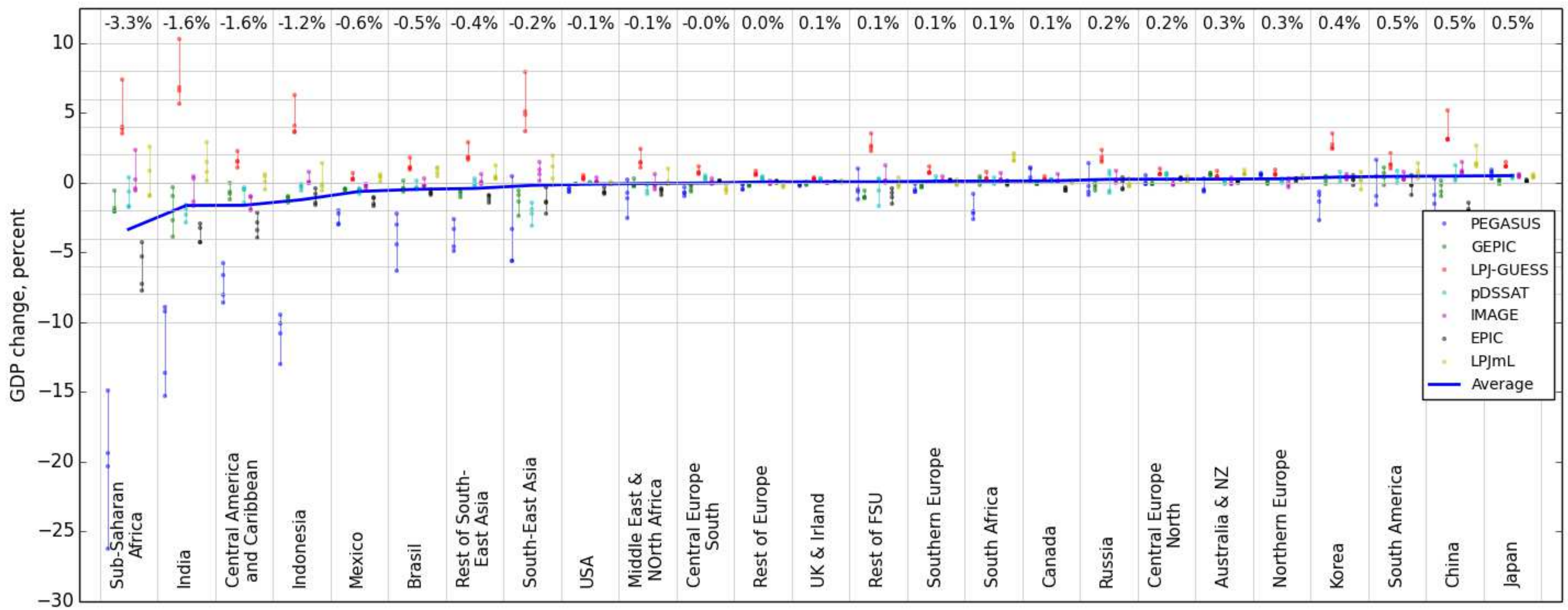
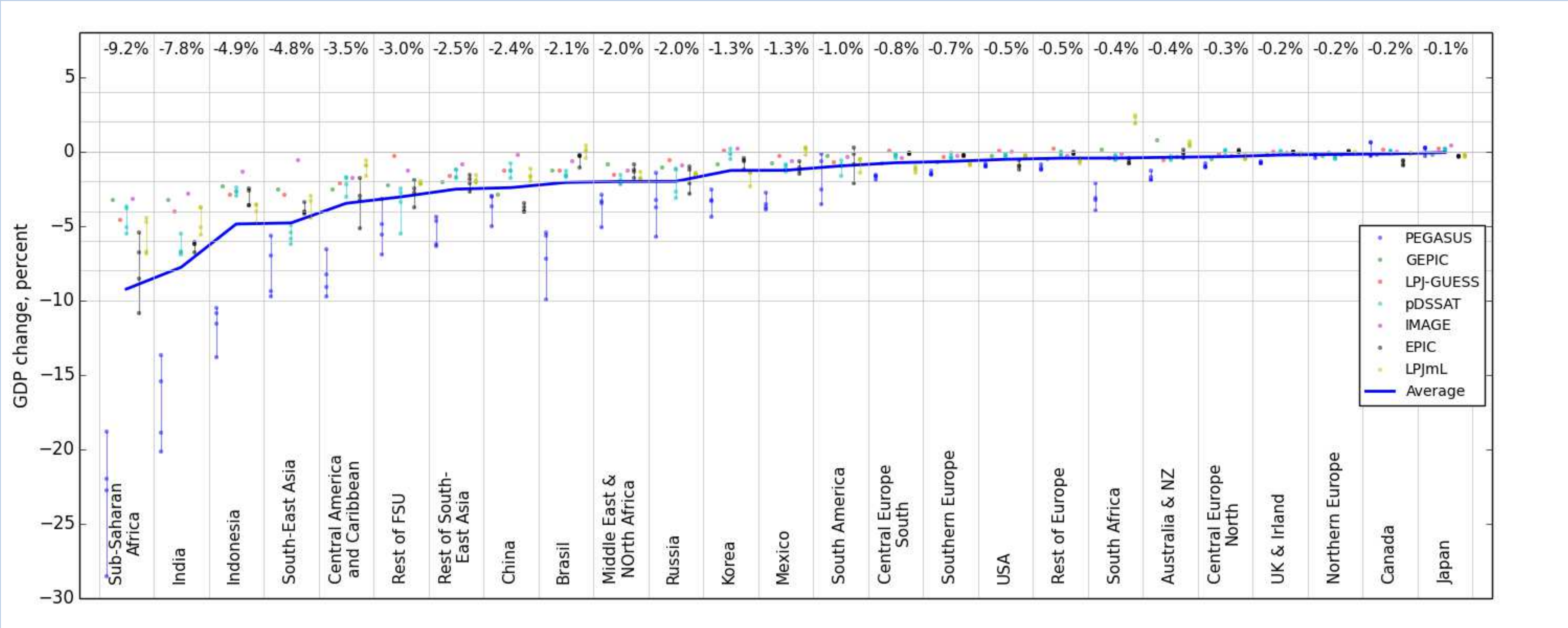
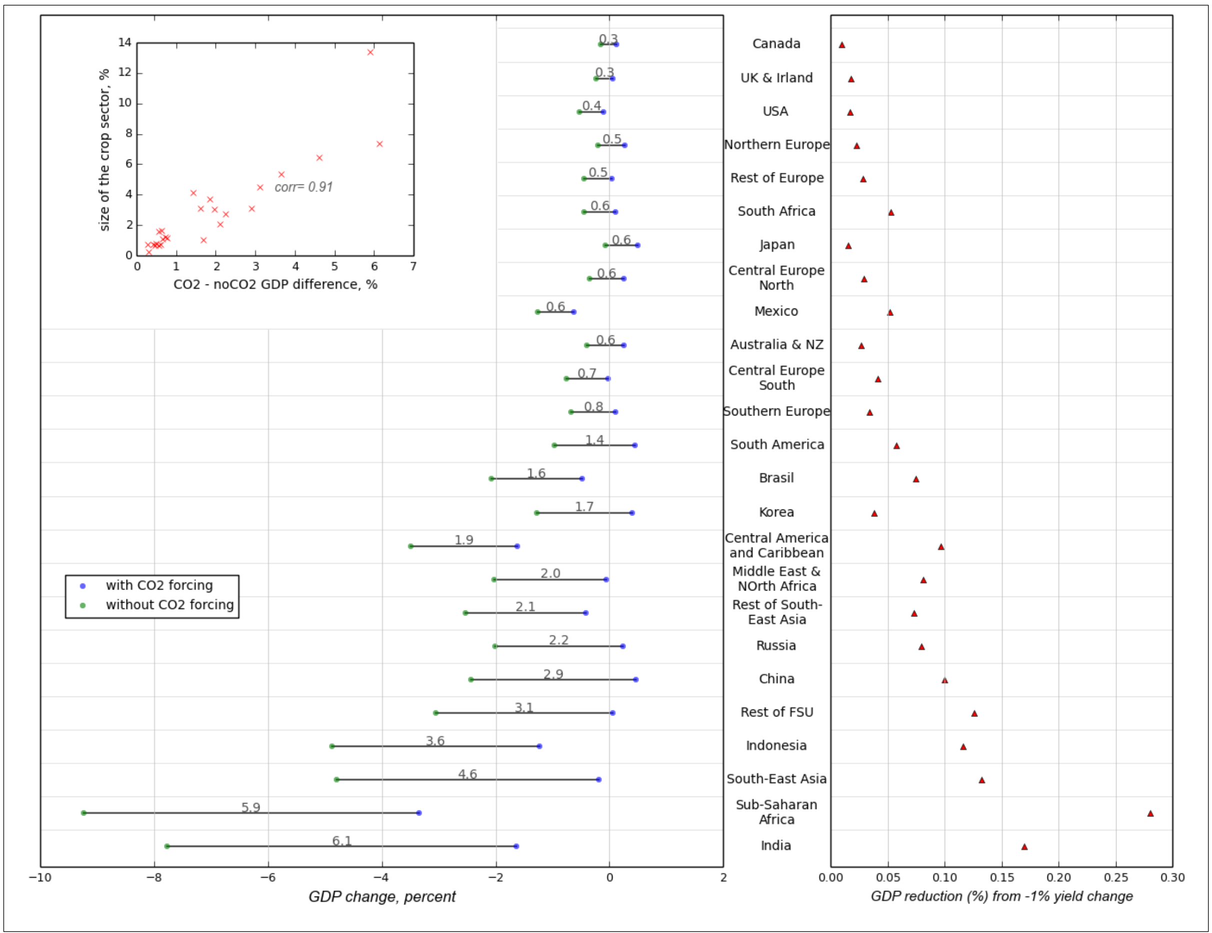


Figure 8: GDP change (%), for 7 crop models (colours) applied to 5 GCM models (points on the lines), without CO_2 fertilisation effect. The vertical lines show the range of results from each crop model due to different GCMs`



The effect and implications of elevated CO_2 from greenhouse gas emissions and the related carbon cycle feedback is explored in Figure 9 which, on the main graph, shows two sets of GDP results: one averaged across all the GCMs and GGCMs without the CO_2 fertilisation effect, and the other average with the CO_2 effect accounted for; the data on the Figure is sorted from the largest difference between the two CO_2 options. The regions which are to be most affected by the crops' productivity from the climate change exhibit the largest difference between effects simulated with- and without the CO_2 fertilisation (around 7% for India and Sub-Saharan Africa).

Figure 9: Average results (across GCMs and GGCMs) with- and without CO_2 forcing



As was previously signalled (discussion on Figure 5 and Figure 6), one important feature partially explaining the degree of divergence between the GDP effects of the CO_2 fertilisation is the relative size of the agricultural crops sector in each region. The share of crops sector in total regional output constitutes a weight applied to the yield productivity change if to assess region-wide effect. The relationship is captured on the scatterplot (upper-left part of Figure 9) showing significant correlations between the difference of GDP with- and without the CO_2 fertilising effect, and the share of the crop sector in total regional output.

The magnitude of this effect is 'normalised' on the right-hand side plot of Figure 9, which shows a change in regional GDP corresponding to one-percent change in crop productivity in this region. For regions with the larger share of GDP being agricultural output, a one percent reduction in yield productivity makes a significant impact on GDP, for example, it is 0.28% of GDP for Sub-Saharan Africa, or 0.17% for India. On the other hand, regions' GDP with small shares of crop production are less vulnerable to the yield productivity changes: the USA's GDP drops by 0.02% in response to 1% crop productivity reduction, and the GDP for Canada is estimated at 0.01%.

It should be noted that these 'normalised' sensitivity of GDP to yield productivity is only indicative and computed as a linear approximation within the range of estimated results.

1.1.3 Comparison with previous results using the FUND model

The Integrated Assessment model FUND also includes a CGE and has previously been used to assess global economic impacts of climate change over the 21st century (tol, 2013). This provides an opportunity to compare and contrast with results fro GEM-E3 driven by ISI-MIP projections, so examine the consequences of the different approaches to using a CGE to assessing global economic impacts at approximately 4°c global warming. This section provides a top-level comparison using the example of impacts on global agriculture.

Approach 1 – use of GEM-E3 with AgMIP/ISI-MIP impacts projections

As described above and in Appendices A and B, GEM-E3 was driven with scenarios of Yield Shock, the change in value of agricultural production derived from the changes in yields projected by a set of seven Global Gridded Crop Models (GGCMs) and four General Circulation Models (GCMs) of climate, performed as part of the Agricultural Model Intercomparison Project (AgMIP) and Inter-Sectoral Impacts Model Intercomparison Project (ISI-MIP). The GCMs were driven with greenhouse gas concentrations from the RCP8.5 scenario, and reached 4°C global warming relative to pre-industrial at a range of dates in the last four decades of the 21st Century. The use of four GCMs allowed uncertainties in regional patterns of climate change at 4°C global warming to be explored, and the use of seven crop models allowed exploration of uncertainties in the crop responses. A further uncertainty that was explored was that arising from the plant physiological effects of increasing CO_2 – two sets of crop model simulations were performed with the same climate projections, one with the models responding to increased CO_2, and one with crops experiencing present-day CO_2 throughout. Results from all permutations were input to the GEM-E3 analysis. Current socioeconomic conditions were assumed, in order to isolate the climate and CO_2 effects from changes in the economy and society. Hence the results do not include effects of changes in exposure, vulnerability or adaptation. Impacts on GDP are therefore relative to present-day GDP and do not include adaptation.

Approach 2 – use of the FUND Integrated Assessment Model

FUND is an Integrated Assessment Model (IAM) which, like other IAMs, uses relatively simple sub-models of various components of the climate and socioeconomic system to generate projections of changes in the entire system within the same modelling framework. The model includes a simple climate model which is driven by a scenario of greenhouse gas emissions, and simulates global temperature changes and carbon cycle feedbacks. In the projections published by Tol (2013), global warming reached nearly 3.75°C by 2100. Different impacts sectors are assessed in different ways, but agricultural impacts are represented with a response function translating changes in global mean surface temperature directly to changes in agricultural production expressed in monetary terms, without an intermediate step of explicitly simulating regional patterns of climate change or responses of crop yield. Importantly, the response function includes the influence of CO_2 fertilization and also adaptation to climate change. Socioeconomic factors such as population, economic growth and technology also change over time for reasons unconnected with climate change, so the projected impacts of climate change on GDP (after adaptation) are relative to a scenario of future GDP not the current GDP.

Comparison of projected economic impacts at 4°C global warming

A direct, systematic comparison is difficult because of very different methodologies in the two studies. One key difference is adaptation, which was included in FUND and excluded in GEM-E3, for reasons specific to each study. The inclusion of adaptation in FUND also makes the rate of climate change important as well as the magnitude – slower warming allows more time to adapt. Nevertheless, if these studies are used to help inform an answer the question "What are the economic impacts of 4°C global warming?", it is useful to have some insights into where their similarities and differences.

Using FUND, Tol (2013) projected the impacts of climate change and CO2 fertilization on agriculture to exert a positive influence on global GDP, after adaptation, throughout the 21st Century. This was attributed to the dominant effect of CO2 fertilization, which more than offset the negative impacts of climate change. The magnitude of the net positive impacts was projected to decline after the mid-21st Century as the CO2 fertilization effect began to saturate while climate change impacts continue to grow. Nevertheless, at the end of the simulation in 2100, with global warming approaching 3.75°C relative to 1900, the net impacts on agricultural production remain positive at 0.8% of GDP. When further impacts in other sectors are also considered, the positive impacts on agriculture result in net positive impacts in GDP in some countries, particularly China. In many countries, however, the overall impact on GDP is negative, often due to the dominance of negative health impacts, especially in Africa, south Asia, Russia and much of South America.

In this report for HELIX, the GEM-E3 model also projects positive impacts on GDP via agriculture in some countries at 4°C global warming, including CO_2 fertilization effects but not adaptation, with China and Japan projected to experience the largest positive impacts at 0.47% and 0.50% respectively. Other countries, however, are projected to see negative impacts on GDP due to agriculture, with the largest negative impacts being -3.35% in Sub-Saharan Africa. The total impact on global GDP is -0.02%. When the CO_2 fertilization effect is excluded in order to quantify the impact of climate change alone, negative impacts on GDP are simulated in all countries. GDP in China is simulated to decrease by 2.43%, and Sub-Saharan Africa again sees the largest simulated decrease, of 9.24%. Total global GDP is simulated to decrease by 1.15% as a result of climate change impacts alone. The latter should not be regarded as a projection – although there are large uncertainties in the future response of crops to CO_2 fertilization, the impact would not be expected to be zero. However, the substantial difference between the 'with CO_2 fertilization' and 'without CO_2 fertilization' results demonstrates the importance of reducing the uncertainties in the relative contribution of the radiative and physiological impacts of CO_2.

Summary

Two Computable General Equilibium models of the global economy, GEM-E3 and a Model within the FUND IAM, have been used to assess the impacts of climate change on agricultural production and consequent changes in GDP at approximately 4°C global warming (Table 1). Although the economic models themselves are similar to each other, they have been applied in very different ways, with FUND using simple approaches for a full-system view of the global climate and socioeconomic system in a single model, and GEM-E3 using greater resolution and a process-based approach with a number of models. Both consider CO_2 fertilization, but only one (FUND) includes adaptation. The results of GEM-E3 suggest that the net impacts on GDP would be negative when there is no adaptation and impacts are relative to global economic state the same as today's. The results of FUND suggest that positive net impacts on a future economy may be possible even at the global scale, if appropriate adaptation takes place. CO_2 fertilization makes a substantial difference to the results, and further work in HELIX will address the implications of uncertainties in the relative magnitude of the radiative and physiological effects of CO_2.

Table 4: Summary of comparison of FUND and GEM-E3 projections of impacts on agriculture at approximately 4°C

Model name	FUND	GEM-E3
Source of climate projection(s)	Simple climate model	5 General Circulation Models (CMIP5 subset)
Method for crop response	Response function relating to global mean temperature	7 Global Gridded Crop Models (ISI-MIP)
CO_2 fertilization included?	Yes	Yes
Adaptation included?	Yes	No
Counterfactual state	Future economy	Present-day economy
Global warming (°C)	3.50 - 3.75	4.0
Impact on GDP (%)	0.8	-0.02

1.2 Coastal Impacts

The coastal damage impacts assessed in this section relate to capital damage caused by flood and land loss and costs related to forced migration of people. The coastal damage data is based on data from the ClimateCost project[12] and input from the DIVA model[13] - the same coastal model as in the ISI-MIP. The reason for using the ClimateCost data rather than the ISI-MIP as input into SLR assessment in this project, is different scope of DIVA output data available from the two sources, with the key difference in the coverage of data reporting on impact of SLR on households. While DIVA output available via ClimateCost provides data on, inter alia, number of people at risk of flooding and number of people forced to migrate, the ISI-MIP data does not give the forced migration figures. The migration input is important for the study because it is used in the economic analysis in order to compute the constituent impact of sea flooding on households' welfare.

The scenario used assumes a rise of sea level by 2100 of 0.47m, which is consistent with the A1B IMAGE scenario assuming 3.8°C warming by the 2090s. The methodology of the economic analysis of coastal impacts follows that of Pycroft *et al.* (2015)[14].

A related analysis, also based on the DIVA model, was provided by Hinkel *et al.* (2013) who studied coastal flood damage due to climate-induced sea level rise. While Hinkel *et al.* explore variability in coastal damage and adaptation options under uncertainties arising from range of factors related to socio-economics, population, topography, and protection, they stop short of analysis of economic consequences of such computed impacts. In contrast, this study brings the impact data (DIVA output) into a consistent macroeconomic framework in order to explore economic implications of the coastal damage.

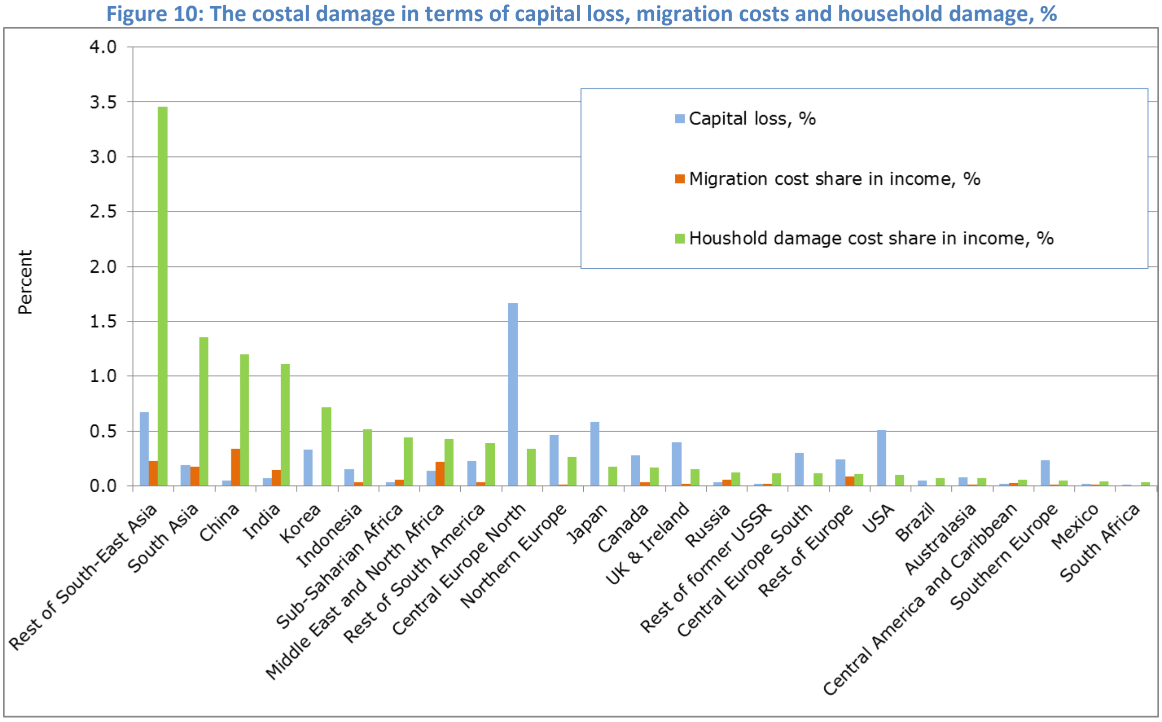
[12] http://www.climatecost.cc
[13] http://www.diva-model.net/
[14] Subsequently to the article, a critique (Tol *et al.* 2016) and a rebuttal (Pycroft *et al.* 2016) were published.

1.2.1 The coastal shock

There are two types of impact shock being introduced to the economic CGE model in order to represent the coastal impacts: coastal damage and forced migration. The coastal damage is accounted for as damage to capital (70%) and to households (30%) – the spilt follows the Climate Cost methodology. Capital damage reduces capital stock in each region, while household damage raises the obliged consumption of households. Migration cost is based on triple GDP per capita for the number of people forced to migrate where the migration cost increases subsistence share of household incomes.

Figure 10 illustrates magnitudes of the regional coastal impacts (see Table 15 in Appendix C for numerical values). Of the two main channels of impact, in percentage terms, the coastal damage is much larger than the migration costs. Within the damage impact the proportional damage to households appears to be bigger than the capital loss in the developing regions, while an opposite relation can be noticed in more developed regions.

Figure 10: The costal damage in terms of capital loss, migration costs and household damage, %



1.2.2 Results

Table 5 presents economic implication of the coastal impacts in two measures: GDP and EV (welfare), both in percentage change and absolute change (bn US$).

Table 5: GDP and welfare effects of the SLR

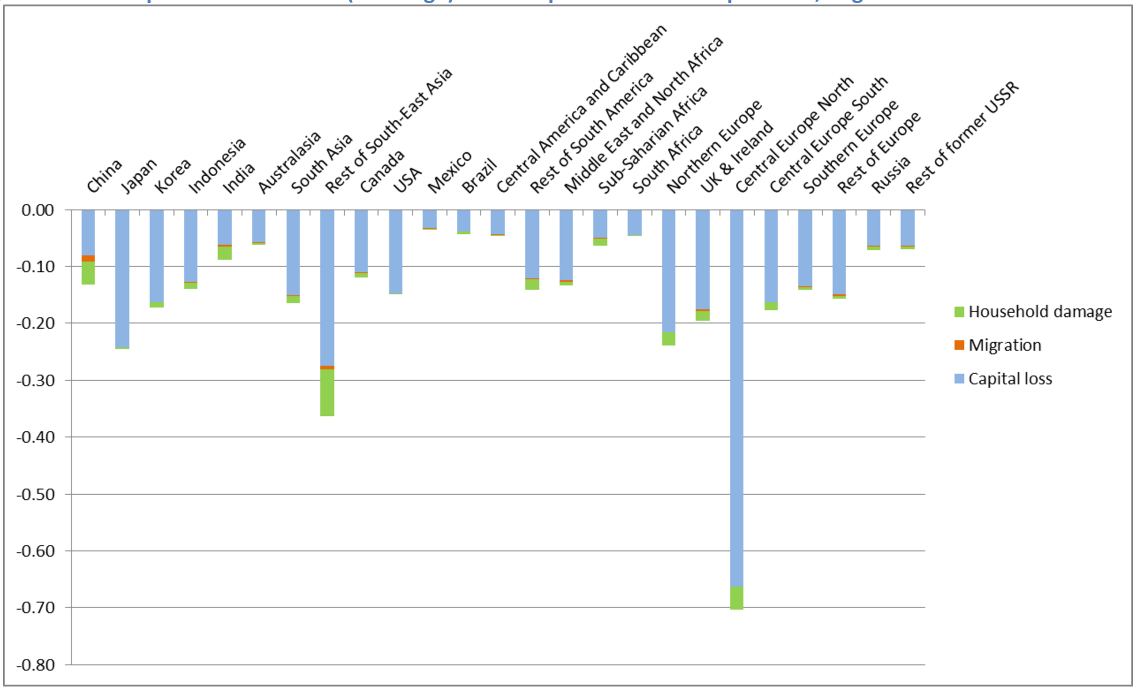
	GDP %	EV %	GDP bn US$	EV bn US$
China	-0.13	-1.80	-5	-23
Japan	-0.25	-0.67	-11	-15
Korea	-0.17	-1.08	-2	-6
Indonesia	-0.14	-0.76	-1	-2
India	-0.09	-1.39	-1	-9
Australasia	-0.06	-0.16	-1	-1
South Asia	-0.16	-1.79	-1	-6
Rest of South-East Asia	-0.36	-4.62	-4	-28
Canada	-0.12	-0.44	-2	-3
USA	-0.15	-0.34	-21	-31
Mexico	-0.03	-0.08	0	0
Brazil	-0.04	-0.14	-1	-1
Central America and Caribbean	-0.05	-0.12	0	0
Rest of South America	-0.14	-0.68	-1	-4
Middle East and North Africa	-0.13	-0.85	-3	-9
Sub-Saharian Africa	-0.06	-0.55	0	-2
South Africa	-0.05	-0.07	0	0
Northern Europe	-0.24	-0.80	-3	-4
UK & Ireland	-0.20	-0.49	-6	-9
Central Europe North	-0.70	-1.81	-36	-50
Central Europe South	-0.18	-0.44	-6	-9
Southern Europe	-0.14	-0.30	-6	-7
Rest of Europe	-0.16	-0.43	-2	-2
Russia	-0.07	-0.24	-1	-1
Rest of former USSR	-0.07	-0.17	0	0
World	-0.20	-0.73	-113	-223

The global GDP falls by 0.2% which reflects 113bn US$ reduction. The largest GDP loss is estimated for Central Europe North (0.7%) and Rest of South East Asia (0.36%). Other EU regions' GDP change in range 0.18% to 0.24%, which is close to the global average.

In the welfare terms (EV), the global reduction is 0.73% or 223 bn US$. The welfare impacts are largest in Asian regions with the Rest of South East Asia loss of 4.62%. The EU regions' welfare reductions are in range of 0.3% to 0.8% with Central Europe North loss of 1.81%.

The above GDP impacts are further decomposed into impacts due to the capital loss, migration and household damage in Figure 11.

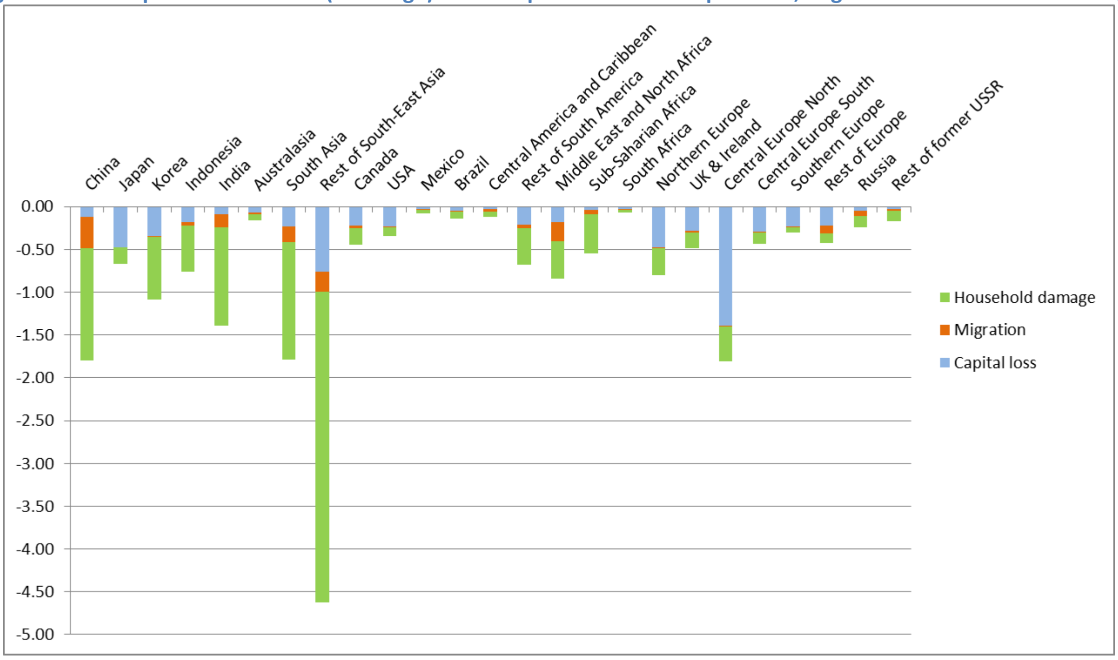
Figure 11: Decomposition of the GDP (% change) into components due to capital loss, migration and household damage



It is clear that the vast majority of GDP loss is due to the capital loss. The household damage makes a significant impact on the GDP loss in some regions, mainly in the rest of South-East Asia, China and Central Europe North. The cost of migration makes a marginal impact on the GDP change.

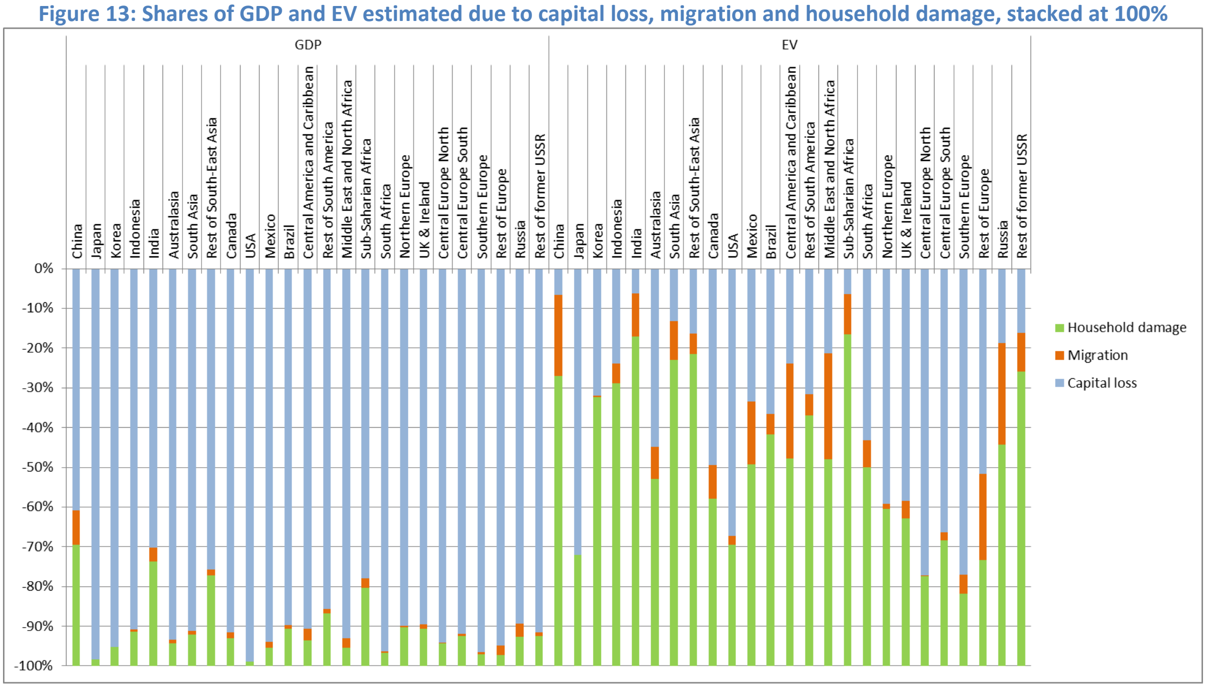
The importance of the impacts is very different when analysed from the perspective of welfare implications. As shown in Figure 12, the household damage is a very important component of the welfare loss. Capital loss is a minor share of the welfare reduction with exception of Central Europe North and Northern Europe where it contributes more than half to the EV change. Also, migration costs play more important role for the welfare reduction than for the GDP change.

Figure 12 Decomposition of the EV (% change) into components due to capital loss, migration and household damage



The proportional contribution of the coastal damage impacts are compared on Figure 13, which clearly emphasis that the capital loss is the main driver of the GDP reduction, while household damage and migrations are the main drivers of the welfare loss.

Figure 13: Shares of GDP and EV estimated due to capital loss, migration and household damage, stacked at 100%



1.3 Floods

The river flood analysis is based on the results of the ISI-MIP runs (Dankers et al. 2013). ISI-MIP considered ten different hydrological models and five GCMs, generating runoff projections at the global scale for each of the 50 runs. The discussion that follows in based on a preliminary analysis and shows the methodology and kind of results that can be obtained.

It is very important to remark two major developments which have been accomplished in this study. Firstly, PIK has produced inundation maps based on the ISI-MIP runoffs results. Secondly, JRC has estimated the economic direct effects of the simulated water levels from the inundated maps, using a global database of depth-damage functions.

Before presenting preliminary results of flood damages, this section presents the methodology to translate water levels in flood inundation maps into economic damages. The methodology is the same as that followed in the JRC PESETA II project, based on the Huizinga (2007) depth-damage functions, but extended to the whole planet.

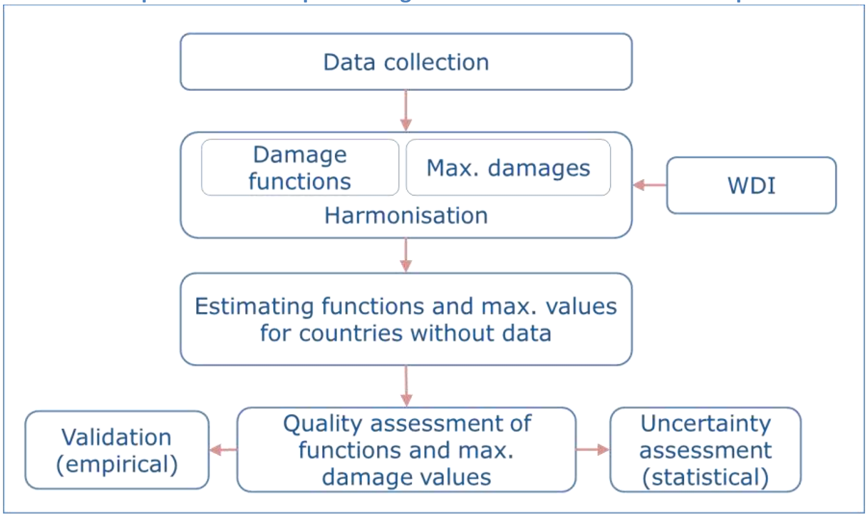
Assessing potential damage of flood events is an important component in flood risk management. Determining direct flood damage is commonly done using depth-damage curves, which denote the flood damage that would occur at specific water depths per asset or land-use class. Damage estimates in this section build on a novel, globally consistent database of depth-damage curves. The dataset contains damage curves depicting percent of damage as a function of water depth as well as maximum damage values for the following assets and land use classes:

- Residential buildings,
- Commerce,
- Industry,
- Transport,
- Infrastructure, and
- Agriculture.

Based on an extensive literature survey concave damage curves have been developed for each continent, while differentiation in flood damage between countries is established by determining maximum damage values at the country scale. These maximum damage values are based on construction cost surveys from multinational construction companies, which provide a coherent set of detailed building cost data across dozens of countries. A consistent set of maximum flood damage values for all countries was computed using statistical regressions with socio-economic World

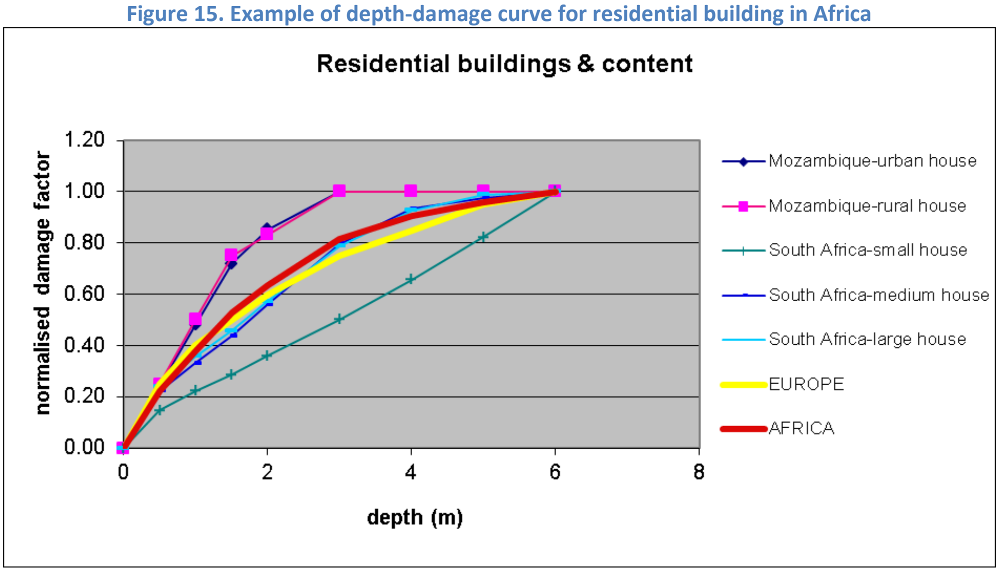
Development Indicators from the World Bank. The main stages of the development are shown on the Figure 14.

Figure 14. Development of the depth-damage functions for the river flood impact assessment



The damage curves are specified for each damage class (residential buildings, commerce, industry, transport, infrastructure, and agriculture) and for each continent. An example of the function for a residential building in Africa is shown in Figure 15, which depicts individual data collected from literature survey, as well as the aggregate damage curve for Africa and, for comparison, for Europe.

Figure 15. Example of depth-damage curve for residential building in Africa



The fractional damage indicated for each continent is applied to maximum damage values, defined at a country level, to compute the country-specific level of damage. Table 6shows examples of maximum damage values for three African countries: Ethiopia, Tanzania and Egypt. The values shown in the Table are provided for different possible measures of residential area: building based, land-use based and object based (assuming 100^2m per object).

Table 6. Maximum damage values for residential buildings in selected African countries

Country	***Building based***	***Land-use based***	***Object based***
	(€/m2, 2010)	***(€/m2, 2010)***	***(€/object, 2010)***
Ethiopia	123.30	24.66	12329.51
Tanzania	145.12	29.02	14511.82
Egypt	276.74	55.35	27673.90

Further, the damage curves and maximum damage values can be adjusted for specific local circumstances, such as urban vs. rural locations, use of specific building material, etc.

The following two tables present the first preliminary results of applying the noted global database of depth-damage functions to the PIK inundation maps. They are illustrative of the kind of results that can be obtained, providing a first indication of the range of order of magnitude. These results are subject to review and will be updated in the remainder of the HELIX project Work Package 5.

Table 7 presents for a selected set of representative countries the direct damages (in million Euro) for a specific hydrological model (DBH) and climate model (GFDL_ESM2M). The direct damages have five components: agriculture, residential, infrastructure, industry and commerce. The 'hist' columns present the impact estimation for the control period (average over the 1971-2004 period) and the 'rcp' columns present the impact estimation under climate change (average over the 2079-2098 period).

Table 7. Estimated direct damage values in selected countries and global, DBH_GFDL_ESM2M

	Agriculture		**Residential**		**Infrastructure**		**Industry**		**Commerce**		**TOTAL**	
	hist	rcp	hist	rcp	hist	rcp	hist	rcp	hist	rcp	hist	rcp
Australia	2	0	2,103	2,623	11	14	917	1,175	1,531	1,913	4,564	5,726
Bangladesh	270	1,864	324	2,323	2	16	197	1,416	273	1,935	1,066	7,554
Brazil	190	131	1,210	1,373	35	40	652	739	955	1,082	3,043	3,366
Canada	2	20	273	2,772	21	220	131	1,337	180	1,931	606	6,280
China	909	2,800	16,867	53,048	321	998	9,168	28,791	13,660	43,226	40,926	128,863
Italy	25	44	1,401	1,623	30	34	471	585	1,283	1,438	3,210	3,725
Japan	130	731	285	1,316	23	105	136	630	213	985	786	3,767
Kazakhstan	8	25	929	3,779	28	111	487	1,981	744	3,046	2,195	8,941
Myanmar	510	1,012	82	187	1	2	49	111	69	156	710	1,467
Malaysia	169	528	288	631	9	19	152	332	231	502	848	2,011
Peru	57	240	150	1,073	2	17	89	625	125	887	423	2,843
Philippines	158	360	378	1,010	4	12	216	577	320	837	1,076	2,796
Pakistan	714	191	1,325	264	11	2	791	158	1,098	219	3,938	834
Russian Federation	46	275	1,416	13,379	13	127	728	6,898	1,119	10,489	3,323	31,168
Sudan	37	62	677	2,598	7	25	388	1,516	556	2,160	1,665	6,361
Sweden	1	1	279	1,141	7	30	105	436	235	954	627	2,562
Thailand	539	1,129	723	871	15	18	392	472	581	701	2,249	3,191
Ukraine	39	13	1,278	325	19	5	688	176	1,072	272	3,096	790
United Kingdom	2	1	572	572	12	12	261	241	444	467	1,291	1,293
United States	21	21	1,977	2,444	153	182	937	1,130	1,327	1,573	4,416	5,350
Vietnam	464	1,339	76	296	1	3	44	173	62	242	647	2,053
Global	6,510	19,342	40,872	112,012	898	2,288	21,221	59,434	32,609	89,846	80,706	230,939

Under the historical control, global damage is estimated to be around 80 billion Euro globally, which have of it occurring in China. Under climate change, the overall global damage could triple, reaching 230 billion. The damages to residential buildings, 40 billion Euro, appear to represent approximately half of the overall damage.

In some countries, such as Bangladesh, Canada and the Russian Federation, the damages under climate change are much larger than those under the control scenario, by a factor of seven to ten.

Table 8 represents the estimates of direct damages for the combination of hydrological and climate models yielding the highest global damage (the JULES hydrological model and the IPSL_CM5A_LR climate model). Thus under climate change the overall global damage could be around half trillion Euro, more than twice the figure discussed above for the other hydrological/climate model combination. That figure is around five times bigger than the damages under the control run. Almost half of the additional damage is undergone by China, with an overall simulated damage of 270 billion Euro.

Table 8. Estimated direct damage values in selected countries and global, JULES_IPSL_CM5A_LR

	Agriculture		Residential		Infrastructure		Industry		Commerce		TOTAL	
	hist	rcp	hist	rcp	hist	rcp	hist	rcp	hist	rcp	hist	rcp
Australia	3	21	4,419	16,318	24	88	2,006	7,259	3,236	11,843	9,689	35,529
Bangladesh	289	1,738	350	1,480	2	10	214	901	292	1,236	1,147	5,364
Brazil	182	1,274	1,268	9,761	39	299	675	5,201	991	7,635	3,155	24,170
Canada	2	5	515	1,649	40	128	247	797	350	1,108	1,153	3,688
China	846	5,303	16,549	111,180	313	2,129	8,988	60,555	13,460	89,943	40,155	269,110
Italy	43	26	1,795	1,069	38	23	681	346	1,561	997	4,117	2,461
Japan	11	1,063	15	1,795	1	142	7	858	11	1,358	46	5,216
Kazakhstan	3	2	342	255	10	7	179	134	274	210	808	608
Myanmar	509	1,016	88	161	1	1	52	96	74	135	725	1,409
Malaysia	96	721	259	1,686	7	49	136	887	208	1,351	706	4,695
Peru	61	747	123	2,873	2	50	74	1,612	104	2,309	364	7,591
Philippines	166	658	453	1,521	5	19	260	872	382	1,252	1,266	4,320
Pakistan	653	487	1,225	993	10	8	733	595	1,014	821	3,634	2,905
Russian Federation	43	132	1,302	6,647	12	64	667	3,405	1,036	5,264	3,060	15,512
Sudan	39	177	1,034	10,492	10	99	596	6,157	847	8,587	2,527	25,512
Sweden	1	12	275	4,599	7	120	109	1,868	224	3,699	616	10,298
Thailand	429	1,161	509	980	10	20	275	532	409	787	1,632	3,480
Ukraine	63	91	2,538	4,164	37	61	1,381	2,238	2,118	3,500	6,137	10,054
United Kingdom	2	70	727	19,722	16	425	320	8,871	577	15,477	1,641	44,565
United States	8	89	1,402	15,440	109	1,138	666	7,075	944	9,656	3,129	33,397
Vietnam	305	1,485	85	547	1	5	49	319	70	448	510	2,805
Global	6,433	30,555	45,133	253,802	911	5,673	23,450	132,124	36,040	200,320	86,218	512,690

It is important to recall that all these figures are subject to additional review by the authors, as it seems e.g. that the damages under the control scenario overstate those from other sources (by a factor of two to three[15]).

[15] The overestimation is partly due to the fact that recent exposure data were used (e.g. land cover map of 2009), which means that exposure for the past flood events, especially in developing countries, are overestimated. These estimated figures will be adjusted in the coming months.

Those direct economic damages, once reviewed, can be integrated under the economic general equilibrium model in a similar way to that in the JRC PESETA II project. Specifically, the effects due to river floods have two main components: damages to residential buildings and damages to production sectors (agriculture, infrastructure, industry and commerce). The former component is interpreted as an additional obliged consumption of households, which leads to a welfare loss, in a similar way to the coastal impact analysis. The latter component is to be implemented in the model as a capital loss, also mimicking the coastal impact analysis.

4 The way forward: plan for the rest of HELIX WP5

This report has presented the main methodological aspects and preliminary results of integrating the quantifiable ISI-MIP fast track climate impacts into the economic CGE CAGE GEM-E3 model. Climate impacts in agriculture, coastal areas and river floods have been considered. Other climate impacts are also to be considered in the rest of Work Package 5 of HELIX. The plan regarding how to integrate them in the economic model is discussed in this final section. For some cases, like energy and human health, the JRC PESETA II project or a similar methodology will be implemented. For other cases, like human migration, a first set of ideas is put forward.

Regarding the heating and cooling demand changes (to be estimated with the POLES and TIAM-UCL models), they are to be integrated into the economic CGE model as changes in residential and service sectors energy demand.

Transport-related impacts will be at first modelled in a similar way to that followed in the JRC PESETA II project, which focused on the damages to transport infrastructure. Additional costs for road asphalt (due to heat stress) and bridge scour (due to river flows) were modelled as additional obliged consumption, implicitly assuming that the households would ultimately undergo those costs. All other damages to transport infrastructure, associated with extreme floods and winter conditions, were interpreted as capital losses in GEM-E3, because they can be interpreted as affecting firms (the capital stock of the economy).

A more challenging area relates to the migration climate-induced effects. Migration flows, if the partner in charge of that impact area can provide reliable estimates of bilateral migration flows due to climate change, the CGE model will be shocked with the number of migrants coming to the destination countries and leaving the origin regions. The plan is to raise the labour supply of the destination countries and decrease the labour supply in the origin countries, with an assumption of the sectoral allocation (at first, it could be a split between agriculture and industry; a sectoral migration matrix could be defined if some solid evidence is based). This CGE analysis could be improved following literature developments, such as that of the GMIG (Walmsley et al, 2007) and the GLOBE_MIG (McDonald et al., 2009) models.

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

A second considered effect was the increase in household health system expenditures due to morbidity, which was imposed on households as additional obliged consumption that did not lead to an increase in welfare due to increased consumption volumes. The third effect was the reduction in total available hours (working and leisure hours) due to both morbidity and mortality of the working age population. The fourth effect was a typical non-market impact due to mortality, which does not affect the price system. The number of premature deaths was considered as damage to the total welfare of the population. This damage was calculated by using the statistical value of life method. The value of statistical life was assumed to be €1.09 million (same value for all EU member states), the low-end of the range of estimates considered in the recent review of the European Clean Air Policy Package (European Commission, 2013).

References:

Bosello F, Eboli F, Pierfederici R (2012). Assessing the Economic Impacts of Climate Change. An Updated CGE Point of View. FEEM Nota di Lavoro 2.2012.

Ciscar JC, Iglesias A, Feyen L, Szabó L, Van Regemorter D, Amelung B, Nicholls R, Watkiss P, Christensen OB, Dankers R, Garrote L, Goodess CM, Hunt A, Moreno A, Richards J, Soria A (2011), Physical and economic consequences of climate change in Europe. Proc. Natl Acad. Sci. USA 108:2678-2683 doi:10.1073/pnas.1011612108.

Ciscar JC, L. Szabó, D. van Regemorter and A. Soria (2012), The integration of PESETA sectoral economic impacts into the GEM-E3 Europe model: methodology and results. Climatic Change 112:127–142, DOI 10.1007/s10584-011-0343-y

Dankers, R., Arnell, N.W., Clark, D.B., Falloon, P.D., Fekete, B.M., Gosling, S.N., Heinke, J., Kim, H., Masaki, Y., Satoh, Y., Stacke, T., Wada, Y, Wisser, D. (2013) First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. Proc. Natl Acad. Sci. USA (111) 3257-3261.

European Commission (2013). Impact Assessment, Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions -a Clean Air Programme for Europe. Commission Staff Working Document, http://ec.europa.eu/environment/air/pdf/clean_air/Impact_assessment_en.pdf.

Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S.J., Marzeion, B., Fettweis, X., Ionescu, C., Levermann, A. (2013): Coastal flood damages and adaptation costs under 21st century sea-level rise. Proc. Natl. Acad. Sci. USA, 111, 9, 3292-3297. doi: 10.1073/pnas.1222469111

Houser T, Kopp R, Hsiang S, Larsen K, Delgado M, Jina A, Mastrandrea M, Mohan, Muir-Wood SR, Rasmussen DJ, Rising J, Wilson P (2015). Economic Risks of Climate Change: An American Prospectus. Columbia University Press.

Huizinga HJ (2007) Flood damage functions for EU member states. (Technical Report, HKV Consultants. Implemented in the framework of the contract #382441-F1SC awarded by the European Commission - Joint Research Centre, Ispra, Italy).

Kovats, R.S., Lloyd, S.J. (2011). Climate Change Impacts on Health in Europe, Deliverable D2E., ClimateCost project.

McDonald, S., Sonmez, Y. and Thierfelder, K. (2009). Turkey and the EU: Economic Integration and Labour Migration. 12th Global Economic Analysis Conference, "Trade Integration and Sustainable Development: Looking for an Inclusive World", ECLAC, Santiago, Chile, June 2009

OECD (2015). The Economic Consequences of Climate Change, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264235410-en

Pycroft J, Abrell J, Ciscar JC (2015). The Global Impacts of Extreme Sea-Level Rise: A Comprehensive Economic Assessment. Environmental and Resource Economics

Pycroft, J., Abrell, J. and Ciscar, J-C. (2016) Response to "Comment on 'The Global Impacts of Extreme Sea-Level Rise: A Comprehensive Economic Assessment"' (Richard Tol, Robert J. Nicholls, Sally Brown, Jochen Hinkel, Athanasios T. Vafeidis, Tom Spencer and Mark Schuerch) Environ Resource Econ 64

Rosenzweig, Cynthia, Joshua Elliott, Delphine Deryng, Alex C. Ruane, Christoph Muller, Almut Arneth, Kenneth J. Boote et al. "*Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison*." Proceedings of the National Academy of Sciences 111. (2014): 3268-3273

Schleussner, C.F., Lissner, T. K., Fischer, E. M., Wohland, J., Perrette, M., Golly, A., Rogelj, J., Childers, K., Schewe, J., Frieler, K., Mengel, M., Hare, W., and Schaeffer, M.: "*Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 °C and 2 °C*", Earth Syst. Dynam., 7, 327-351, doi:10.5194/esd-7-327-2016, 2016.

Shoven J, Whalley J (1992). Applying General Equilibrium, Cambridge University Pres

Tol, R.S.J. (2013) The economic impact of climate change in the 20th and 21st Centuries. Climatic Change 117:795-808

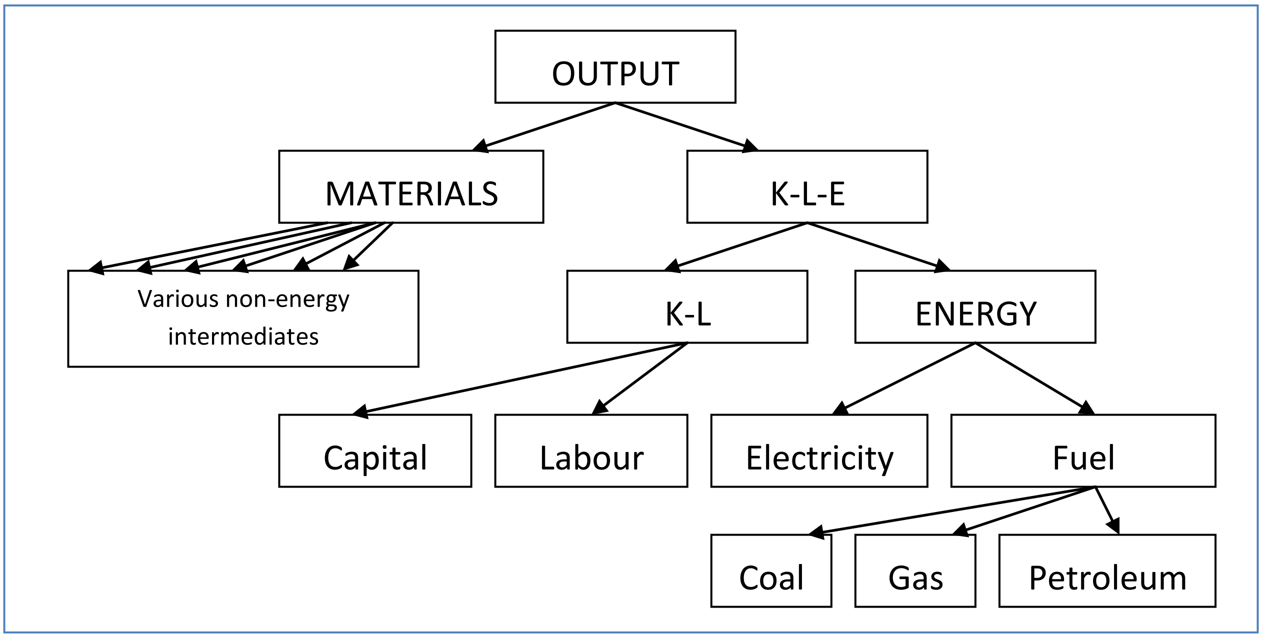
Tol, R.S.J., R. J. Nicholls, S. Brown, J. Hinkel, A. T. Vafeidis, T. Spencer, Mark Schuerch (2016) Comment on 'The Global Impacts of Extreme Sea-Level Rise: A Comprehensive Economic Assessment' Environ Resource Econ 64: 341. doi:10.1007/s10640-015-9993-y

Walmsley, T, Winters, A. and Ahmed, S.A., (2007). "Measuring the Impact of the Movement of Labor Using a Model of Bilateral Migration Flows". https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=2529

Appendix A Description of the CAGE-GEME3 model

Producers seek to maximise profits subject to their production technology and the cost of inputs. The production technology is modelled using a nested constant elasticity of substitution (CES) function which is summarised in below.

Figure 16: Production structure in the CAGE model



NOTE: K-L-E REFERS TO THE CAPITAL-LABOUR-ENERGY BUNDLE AND K-L TO THE CAPITAL-LABOUR BUNDLE.

As shown, output is produced by combining capital (K) and labour (L) with energy (E) and other intermediate inputs. All combinations of inputs are treated as imperfect substitutes, as governed by CES functions (though some are given low elasticity values to reflect low levels of substitutability).

All commodities enter the marketplace. Production from each country can be sold either within that country or exported. Similarly, the purchase of goods and services can be either of domestic production or imports. Total domestic demand consists of that from households, government, investment, intermediate inputs, and inputs for transport margins used for trade. The extent to which this domestic demand is satisfied by imports or domestic production is governed by a two-level constant elasticity of substitution function reflecting the imperfect substitutability at both levels. On the lower level, imports from different regions are combined, and on the upper level, the composite import commodity is combined with domestic production (the Armington function, Armington, 1969).

The economic institutions included in the model are households, government, firms and the rest of the world. Households purchase marketed commodities at market prices, meaning that the prices include commodity taxes. Households maximise their utility or well-being based on their preferences and the relative prices of goods and services, subject to their income constraints. Household consumption also has a nested structure, with households first choosing between energy and non-energy commodities and then on consumption within these categories. Substitutability within each nest is determined by a constant elasticity of substitution function.

There are general constraints to the system (which are not directly considered by any of the particular economic agents). The zero profit constraint in production is imposed as firms are assumed to operate in a competitive environment. There are also zero profit constraints on domestic economic institutions – households, governments and investment – which mean that all income to institutions must be accounted for with either spending or saving. With respect to imports and transport margins, the zero profit conditions imply that their prices are also constrained to match their costs, inclusive of margins and taxes, as appropriate.

The macroeconomic closure rules govern the savings-investment behaviour, aggregate government finances, the behaviour of factor markets and the trade balance between each country and the rest of the world. The savings-investment closure maintains a constant volume of investment, and any change in the price of investment goods is adjusted for by changing the value of household savings. The government closure allows public consumption to be flexible in terms of quantity, then any additional revenue to government raises government income, and hence raises government expenditure. In that case, government consumption is modelled with a Leontief function, i.e. an increase (fall) in government expenditure proportionally increases (decreases) consumption of all commodities. The factor-market closure fixes the aggregate volume of both capital and labour at the regional level. Both capital and labour can move between sectors, however capital and labour are immobile across regions. Thus, returns to capital and wage rate of labour adjust to clear the market, and the wage and capital prices are region specific. The rest-of-the-world closure fixes the current account balance between regions at the benchmark level, with prices adjusting to ensure that all production from each region is either consumed domestically or exported.

Table 9: List of region-codes and geographical aggregation.

Country code used	Country	List of countries
CHN	China	China
JPN	Japan	Japan
KOR	Korea	Korea
IDN	Indonesia	Indonesia
RUS	Russia	Russia
IND	India	India
USA	USA	USA
CAN	Canada	Canada
MEX	Mexico	Mexico
BRA	Brazil	Brazil
ZAF	South Africa	South Africa
GBIRL	UK & Ireland	UK, Ireland
NEU	Northern Europe	Denmark, Estonia, Finland, Lithuania, Latvia, Sweden
CEUN	Central Europe (North)	Poland, Netherlands, Luxembourg, Germany, Belgium
CEUS	Central Europe (South)	Austria, Czech Republic, France, Hungary, Romania, Slovakia, Slovenia, Croatia
SEU	Southern Europe	Bulgaria, Cyprus, Spain, Greece, Italy, Malta, Portugal
AUZ	Australasia	Australia, New Zealand, rest of Oceania
SAsia	South Asia	Bangladesh, Iran, Sri Lanka, Nepal, Pakistan, rest of South Asia
SSA	Sub-Saharan Africa	Botswana, Cote d'Ivore, Cameroon, Ethiopia, Ghana, Kenya, Madagascar, Mozambique, Mauritius, Malawi, Namibia, Nigeria, Senegal, Tanzania, Uganda, South Central Africa, Central Africa, rest of Eastern Africa, Rest of South African Customs Union, Rest of Western Africa, Zambia, Zimbabwe
RoEUR	Rest of Europe	Albania, Switzerland, Norway, Rest of Eastern Europe, Rest of EFTA, Rest of Europe
RoSEAsia	Rest of South-east Asia	Cambodia, Laos, Mongolia, Malaysia, Philippines, Singapore, Thailand, Taiwan, Vietnam, Rest of East Asia, Rest of Southeast Asia, Rest of the World
RoFSU	Rest of Former USSR	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Ukraine, Rest of Former Soviet Union
MENA	Middle East & North Africa	United Arab Emirates, Bahrain, Egypt, Israel, Kuwait, Morocco, Oman, Qatar, Saudi Arabia, Tunisia, Turkey, Rest of North Africa, Rest of Western Asia
CAMCAR	Central. America & Caribbean	Costa Rica, Guatemala, Honduras, Nicaragua, Panamá, El Salvador, Rest of Central America, Caribbean, Rest of North America
SAmer	Rest of South America	Argentina, Bolivia, Chile, Colombia, Ecuador, Peru, Paraguay, Uruguay, Venezuela, Rest of South America

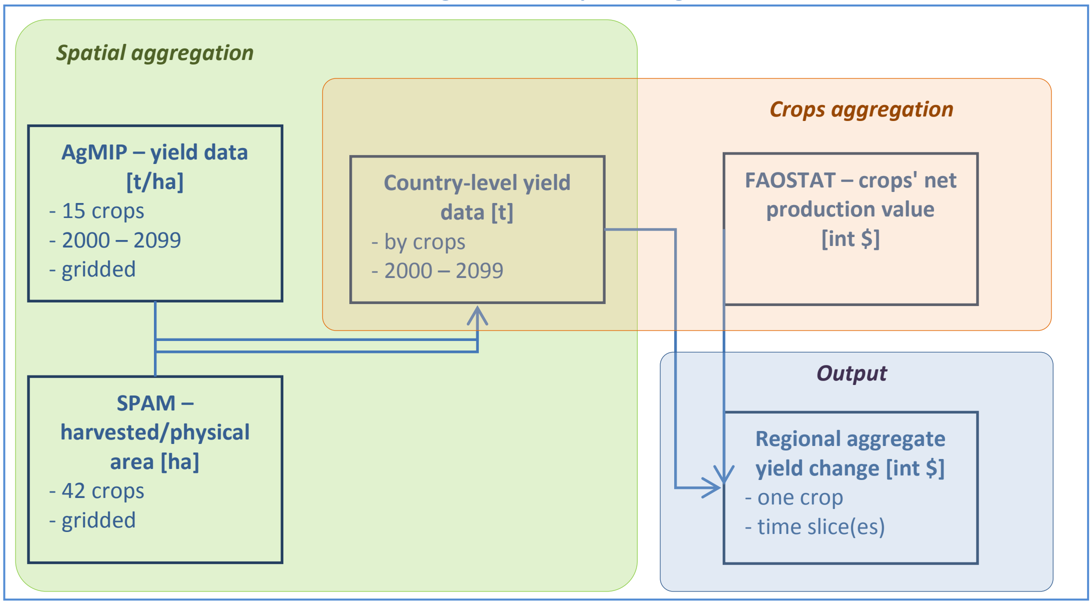
Table 10: List of sector codes and sectoral aggregation

AGR	Agriculture	Bovine cattle, sheep and goats, horses, animal products nec, raw milk, wool, silk-worm cocoons, fishing
Crops	Crops	Paddy rice, wheat, cereal, grains nec, vegetables, fruit, nutsv oil seeds, sugar cane, sugar beet, plant-based fibers, crops nec
Forest	Forestry	Forestry
COA	Coal Mining	Coal
CRU	Crude Oil Extraction	Oil
GAS	Natural Gas	Gas, gas manufacture, distribution
P_C	Refined Oil	Petroleum, coal products
ELE	Electricity	Electricity
MET	Metals	Ferrous metals, metals nec, metal products
CHE	Chemicals	Chemical, rubber, plastic products
EINT	Energy Intensives	Minerals nec, paper products, publishing, mineral products nec
EEQU	Electronic equipment	Electronic equipment
TEQU	Transport Equipment	Motor vehicles and parts, transport equipment nec
OEQU	Other Equipment	Machinery and equipment nec, manufactures nec
CONC	Consumer Goods	Bovine meat products, meat products nec, vegetable oils and fats, airy products, processed rice, sugar, food products nec, beverages and tobacco products, textiles, wearing apparel, leather products, wood products
CNS	Construction	Construction
TRN	Transport	Transport nec, water transport, air transport
MSER	Market Services	Water, trade, communication, financial services nec, insurance, business services nec, dwellings
NMSER	Non-market Services	Recreational and other services, public administration, Defense, Education, Health

Appendix B Aggregating AgMIP data for economic model

The method builds on the AgMIP data simulated with the CGE model, which requires two types of aggregation to be addressed: spatial dimension and differentiated crops representation (Figure 17). The data processing steps are discussed in turn below, followed by discussion on data availability, and strengths and limitations of the approach.

Figure 17: Data processing overview



Spatial aggregation

The ISI-MIP provides yields data on a regular 0.5^{o} x 0.5^{o} grid level resolution, while the SPAM data is available at even finer $1/12^{o}$, hence it has to be aggregated to fit the CGE model which requires information at the level of administrative units (countries and regions).

Because the yield (kg/ha) does not carry information about absolute production or cultivated area, an additional data (a weighting criterion) has to be brought in in order to aggregate the grid-level data into country- and region representations. Following Müller and Robertson (2014) we use data on actual physical production areas[16] for the individual crops from the Spatial Production Allocation Model (SPAM) data (You et al., 2014) to construct the weighting factor:

$$YldWeight_{gs,c,r} = \frac{SPAMarea_{gs,c,r}}{\sum_{gs\in r} SPAMarea_{gs,c,r}} \qquad so: \sum_{r} YldWeight_{gs,c,r} = 1$$

[16] Physical production area is a "measured in hectare, and represents the actual area where a crop is grown, not counting how often production was harvested from it. Physical area is calculated for each production system and crop, and the sum of all physical areas of the four production systems constitutes the total physical area for that crop".

Where *gs* denotes SPAM grid square, *r* denotes region[17] and *c* denotes crops.

Then, the weighting factor is used to spatially aggregate grid-level AgMIP yield data to the regional level:

$$ChYldSPAM_{c,r} = \sum_{gs \in r} YldAgMIP_{gs,c,r} * YldWeight_{gs,c,r}$$

The crops' categories available from SPAM database cover most of the crops provided by the ISI-MIP data, with the following mapping:

Table 11: mapping between AgMIP and SPAM crop categories

ISI-MIP	**SPAM**
wheat	whea
barley	barl
Sugarcane	sugc
Sugar beet	sugb
Ground nuts	grou
soy	soyb
maize	maiz
rice	rice
millet	mill
cassava	cass
sorghum	sorg
Sunflower & rapeseed	ooil
Not Applicable	
Managed grass	Pota
field pea	swpy
	banp
	bean
	opul
	coff
	cott
	ofib
	othe

Additionally, both ISI-MIP and SPAM distinguish between irrigated and non-irrigated (rain-fed) crops thus the above aggregation would need to be repeated for the two types of crops/land.

Crops aggregation

[17] Note: the macroeconomic (CGE) model used for assessment of changes in crop productivity uses aggregation of countries (regions) in some instances, which may require additional aggregation of country-shocks into regional-shocks.

In order to investigate the economic implication of climate-induced change in crop productivity with the CGE model, the individual crops' yields need to be aggregated into single crop category. For this purpose we use data on Net Production Value per Crop from the Food and Agriculture Organization (FAOSTAT) of the United Nations[18]. Firstly, we take a 5-year average of crops production to reduce effect of any single-year phenomena:

$$FAOprodAvg_{r,c} = \frac{\sum_r FAOprod_{r,c,t}}{5} \quad \text{where, for example, } t = 2010 \text{ to } 2015$$

Where r denotes region, c denotes crops and t denotes year.

The crops' yield change *(ChYldSPAM)* is applied to the averaged crop production to observe the change in the production and, subsequently, the aggregation to one crop category and computation of percentage change is computed:

$$FAOprodClim_{c,r} = FAOprodAvg_{c,r} \times ChYldSPAM_{c,r}$$

$$YldShock_r = \frac{\sum_c FAOprodClim_{r,c} - \sum_c FAOprodAvg_{r,c}}{\sum_c FAOprodAvg_{r,c}}$$

Where $YldShock_r$ can be used directly with the CGE model.

Choice of GCM and crop models

Table 12 and Table 13 provide an overview of data available from the AgMIP for the different data GCMs and GGCMs.

[18] http://faostat3.fao.org/home/E

Table 12: Availability of data with transient CO_2 levels fixed at year 2000 level

Crop model	GCM	RCPs					Crops															
		hist	rcp2p6	rcp4p5	rcp6p0	rcp8p5	bar	ben	cas	cot	mai	mil	nut	pea	rap	ric	sgb	sor	soy	sug	sun	whe
	gfdl-esm2m	1980-2010	-	-	-	2005-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	hadgem2-es	1980-2010	2005-2099	2005-2099	2005-2099	2005-2099	8p5	8p5	8p5	8p5	all	8p5	8p5	-	8p5	all	-	8p5	all	8p5	8p5	all
epic	ipsl-cm5a-lr	1980-2010	-	-	-	2005-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	miroc-esm-chem	1980-2010	-	-	-	2005-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	noresm1-m	1980-2010	-	-	-	2005-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	gfdl-esm2m	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	hadgem2-es	1971-2004	2005-2099	2005-2099	2005-2099	2005-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
gepic	ipsl-cm5a-lr	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	miroc-esm-chem	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	noresm1-m	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	gfdl-esm2m	1971-2000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	hadgem2-es	1971-2000	-	-	-	2005-2099	-	-	all	-	all	all	all	-	-	all	-	all	all	all	all	all
image	ipsl-cm5a-lr	1971-2000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	miroc-esm-chem	1971-2000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	noresm1-m	1971-2000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	gfdl-esm2m	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	hadgem2-es	1971-2004	2005-2099	2005-2099	2005-2099	2005-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
lpj-guess	ipsl-cm5a-lr	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	miroc-esm-chem	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	noresm1-m	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	gfdl-esm2m	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	all	-	all	all	all	all	all	all	all	-	all	all	all	all
	hadgem2-es	1971-2004	2005-2099	2005-2099	2005-2099	2005-2099	-	-	all	-	all	all	all	all	all	all	all	-	all	all	all	all
lpjml	ipsl-cm5a-lr	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	all	-	all	all	all	all	all	all	all	-	all	all	all	all
	miroc-esm-chem	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	all	-	all	all	all	all	all	all	all	-	all	all	all	all
	noresm1-m	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	all	-	all	all	all	all	all	all	all	-	all	all	all	all
	gfdl-esm2m	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	hadgem2-es	1971-2004	2005-2099	2005-2099	2005-2099	2005-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
pdssat	ipsl-cm5a-lr	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	miroc-esm-chem	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	noresm1-m	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	gfdl-esm2m	1971-2005				2006-2099	-	-	-	-	all	-	-	-	-	-	-	-	all	-	-	all
	hadgem2-es	1971-2004	2005-2099	2005-2099	2005-2099	2005-2099	-	-	-	-	all	-	-	-	-	-	-	-	all	-	-	all
pegasus	ipsl-cm5a-lr	1971-2005				2006-2099	-	-	-	-	all	-	-	-	-	-	-	-	all	-	-	all
	miroc-esm-chem	1971-2005				2006-2099	-	-	-	-	all	-	-	-	-	-	-	-	all	-	-	all
	noresm1-m	1971-2005				2006-2099	-	-	-	-	all	-	-	-	-	-	-	-	all	-	-	all

Table 13: Availability of data with transient CO_2 provides CO_2 fertilisation effect (either in the model or simulated manually by the modellers).

Crop model	GCM	RCPs					Crops															
		hist	rcp2p6	rcp4p5	rcp6p0	rcp8p5	bar	ben	cas	cot	mai	mil	nut	pea	rap	ric	sgb	sor	soy	sug	sun	whe
	gfdl-esm2m	1980-2010	2005-2099	-	-	2005-2099	all	all	all	all	all	all	all	-	all	all	-	all	all	all	all	all
	hadgem2-es	1980-2010	2005-2099	2005-2099	2005-2099	2005-2099	all	all	all	all	all	all	all	-	all	all	-	all	all	all	all	all
epic	ipsl-cm5a-lr	1980-2010	2005-2099	-	-	2005-2099	all	all	all	all	all	all	all	-	all	all	-	all	all	all	all	all
	miroc-esm-chem	1980-2010	2005-2099	-	-	2005-2099	all	all	all	all	all	all	all	-	all	all	-	all	all	all	all	all
	noresm1-m	1980-2010	2005-2099	-	-	2005-2099	all	all	all	all	all	all	all	-	all	all	-	all	all	all	all	all
	gfdl-esm2m	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	hadgem2-es	1971-2004	2005-2099	2005-2099	2005-2099	2005-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
gepic	ipsl-cm5a-lr	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	miroc-esm-chem	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	noresm1-m	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	gfdl-esm2m	1971-2005	2006-2099	-	-	2006-2099	-	-	all	-	all	all	all	-	-	all	-	all	all	all	all	all
	hadgem2-es	1971-2004	2005-2099	2005-2099	2005-2099	2005-2099	-	-	all	-	all	all	all	-	-	all	-	all	all	all	all	all
image	ipsl-cm5a-lr	1971-2005	2006-2099	-	-	2006-2099	-	-	all	-	all	all	all	-	-	all	-	all	all	all	all	all
	miroc-esm-chem	1971-2005	2006-2099	-	-	2006-2099	-	-	all	-	all	all	all	-	-	all	-	all	all	all	all	all
	noresm1-m	1971-2005	2006-2099	-	-	2006-2099	-	-	all	-	all	all	all	-	-	all	-	all	all	all	all	all
	gfdl-esm2m	1971-2005	2006-2099	-	-	2006-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	hadgem2-es	1971-2004	2005-2099	2005-2099	2005-2099	2005-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
lpj-guess	ipsl-cm5a-lr	1971-2005	2006-2099	-	-	2006-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	miroc-esm-chem	1971-2005	2006-2099	-	-	2006-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	noresm1-m	1971-2005	2006-2099	-	-	2006-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	gfdl-esm2m	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	all	-	all	all	all	all	all	all	all	-	all	all	all	all
	hadgem2-es	1971-2004	2005-2099	2005-2099	2005-2099	2005-2099	-	-	all	-	all	all	all	all	all	all	all	-	all	all	all	all
lpjml	ipsl-cm5a-lr	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	all	-	all	all	all	all	all	all	all	-	all	all	all	all
	miroc-esm-chem	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	all	-	all	all	all	all	all	all	all	-	all	all	all	all
	noresm1-m	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	all	-	all	all	all	all	all	all	all	-	all	all	all	all
	gfdl-esm2m	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	hadgem2-es	1971-2004	2005-2099	2005-2099	2005-2099	2005-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
pdssat	ipsl-cm5a-lr	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	miroc-esm-chem	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	noresm1-m	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	-	-	all	-	-	-	-	all	-	-	all	-	-	all
	gfdl-esm2m	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	-	-	all	-	-	-	-	-	-	-	all	-	-	all
	hadgem2-es	1971-2004	2005-2099	2005-2099	2005-2099	2005-2099	-	-	-	-	all	-	-	-	-	-	-	-	all	-	-	all
pegasus	ipsl-cm5a-lr	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	-	-	all	-	-	-	-	-	-	-	all	-	-	all
	miroc-esm-chem	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	-	-	all	-	-	-	-	-	-	-	all	-	-	all
	noresm1-m	1971-2005	2006-2099	2006-2099	2006-2099	2006-2099	-	-	-	-	all	-	-	-	-	-	-	-	all	-	-	all

Table 14: Percentage change in crop yield by GCM and GCCM at 4^{o}C warming.

GCM	GGCM	Australia & NZ		Brasil		Central America and Caribbean		Canada		Central Europe North		Central Europe South		China		UK & Irland		Indonesia		India		Japan		Korea	
		co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2
EPIC	hadgem2-es	0.12	-0.09	-0.08	-0.19	-0.42	-0.53	-0.31	-0.46	0.26	0.11	0.12	0.01	-0.19	-0.33	0.23	0.14	-0.14	-0.30	-0.19	-0.33	0.03	-0.16	0.02	-0.20
	ipsl-cm5a-lr	0.15	0.07	-0.13	-0.04	-0.43	-0.37	-0.20	-0.35	0.17	0.08	0.09	0.01	-0.19	-0.32	0.15	0.12	-0.14	-0.29	-0.25	-0.37	0.06	-0.14	0.11	-0.10
	miroc-esm-chem	0.20	0.15	-0.13	-0.04	-0.30	-0.27	-0.20	-0.34	0.20	0.12	0.09	0.04	-0.18	-0.29	0.20	0.19	-0.08	-0.22	-0.26	-0.34	0.03	-0.13	0.13	-0.07
	noresm1-m	0.20	0.04	-0.15	-0.06	-0.36	-0.37	-0.35	-0.47	0.20	0.06	0.09	0.01	-0.14	-0.31	0.19	0.14	-0.05	-0.23	-0.20	-0.35	0.12	-0.13	0.21	-0.04
GEPIC	hadgem2-es	0.58	0.53	-0.09	-0.25	-0.17	-0.31	-0.09	-0.17	-0.01	-0.17	-0.07	-0.21	-0.10	-0.25	0.03	-0.16	-0.07	-0.19	-0.02	-0.20	0.08	-0.11	0.05	-0.18
	ipsl-cm5a-lr	0.46		-0.12		-0.11		-0.07		-0.01		-0.19		-0.07		-0.21		-0.12		-0.24		0.05		0.17	
	miroc-esm-chem	0.45		-0.08		-0.09		-0.04		-0.03		-0.15		-0.02		-0.11		-0.09		-0.17		-0.03		-0.02	
	noresm1-m	0.60		0.03		-0.01		-0.08		0.14		-0.06		0.02		0.11		-0.09		-0.07		0.13		0.13	
IMAGE	hadgem2-es	-0.04	-0.15	-0.04	-0.12	-0.13	-0.22	0.04	-0.05	-0.03	-0.12	-0.05	-0.13	0.08	-0.02	-0.02	-0.09	0.00	-0.13	-0.09	-0.18	0.20	0.22	0.13	0.05
	ipsl-cm5a-lr	-0.08		-0.05		-0.27		0.12		-0.11		-0.03		0.09		-0.07		0.00		0.02		0.24		0.06	
	miroc-esm-chem	0.08		-0.05		-0.15		0.17		-0.07		0.02		0.09		-0.04		0.01		-0.11		0.34		0.08	
	noresm1-m	0.18		0.05		-0.25		0.75		0.09		0.08		0.18		0.01		0.10		0.03		0.37		0.20	
LPJ-GUESS	hadgem2-es	0.10	-0.23	0.27	-0.25	0.20	-0.26	0.30	-0.02	0.23	-0.03	0.24	0.05	0.42	-0.12	0.18	-0.03	0.49	-0.24	0.70	-0.25	0.94	0.09	1.06	0.02
	ipsl-cm5a-lr	0.16		0.29		0.27		0.31		0.24		0.20		0.42		0.16		0.56		0.75		1.00		1.22	
	miroc-esm-chem	0.16		0.23		0.29		0.26		0.26		0.29		0.41		0.25		0.49		0.56		1.02		1.02	
	noresm1-m	0.34		0.49		0.44		0.56		0.52		0.46		0.84		0.35		1.07		1.41		1.46		1.84	
LPJmL	hadgem2-es	0.47	0.29	0.19	-0.01	-0.02	-0.16	0.11	-0.06	0.01	-0.16	-0.24	-0.37	0.16	-0.17	0.01	-0.13	-0.01	-0.30	0.12	-0.23	0.20	-0.18	-0.14	-0.51
	ipsl-cm5a-lr	0.48	0.30	0.11	-0.09	-0.09	-0.22	0.05	-0.12	0.04	-0.13	-0.19	-0.32	0.13	-0.18	0.04	-0.11	-0.04	-0.35	0.06	-0.30	0.25	-0.14	0.06	-0.31
	miroc-esm-chem	0.48	0.26	0.29	0.08	0.04	-0.10	0.05	-0.11	0.06	-0.12	-0.18	-0.31	0.15	-0.16	0.07	-0.10	0.00	-0.28	0.01	-0.32	0.22	-0.11	0.04	-0.31
	noresm1-m	0.81	0.46	0.32	0.01	0.06	-0.15	0.18	-0.07	0.20	-0.06	-0.11	-0.29	0.35	-0.12	0.17	-0.05	0.19	-0.27	0.24	-0.24	0.39	-0.13	0.25	-0.33
pDSSAT	hadgem2-es	-0.03	-0.21	-0.09	-0.28	-0.08	-0.23	0.23	-0.04	0.37	0.11	0.08	-0.10	0.04	-0.13	0.12	-0.05	-0.06	-0.25	-0.11	-0.31	0.26	0.07	0.02	-0.11
	ipsl-cm5a-lr	0.04	-0.16	-0.07	-0.28	-0.18	-0.35	0.25	-0.05	0.44	0.14	0.16	-0.06	0.02	-0.16	0.18	-0.03	-0.02	-0.23	-0.15	-0.37	0.25	0.04	0.11	-0.02
	miroc-esm-chem	0.04	-0.14	-0.08	-0.27	-0.07	-0.22	0.28	0.01	0.14	-0.06	0.15	-0.03	0.05	-0.12	0.47	0.24	-0.03	-0.21	-0.18	-0.37	0.16	-0.01	0.12	0.00
	noresm1-m	0.14	-0.11	0.04	-0.22	-0.06	-0.27	0.35	-0.01	0.37	0.07	0.23	-0.01	0.14	-0.08	0.39	0.11	0.00	-0.23	-0.13	-0.38	0.32	0.07	0.24	0.07
PEGASUS	hadgem2-es	-0.23	-0.49	-0.42	-0.59	-0.55	-0.57	0.08	-0.26	0.09	-0.22	-0.23	-0.40	-0.09	-0.26	0.07	-0.28	-0.58	-0.61	-0.46	-0.58	0.51	0.14	-0.17	-0.45
	ipsl-cm5a-lr	-0.23	-0.50	-0.65	-0.76	-0.67	-0.69	0.25	-0.16	0.09	-0.24	-0.18	-0.37	-0.23	-0.38	-0.03	-0.37	-0.66	-0.69	-0.61	-0.70	0.48	0.11	-0.26	-0.53
	miroc-esm-chem	-0.19	-0.46	-0.54	-0.67	-0.65	-0.67	0.29	-0.12	0.07	-0.23	-0.16	-0.34	-0.15	-0.31	-0.09	-0.39	-0.60	-0.63	-0.58	-0.68	0.15	-0.15	-0.51	-0.68
	noresm1-m	0.15	-0.38	-0.35	-0.61	-0.61	-0.64	0.25	-0.26	0.37	-0.16	-0.07	-0.36	0.03	-0.27	0.01	-0.44	-0.54	-0.60	-0.44	-0.62	0.65	0.08	-0.16	-0.55

Table 14 cont.

GCM	GGCM	Middle East & NOrth Africa		Mexico		Northern Europe		Rest of Europe		Rest of FSU		Rest of South-East Asia		Sub-Saharan Africa		Russia		South America		South-East Asia		Southern Europe		USA		South Africa	
		co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2	co2	noco2
EPIC	hadgem2-es	-0.08	-0.22	-0.33	-0.40	0.27	0.10	0.03	-0.07	-0.05	-0.21	-0.22	-0.36	-0.29	-0.39	-0.06	-0.26	0.03	-0.12	-0.11	-0.28	0.10	-0.04	-0.44	-0.57	0.01	-0.09
	ipsl-cm5a-lr	-0.04	-0.09	-0.41	-0.33	0.09	0.10	0.08	0.00	-0.02	-0.15	-0.17	-0.29	-0.31	-0.33	0.10	-0.12	-0.12	-0.28	-0.11	-0.29	0.09	-0.06	-0.23	-0.35	0.04	-0.17
	miroc-esm-chem	-0.12	-0.17	-0.32	-0.24	0.19	0.13	0.02	-0.05	-0.08	-0.20	-0.15	-0.27	-0.18	-0.22	0.03	-0.16	-0.05	-0.17	-0.17	-0.29	0.09	-0.02	-0.41	-0.52	0.03	-0.16
	noresm1-m	-0.06	-0.15	-0.41	-0.32	0.24	0.09	0.01	-0.08	-0.13	-0.29	-0.15	-0.24	-0.22	-0.27	-0.06	-0.33	-0.05	-0.05	-0.03	-0.25	0.15	-0.04	-0.37	-0.49	0.11	-0.06
GEPIC	hadgem2-es	-0.04	-0.10	-0.15	-0.24	0.03	-0.09	-0.13	-0.19	-0.11	-0.18	-0.15	-0.28	-0.09	-0.13	-0.08	-0.14	0.05	-0.08	-0.05	-0.19	-0.10	-0.20	-0.07	-0.23	0.12	0.08
	ipsl-cm5a-lr	-0.02		-0.21		-0.03		-0.07		-0.09		-0.12		-0.09		-0.04		-0.03		-0.11		-0.11		-0.09		0.19	
	miroc-esm-chem	-0.01		-0.16		0.01		-0.08		-0.10		-0.08		-0.09		-0.02		0.11		-0.19		-0.03		-0.10		-0.03	
	noresm1-m	0.05		-0.17		0.08		-0.06		-0.06		-0.11		-0.03		0.01		0.20		-0.08		-0.06		-0.07		0.03	
IMAGE	hadgem2-es	-0.07	-0.18	-0.09	-0.18	0.03	-0.08	-0.05	-0.12	0.00	-0.12	0.00	-0.12	-0.03	-0.14	-0.01	-0.13	0.05	-0.06	0.08	-0.06	0.02	-0.09	0.07	0.01	0.07	-0.02
	ipsl-cm5a-lr	-0.03		-0.12		-0.16		-0.04		0.01		0.01		-0.03		0.04		0.05		0.05		0.05		0.07		0.08	
	miroc-esm-chem	-0.04		-0.04		-0.09		0.01		0.00		0.01		0.00		0.01		0.05		0.01		0.06		0.10		0.04	
	noresm1-m	0.10		-0.03		0.15		0.07		0.12		0.13		0.10		0.13		0.14		0.13		0.15		0.35		0.20	
LPJ-GUESS	hadgem2-es	0.23	-0.21	0.11	-0.07	0.30	0.02	0.32	0.13	0.29	-0.03	0.37	-0.21	0.16	-0.20	0.27	-0.08	0.24	-0.11	0.61	-0.23	0.29	-0.12	0.41	0.08	0.02	-0.10
	ipsl-cm5a-lr	0.25		0.06		0.29		0.26		0.31		0.42		0.18		0.34		0.25		0.58		0.27		0.31		0.04	
	miroc-esm-chem	0.17		0.08		0.24		0.30		0.25		0.40		0.18		0.25		0.18		0.40		0.35		0.26		0.05	
	noresm1-m	0.46		0.24		0.49		0.50		0.41		0.75		0.39		0.42		0.40		1.16		0.55		0.60		0.17	
LPJmL	hadgem2-es	-0.01	-0.23	0.16	0.07	0.15	-0.03	-0.17	-0.28	-0.03	-0.17	0.04	-0.29	-0.06	-0.28	-0.05	-0.21	0.14	-0.11	0.10	-0.22	-0.10	-0.28	-0.07	-0.24	0.81	0.70
	ipsl-cm5a-lr	-0.03	-0.23	0.01	-0.06	0.17	-0.02	-0.09	-0.21	-0.03	-0.18	0.08	-0.26	-0.05	-0.28	-0.02	-0.18	0.04	-0.21	0.02	-0.31	-0.05	-0.24	-0.06	-0.23	0.78	0.68
	miroc-esm-chem	-0.03	-0.24	0.13	0.04	0.16	-0.03	-0.15	-0.25	-0.06	-0.20	0.04	-0.29	0.03	-0.19	-0.05	-0.20	0.09	-0.15	-0.02	-0.32	-0.05	-0.23	-0.07	-0.24	0.98	0.86
	noresm1-m	0.15	-0.19	0.23	0.09	0.31	0.04	-0.03	-0.19	0.00	-0.20	0.25	-0.23	0.11	-0.21	0.03	-0.20	0.27	-0.10	0.18	-0.25	0.04	-0.21	0.07	-0.19	1.24	1.01
pDSSAT	hadgem2-es	-0.02	-0.20	-0.16	-0.25	0.01	-0.18	0.09	-0.08	-0.07	-0.28	-0.04	-0.25	-0.08	-0.21	-0.11	-0.32	0.08	-0.14	-0.15	-0.34	0.04	-0.11	-0.10	-0.26	0.04	-0.05
	ipsl-cm5a-lr	-0.08	-0.27	-0.23	-0.34	0.14	-0.11	0.22	0.01	0.01	-0.24	0.07	-0.16	-0.09	-0.23	0.16	-0.15	0.01	-0.22	-0.18	-0.39	0.05	-0.12	0.06	-0.13	0.01	-0.09
	miroc-esm-chem	-0.11	-0.28	-0.14	-0.24	0.05	-0.15	0.11	-0.06	0.00	-0.22	0.02	-0.17	-0.04	-0.16	0.11	-0.16	0.06	-0.15	-0.24	-0.41	0.08	-0.07	-0.01	-0.18	-0.01	-0.12
	noresm1-m	-0.03	-0.24	-0.17	-0.30	0.17	-0.10	0.24	0.00	-0.19	-0.41	-0.02	-0.24	0.01	-0.16	-0.10	-0.36	0.18	-0.10	-0.13	-0.38	0.22	0.00	-0.01	-0.22	0.12	-0.02
PEGASUS	hadgem2-es	-0.12	-0.36	-0.46	-0.53	0.46	0.00	-0.19	-0.36	-0.03	-0.33	-0.40	-0.49	-0.61	-0.65	-0.08	-0.39	-0.02	-0.23	-0.25	-0.44	-0.16	-0.36	-0.39	-0.49	-0.44	-0.53
	ipsl-cm5a-lr	-0.02	-0.29	-0.60	-0.66	0.50	0.00	-0.05	-0.26	0.13	-0.24	-0.50	-0.58	-0.70	-0.73	0.33	-0.14	-0.29	-0.46	-0.37	-0.54	-0.16	-0.36	-0.30	-0.43	-0.52	-0.60
	miroc-esm-chem	-0.29	-0.48	-0.58	-0.63	0.49	0.03	-0.19	-0.36	-0.09	-0.37	-0.52	-0.59	-0.60	-0.64	-0.01	-0.34	-0.20	-0.38	-0.38	-0.53	-0.11	-0.31	-0.41	-0.51	-0.42	-0.51
	noresm1-m	0.07	-0.35	-0.52	-0.62	0.67	-0.07	-0.04	-0.33	-0.03	-0.43	-0.34	-0.47	-0.50	-0.58	-0.13	-0.53	0.20	-0.20	0.03	-0.38	-0.02	-0.36	-0.31	-0.48	-0.21	-0.39

Appendix C Additional results for coastal impacts

Table 15: The costal damage in terms of capital loss, migration costs and household damage

	Capital loss, %	Migration cost share in income, %	Houshold damage cost share in income, %
China	0.05	0.34	1.20
Japan	0.58	0.00	0.18
Korea	0.33	0.00	0.72
Indonesia	0.16	0.04	0.52
India	0.07	0.15	1.11
Australasia	0.08	0.01	0.07
South Asia	0.19	0.17	1.36
Rest of South-East Asia	0.67	0.23	3.46
Canada	0.28	0.03	0.17
USA	0.51	0.01	0.10
Mexico	0.02	0.01	0.04
Brazil	0.05	0.01	0.07
Central America and Caribbean	0.02	0.03	0.06
Rest of South America	0.23	0.03	0.39
Middle East and North Africa	0.14	0.22	0.43
Sub-Saharian Africa	0.03	0.05	0.44
South Africa	0.02	0.00	0.03
Northern Europe	0.47	0.01	0.27
UK & Ireland	0.40	0.02	0.15
Central Europe North	1.67	0.00	0.34
Central Europe South	0.30	0.01	0.12
Southern Europe	0.23	0.01	0.05
Rest of Europe	0.25	0.09	0.11
Russia	0.04	0.06	0.12
Rest of former USSR	0.02	0.02	0.12