Seventh Framework Programme

Theme 6

Environment

Project: 603864 – HELIX

Full project title:

High-**E**nd c**L**imate **I**mpacts and e**X**tremes

Deliverable: 5.6

Global assessment of socio-economic impacts from GEM-E3 and FUND models including intercomparison where applicable

Original Due date of deliverable31/10/17

Actual date of submission: 31/10/17

Preface

This is a 2-part report with contributions presenting projections of future economic impacts of climate change from two models, GEM-E3 and FUND.

In part 1, the GEM-E3 model is driven with scenarios of a small set of biophysical impacts (coastal flooding, inland flooding, crop yields and energy demand) from HELIX deliverable D4.4, projected using the HELIX high-resolution global climate simulation as presented in HELIX deliverable D3.1. This therefore provides an assessment of the global economic implications of the HELIX climate change impacts projections.

In part 2, an updated version of the FUND model is used to make projections of global economic impacts using its own impact response functions. A wider set of impacts sectors are included, some of which align to those examined in GEM-E3. This provides context for the HELIX-based economic impacts assessments with GEM-E3.

Direct comparison of the two sets of projections is not straightforward due to different experimental designs and forcing scenarios. Nevertheless, some qualitative comparisons can be made. For example, both models agree on the net global economic impact of high-end climate change (3°C global warming and above) being detrimental, although FUND projects beneficial impacts at lower levels of warming while GEM-E3 projects negative impacts at all levels. A key reason for this different is the impact on agriculture – in FUND, the impact response function includes beneficial effects of CO_2 fertilization, and simulates much of the world's most valuable agriculture to occur in conditions below its temperature optimum, both of which enhance crop yields as CO_2 concentrations and temperatures rise. In contrast, GEM-E3 takes its input of crop yields from a crop model which does not include CO_2 fertilization, for reasons explained in HELIX Deliverable D4.4, so global crop yields decline at all levels of global warming. The impacts of CO_2 fertilization on crop yields remains a major uncertainty, especially at higher levels of CO_2 concentration which are difficult to study experimentally with realistic methods such as Free-Air CO_2 Enrichment. Therefore, at this stage it is not possible to be confident in the net effects of CO_2-induced climate change on global crop yields and the consequent economic impacts.

Richard Betts

Global assessment of socio-economic impacts from GEM-E3

October

2017

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EXECUTIVE SUMMARY

The main purpose of this report is to make a global integrated economic assessment of climate impacts for various warming levels, based on the richness of details of biophysical, bottom-up impact models. The HELIX climate runs (from WP2) are integrated into the biophysical impact models (from WP4 and WP5) to produce impact estimates, which are finally integrated into a consistent economic model (a multi-sectoral, multi-region general equilibrium model), and able to derive useful insights regarding the relative importance of the various climate damage mechanisms, and their geographical resolution.

Most of the considered global economic damage (up to 90%) is due to inland flooding and coastal damages. Agricultural damage makes up about 10% of the total damage, while the impact of changes in energy demand is barely noticeable at the aggregate, global level which, however, only masks the regional heterogeneity of results as can be seen from regional results.

From the geographical perspective, the largest climate impacts are simulated to take place in the Asia continent, while Russia and the Rest of the FSU are potentially largely affected by climate change.

Regarding the sensitivity of economic impacts to warming levels, there appears to be a non-linear relationship as impacts rise more than proportionally to higher warming levels.

The worst case scenario analysis shows that impacts can become quite larger than those of the ensemble of climate runs.

Yet there are several key caveats in this analysis, like the exclusion of key impact areas (human health, ecosystem services, etc.). A more comprehensive sensitivity analysis of how results are affected by key assumptions and model features should be conducted in the future.

1 INTRODUCTION

The main purpose of Work Package 5 (WP5) of the HELIX project is to make a comprehensive global assessment of economic impacts due to climate change following a multi-sectoral, bottom-up impact perspective. Biophysical impact estimates derived from sectoral impact models are combined with an economic model in order to produce simulations of the geographical pattern of climate damages. The ultimate outcome of this analysis is a perspective of where climate impact can be higher in relative terms and which impact categories are the most relevant in relative terms.

Yet it is important to note that the power of this approach relies of the disaggregated view of the impacts (across regions and impact categories), as focusing only on the aggregated results (overall damages at the global scale) hides the richness of the results in terms of geographical and impacts resolution. Similar analysis can be found in OECD (2015) for the global case or Hsiang et al. (2017) for USA.

On top of the geographical perspective, the HELIX analysis allows to understand how higher degrees of global warming can potentially affect climate impacts. In particular, the analysis takes into account a set of specific warming levels (WLs), as in other work packages of the project. The WLs considered are 1.5°C, 2°C, 4°C and, for the few sectors for which those warming levels are simulated, 6°C.

The WP5 analysis has had two phases. The first phase delivered report (Deliverable 5.2 in June 2016) presenting a global preliminary assessment based on the existing fast-track ISI-MIP impact results and focused on 4°C.

In the second phase, this report (Deliverable 5.6) presents a more comprehensive global assessment. Rather than the ISI-MIP climate runs, this assessment is based on the new HELIX climate scenarios (from WP3), which go beyond the 4°C warming level, exploring additional warming levels. Furthermore, it also uses the results from the HELIX biophysical impact models (from both WP4 and WP5). Out of the set of impact areas considered in HELIX, four impact categories can be simulated with the economic model: river floods, coastal areas, agriculture and energy. The other sectors (e.g. water, ecosystems, migration and food security) cannot be modelled in economic terms because of the absence of a monetary metrics to value biophysical impacts and establish the consequent linkage with the economic model. Some impacts with an economic dimension were not considered because of their limited geographical scope (e.g. malaria case study).

This report focuses only on the results with the GEM-E3-CAGE model. The report is organised in seven additional sections. Section 2 presents the main elements of the methodology followed to establish the economic integration of the biophysical impacts. Sections 3 to 6 present the results for each of the four impact areas considered (section 3 river floods; section 4 coastal areas; section 5 agriculture; and section 6 energy). Section 7 then offers an overview considering all sectoral impacts together, even if this vision hides the key resolution of impacts at the downscaled level, which is of particular usefulness for adaptation. Section 8 concludes with the main insights and possible directions of further research.

2 METHODOLOGY

Results from the biophysical impacts computations were integrated within an economic framework in order to provide an overview of the relative economic implications (both from the geographical perspective and the ultimate climate impact source) resulting from climate change. This section explains the coverage of the analysis and the methodological economic backbone of the assessment.

2.1 COVERAGE OF THE ASSESSMENT

Table 1 details the mapping between the biophysical impacts and the SWLs. All impact studies cover the 1.5°C, 2°C and 4°C warming levels. The only sector with results for 6°C is agriculture.

Table 1: Coverage of impacts and SWLs for the economic analysis

Impact	SWL1.5	SWL2.0	SWL4.0	SWL6.0
Inland flooding	✓	✓	✓	×
Coastal flooding	✓	✓	✓	×
Agricultural crops	✓	✓	✓	✓
Energy demand	✓	✓	✓	×

The energy and inland floods models have used the EC Earth HELIX climate runs, while the agriculture model has additionally used three climate runs from the HadGEM climate model. The coastal analysis is consistent with the HELIX climate runs. Results are presented for the mean of ensemble of the climate runs and also for the maximum and minimum economic impacts. In this way one can have a notion of the degree of uncertainty derived from the range of climate runs used in the HELIX assessment.

2.2 THE ECONOMIC MODEL INTEGRATING THE BIOPHYSICAL IMPACTS

The economic simulations have been performed with the GEM-E3-CAGE[1] Computable General Equilibrium (CGE) model. CGE 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, on top of the direct damage or 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.

[1] See Appendix. The full model description and mathematical model statement is provided in the Annex of Pycroft et al. (2015).

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 (defined as consumption, 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 (EV).

The model employed for this analysis, GEM-E3-CAGE, 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)[2].

The GTAP database provides input-output tables for a large set of countries/regions and commodity categories. The GEM-E3-CAGE model has 19 sectors and 25 regions[3]. 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[4],

[2] https://www.gtap.agecon.purdue.edu/

[3] The CAGE sectors and regions are detailed in 0 Appendix

[4] The Rest of Europe region includes the following countries: Albania, Bosnia and Herzegovina, Macedonia, Montenegro, Norway, Serbia, and Switzerland

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 SWLs) occurring under the current socioeconomic conditions. Therefore, the climate shock-induced changes would occur in the economy as of today.

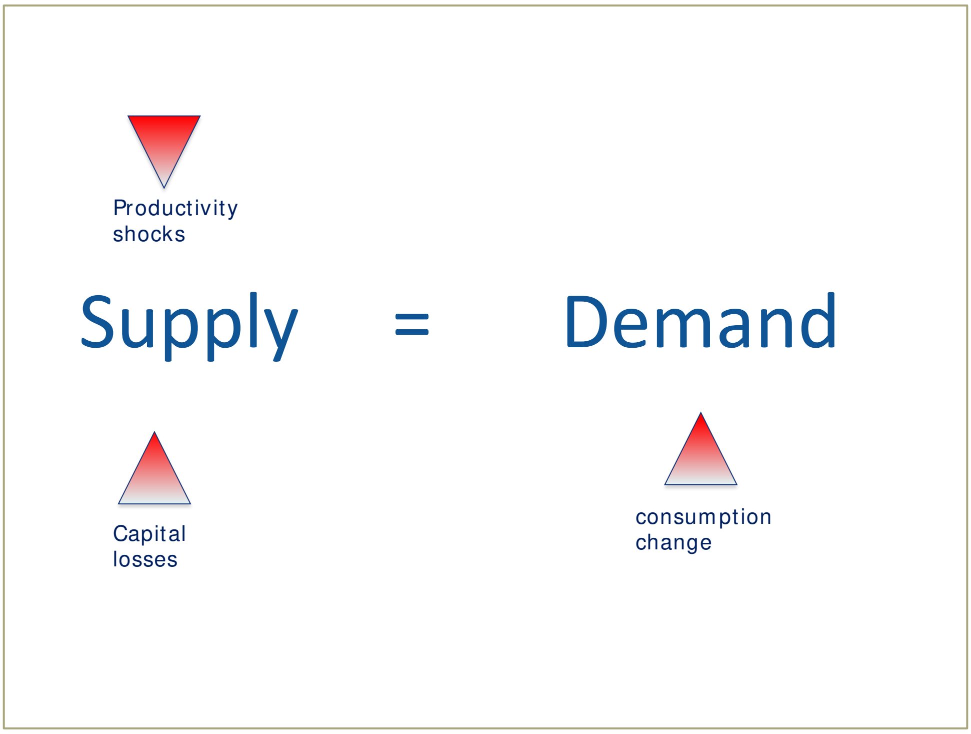
The implications of that choice are widely discussed in Ciscar et al. (2012). In contrast, a 'dynamic' approach would account for changes that the economy and society will undergo until the end of the century, and apply the climate shocks to the version of economy as in the year reaching the SWL level.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

There are two main kinds of results from the CGE analysis: GDP and welfare changes. GDP refer to the production of goods and services of the economy within one year, while welfare can be interpreted as a proxy of household consumption. It is important to note the economic damage associated with changes in consumption or welfare is not accounted for in the GDP change result, while it is in the welfare change result. That is the reason why welfare change is the appropriate metrics to synthesise the economic consequences of climate change within the proposed methodological framework.

2.3 THE IMPLEMENTATION OF THE CLIMATE SHOCKS IN THE ECONOMIC MODEL

There are three main channels through which the direct damages as computed by the biophysical impacts affect the economy (see Figure 1). Two of the channels would affect the supply side of the economy and a third one the demand side.

Figure 1: Overview of climate shocks affecting the economy



Regarding the supply side, firstly, climate change can affect the productivity of the economy. The productivity is defined as the unit of output per unit of input. The clearest case is that of agriculture: climate change can lead to reduced yields (output), while all other factors of production (inputs) are the same. Secondly, climate change can alter the capital stock of the economy, for instance when floods damage infrastructure. These supply-side effects would trigger a series of adjustments in the economy also indirectly affecting sectors and regions different to that where climate change is impacting directly.

Regarding the demand side of the economy, climate change can also influence consumption decisions. For instance, damage to residential buildings due to a flood leads to a change in the consumption behaviour of households as they would repair the damage and consequently reduce other consumption expenditures. There would be a substitution of consumption: additional consumption to repair the dwellings damage (e.g. buy a new fridge) and an equivalent reduction in consumption (e.g. less travelling), keeping the overall consumption constant. As the reparation of the flood damage is part of obliged or compulsory consumption (which would not occur in the absence of climate change), the economic model interprets that there is a welfare loss associated to the damage to residential buildings.

3 INLAND FLOODING

The inland flood damage estimates have been produced by Deliverable 4.4, *Provision of impact simulations based on the new AGCM timeslice simulations for 3 SWLs*, 2017 (see also Alfieri et al 2017).

The inland flood damage assessment consists of damages to agriculture, industry, commerce, infrastructure and residential buildings. Agricultural direct damages are accounted for in the model as a *change* in the productivity of the agricultural sector. Damages to industry, commerce and infrastructure are represented as damage to capital in the economy. Damage to residential structures is represented as an increase in households' subsistence spending.

3.1 FLOOD DIRECT DAMAGE

Table 2 shows the economic direct damage (in absolute terms, bn €) from inland flooding for the control period (1981-2010; *'present'* in the table), and for three SWLs: 1.5°C, 2°C, and 4°C. The damage values of the future climate are provided for minimum, mean and maximum of the climate models' ensemble. In order to compute the damages of a certain WL relative to the present, one needs to subtract the damage values of the present or control period. For instance, the 2°C mean damage (compared to the current damage) would be 31.9 bn € (60.3 bn € of the 2°C scenario minus the 28.4 bn € of the control period).

Table 2: Inland flood direct damage (bn €)

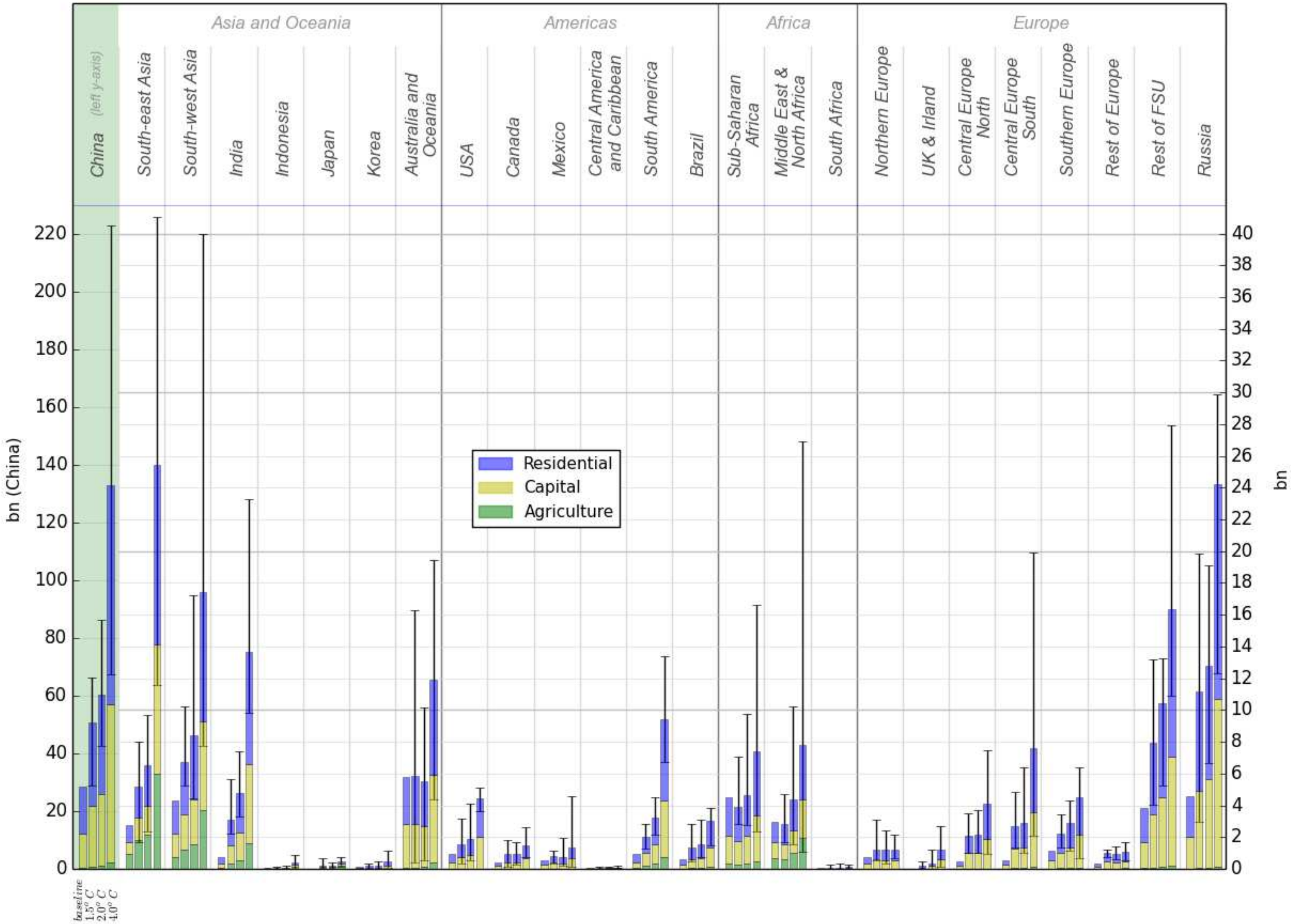
Region	present	1.5C			2.0C			4.0C		
		min	**mean**	max	min	**mean**	max	min	**mean**	max
China	**28.4**	28.8	**50.7**	66.4	42.6	**60.3**	86.3	67.2	**132.9**	223.1
South-east Asia	**2.8**	1.7	**5.2**	8.0	2.4	**6.5**	9.7	11.6	**25.5**	41.0
South-west Asia	**4.3**	5.2	**6.7**	10.3	4.5	**8.4**	17.2	7.7	**17.4**	40.0
India	**0.8**	2.2	**3.1**	5.7	3.3	**4.8**	7.4	9.9	**13.7**	23.3
Indonesia	**0.1**	0.0	**0.1**	0.1	0.0	**0.1**	0.2	0.0	**0.4**	0.9
Japan	**0.0**	0.0	**0.2**	0.7	0.0	**0.2**	0.4	0.1	**0.4**	0.7
Korea	**0.1**	0.0	**0.2**	0.4	0.0	**0.2**	0.5	0.1	**0.5**	1.2
Australia and Oceania	**5.8**	0.4	**5.8**	16.3	0.5	**5.5**	10.1	4.3	**11.9**	19.4
USA	**0.9**	0.4	**1.6**	3.2	0.5	**1.9**	4.1	3.6	**4.5**	5.1
Canada	**0.4**	0.2	**0.9**	1.8	0.3	**1.0**	1.7	0.7	**1.5**	2.6
Mexico	**0.6**	0.3	**0.8**	1.2	0.2	**0.7**	1.9	0.1	**1.4**	4.6
Central America and Caribbean	**0.1**	0.0	**0.1**	0.2	0.0	**0.1**	0.1	0.0	**0.1**	0.2
South America	**0.9**	1.3	**2.1**	2.9	2.2	**3.2**	4.5	6.7	**9.4**	13.4
Brazil	**0.6**	0.5	**1.3**	2.8	0.7	**1.6**	3.1	1.4	**3.0**	3.8
Sub-Saharan Africa	**4.5**	2.8	**3.9**	7.1	2.8	**4.6**	9.8	2.4	**7.4**	16.6
Middle East & North Africa	**3.0**	1.7	**2.9**	4.7	1.6	**4.4**	10.2	1.1	**7.8**	26.9
South Africa	**0.1**	0.0	**0.1**	0.3	0.0	**0.1**	0.4	0.0	**0.1**	0.3
Northern Europe	**0.7**	0.5	**1.2**	3.1	0.3	**1.2**	2.4	0.6	**1.2**	2.2
UK & Irland	**0.0**	0.0	**0.2**	0.5	0.0	**0.4**	1.2	0.1	**1.2**	2.7
Central Europe North	**0.4**	1.0	**2.1**	3.5	1.0	**2.1**	3.7	0.9	**4.1**	7.4
Central Europe South	**0.5**	1.3	**2.7**	4.9	1.0	**2.9**	6.4	2.1	**7.6**	19.9
Southern Europe	**1.2**	1.3	**2.2**	3.5	1.2	**2.9**	4.3	0.7	**4.5**	6.4
Rest of Europe	**0.3**	0.7	**1.0**	1.2	0.6	**0.9**	1.4	0.5	**1.1**	1.7
Rest of FSU	**3.8**	4.0	**8.0**	13.2	5.2	**10.4**	13.3	10.9	**16.4**	27.9
Russia	**4.6**	3.0	**11.2**	19.9	6.7	**12.8**	19.1	12.3	**24.3**	29.9
Global	65	57	114	182	78	137	219	145	298	521

At the global level the flood damage would increase from the estimated current 65bn€ to 114bn€ at 1.5ºC, 137bn€ at 2ºC, and 298bn€ at 4ºC. Most of the global damage would affect Asia, about 60% of the total, with China accounting for about 45% of the world's inland flood damage. Regarding the rest of the continents, Australia and Oceania would undergo 6% of the global damage, the Americas 6%, Africa 13%, and Europe 25%.

There is a wide range of damage estimates associated to the considered climate futures. The simulated damage value can be as low as about half of the mean value, or about 2/3 higher under the worst case.

Figure 2 represents the decomposition of direct damages according to the three damage categories. Note that the China results have a different scale (left axis) from the general scale (right axis). Most of the climate impact is due to residential buildings damages (blue bars). Capital losses (yellow bars) are also very relevant, while agriculture damages (green bars) are in general much less relevant, although for some Asian regions, such as south-east and south-west Asia, they can be relatively large.

Figure 2: Decomposition of Inland flood direct damage (bn €)



3.2 Economic implications

There are two sets of economic results, once the CGE model is run. All changes refer to the impact due to climate change compared to the control period. Starting with the GDP effects, Figure 3 represents the GDP changes (in percentage terms) for all the regions and the various WLs, including also the minimum and maximum ranges (values also in Table 3; absolute GDP changes are reported in Table 4, in bn €).

The global GDP loss is simulated at 0.07% at 1.5^{o}C warming, 0.1% at 2^{o}C and 0.32% at 4^{o}C. In absolute terms, the global GDP loss is simulated to be 34bn€ at 1.5^{o}C warming, 49bn€ at 2^{o}C and 159bn€ at 4^{o}C. That non-linearity of GDP losses to warming level applies also in general terms to the regional damages. At 2C the average GDP losses increase by about half across the regions. From 2^{o}C to 4^{o}C the GDP losses approximately triple for most of the regions.

Regarding the percentage GDP losses, for 1.5^{o}C they reach a maximum of around 0.5% of GDP in few countries (China, Russia and rest of FSU). On the other extreme of the warming level range, at 4^{o}C the largest GDP reductions are simulated for Asia and China (1.5% to 2%), and for Russia and the rest of FSU (1% to 2%). For most of other regions, apart from India and South America, the GDP losses are below 0.5% for the 4^{o}C warming level.

Figure 3: Change in GDP (%)

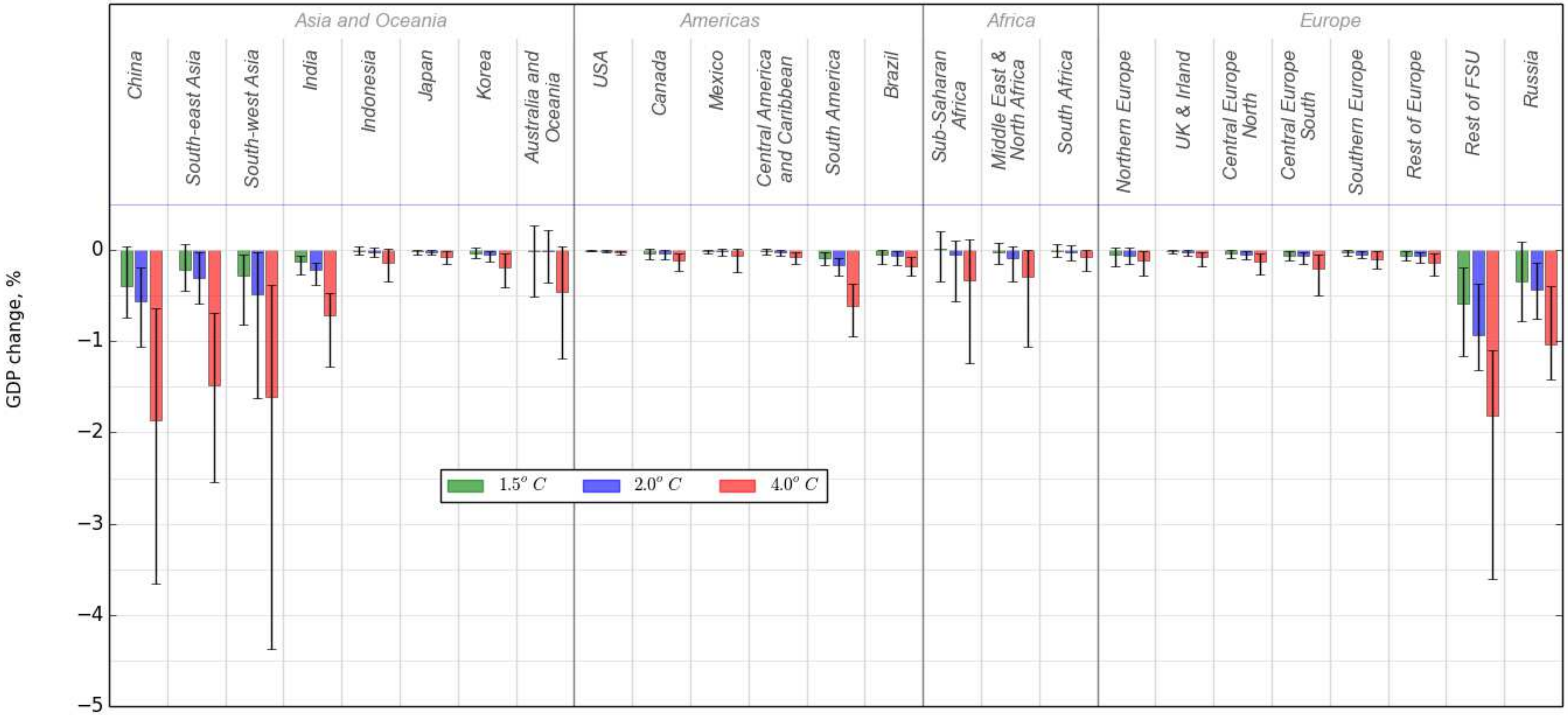


Table 3: Change in GDP (%)

Region	1.5C			2.0C			4.0C		
	min	**mean**	max	min	**mean**	max	min	**mean**	max
China	0.05	**-0.39**	-0.74	-0.19	**-0.56**	-1.06	-0.63	**-1.86**	-3.66
South-east Asia	0.06	**-0.21**	-0.45	-0.02	**-0.31**	-0.59	-0.69	**-1.48**	-2.54
South-west Asia	-0.05	**-0.28**	-0.82	-0.02	**-0.49**	-1.62	-0.38	**-1.61**	-4.38
India	-0.07	**-0.13**	-0.27	-0.13	**-0.22**	-0.38	-0.47	**-0.71**	-1.27
Indonesia	0.04	**-0.01**	-0.05	0.03	**-0.02**	-0.08	0.01	**-0.14**	-0.34
Japan	0.01	**-0.02**	-0.05	0.00	**-0.02**	-0.05	-0.02	**-0.07**	-0.15
Korea	0.03	**-0.04**	-0.09	-0.01	**-0.05**	-0.12	-0.04	**-0.19**	-0.41
Australia and Oceania	0.27	**-0.02**	-0.51	0.22	**-0.01**	-0.35	0.04	**-0.46**	-1.19
USA	0.00	**-0.01**	-0.02	0.00	**-0.01**	-0.02	-0.01	**-0.03**	-0.05
Canada	0.01	**-0.04**	-0.10	0.01	**-0.04**	-0.10	-0.04	**-0.11**	-0.23
Mexico	0.01	**-0.01**	-0.04	0.02	**-0.01**	-0.06	0.02	**-0.06**	-0.24
Central America and Caribbean	0.01	**-0.02**	-0.05	0.00	**-0.02**	-0.06	-0.02	**-0.07**	-0.16
South America	-0.02	**-0.09**	-0.16	-0.09	**-0.17**	-0.29	-0.37	**-0.61**	-0.95
Brazil	0.00	**-0.05**	-0.15	-0.01	**-0.07**	-0.17	-0.08	**-0.18**	-0.28
Sub-Saharan Africa	0.21	**0.02**	-0.34	0.11	**-0.05**	-0.56	0.11	**-0.34**	-1.25
Middle East & North Africa	0.08	**-0.02**	-0.15	0.04	**-0.08**	-0.34	0.00	**-0.29**	-1.06
South Africa	0.07	**-0.01**	-0.08	0.05	**-0.02**	-0.12	0.00	**-0.08**	-0.23
Northern Europe	0.03	**-0.05**	-0.18	0.03	**-0.06**	-0.16	-0.02	**-0.12**	-0.28
UK & Irland	0.00	**-0.01**	-0.04	0.00	**-0.02**	-0.07	-0.02	**-0.08**	-0.17
Central Europe North	0.00	**-0.04**	-0.09	-0.01	**-0.05**	-0.10	-0.03	**-0.13**	-0.27
Central Europe South	-0.02	**-0.06**	-0.11	-0.02	**-0.07**	-0.15	-0.05	**-0.20**	-0.50
Southern Europe	0.00	**-0.03**	-0.06	-0.01	**-0.05**	-0.09	-0.02	**-0.11**	-0.20
Rest of Europe	-0.02	**-0.06**	-0.11	-0.02	**-0.06**	-0.14	-0.04	**-0.14**	-0.27
Rest of FSU	-0.19	**-0.59**	-1.16	-0.37	**-0.94**	-1.31	-1.10	**-1.82**	-3.60
Russia	0.10	**-0.34**	-0.78	-0.14	**-0.43**	-0.75	-0.39	**-1.04**	-1.42
Global	0.01	-0.07	-0.16	-0.02	-0.10	-0.22	-0.11	-0.32	-0.65

Table 4: Change in GDP (bn€)

Region	1.5C			2.0C			4.0C		
	min	**mean**	max	min	**mean**	max	min	**mean**	max
China	1.4	**-12.2**	-23.2	-6.1	**-17.6**	-33.4	-19.9	**-58.4**	-115.0
South-east Asia	0.7	**-2.3**	-4.9	-0.2	**-3.4**	-6.5	-7.5	**-16.2**	-27.8
South-west Asia	-0.2	**-1.3**	-3.9	-0.1	**-2.3**	-7.7	-1.8	**-7.6**	-20.8
India	-0.7	**-1.4**	-2.9	-1.4	**-2.3**	-4.0	-4.9	**-7.5**	-13.5
Indonesia	0.2	**0.0**	-0.2	0.1	**-0.1**	-0.3	0.0	**-0.6**	-1.3
Japan	0.3	**-0.7**	-1.8	-0.1	**-0.8**	-2.0	-0.7	**-2.9**	-5.9
Korea	0.2	**-0.3**	-0.8	-0.1	**-0.5**	-1.1	-0.3	**-1.7**	-3.6
Australia and Oceania	2.5	**-0.2**	-4.6	2.0	**-0.1**	-3.2	0.4	**-4.2**	-10.8
USA	0.4	**-0.7**	-2.0	0.2	**-1.0**	-2.8	-1.7	**-3.6**	-5.7
Canada	0.1	**-0.4**	-1.3	0.1	**-0.5**	-1.3	-0.5	**-1.4**	-2.8
Mexico	0.1	**-0.1**	-0.3	0.1	**-0.1**	-0.6	0.1	**-0.6**	-2.2
Central America and Caribbean	0.0	**-0.1**	-0.2	0.0	**-0.1**	-0.2	-0.1	**-0.3**	-0.5
South America	-0.2	**-0.8**	-1.5	-0.9	**-1.6**	-2.7	-3.4	**-5.7**	-8.9
Brazil	0.0	**-0.6**	-1.8	-0.1	**-0.8**	-2.1	-0.9	**-2.1**	-3.4
Sub-Saharan Africa	1.0	**0.1**	-1.7	0.6	**-0.3**	-2.9	0.6	**-1.7**	-6.4
Middle East & North Africa	1.6	**-0.5**	-2.9	0.8	**-1.7**	-6.8	0.0	**-5.7**	-20.7
South Africa	0.2	**0.0**	-0.2	0.1	**0.0**	-0.3	0.0	**-0.2**	-0.6
Northern Europe	0.3	**-0.5**	-1.7	0.3	**-0.6**	-1.5	-0.1	**-1.1**	-2.7
UK & Irland	0.1	**-0.4**	-1.1	0.0	**-0.7**	-1.9	-0.5	**-2.3**	-4.9
Central Europe North	-0.1	**-2.0**	-4.3	-0.6	**-2.4**	-4.8	-1.5	**-6.1**	-12.5
Central Europe South	-0.6	**-1.9**	-3.7	-0.7	**-2.2**	-5.1	-1.7	**-6.6**	-16.4
Southern Europe	-0.1	**-1.1**	-2.3	-0.4	**-1.7**	-3.3	-0.6	**-4.0**	-7.5
Rest of Europe	-0.1	**-0.5**	-1.0	-0.2	**-0.6**	-1.2	-0.4	**-1.2**	-2.4
Rest of FSU	-0.6	**-1.9**	-3.8	-1.2	**-3.1**	-4.3	-3.6	**-6.0**	-11.8
Russia	1.0	**-3.7**	-8.4	-1.5	**-4.6**	-8.1	-4.2	**-11.2**	-15.2
Global	7	-34	-81	-9	-49	-108	-53	-159	-323

Regarding the welfare changes, a more appropriate metrics for assessing the economic consequences of climate change, Figure 4 represents the regional values. The numerical values of the welfare changes in percentage terms appear in Table 5 and the absolute values (in bn €) are reported in Table 6. Changes in welfare are larger when compared to GDP because the damage to the residential structures is considered as affecting households' spending and welfare but not directly impacting on the economic activity or production (GDP) of the economy.

The non-linearity of economic damages regarding warming levels is also apparent in terms of welfare changes. Thus, for instance, China would undergo a welfare loss of close to 3% under 2^{o}C, which could more than triple under a 4^{o}C future.

China is the region that could register the highest welfare loss, almost 10% under the 4^{o}C case. The Rest of FSU appears also very vulnerable to inland flooding, with welfare losses that could amount to 7.6% of consumption. Russia and the south-east and south-west Asia regions could face welfare losses close to 5% under the 4^{o}C scenario.

Figure 4: Welfare change (%)

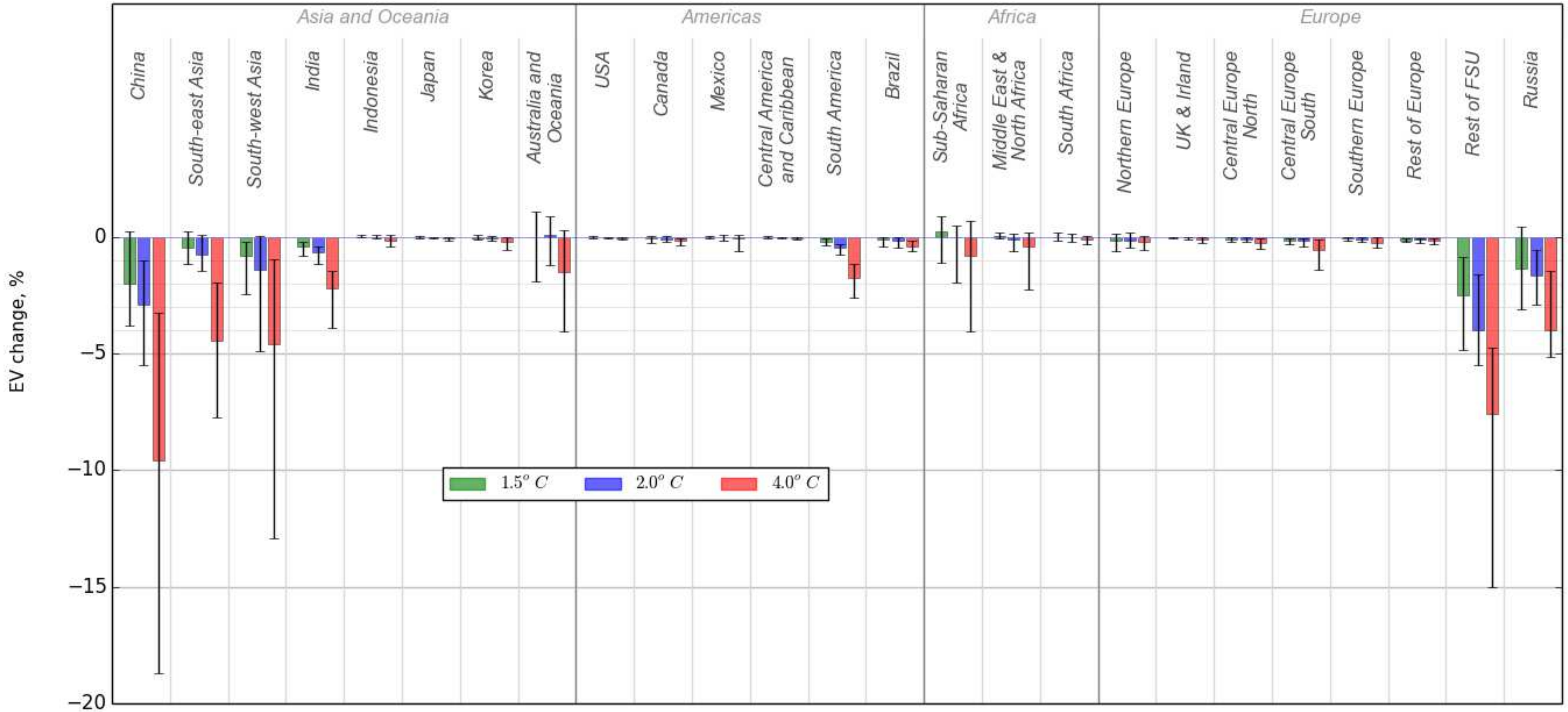


Table 5: Welfare change (%)

Region	1.5C			2.0C			4.0C		
	min	**mean**	max	min	**mean**	max	min	**mean**	max
China	0.22	**-2.03**	-3.81	-1.03	**-2.91**	-5.48	-3.27	**-9.57**	-18.72
South-east Asia	0.25	**-0.49**	-1.15	0.11	**-0.76**	-1.45	-1.94	**-4.46**	-7.76
South-west Asia	-0.21	**-0.84**	-2.44	0.03	**-1.43**	-4.89	-0.98	**-4.60**	-12.93
India	-0.21	**-0.39**	-0.84	-0.42	**-0.67**	-1.17	-1.46	**-2.19**	-3.91
Indonesia	0.07	**0.00**	-0.01	0.07	**-0.01**	-0.06	0.07	**-0.18**	-0.42
Japan	0.01	**-0.02**	-0.07	0.00	**-0.03**	-0.07	-0.02	**-0.09**	-0.17
Korea	0.09	**-0.04**	-0.14	0.01	**-0.07**	-0.17	0.00	**-0.24**	-0.54
Australia and Oceania	1.08	**-0.01**	-1.89	0.89	**0.06**	-1.21	0.29	**-1.50**	-4.05
USA	0.01	**-0.01**	-0.04	0.01	**-0.02**	-0.06	-0.04	**-0.07**	-0.10
Canada	0.01	**-0.09**	-0.26	0.03	**-0.10**	-0.23	-0.08	**-0.18**	-0.38
Mexico	0.02	**-0.03**	-0.08	0.07	**-0.01**	-0.15	0.09	**-0.09**	-0.59
Central America and Caribbean	0.01	**-0.01**	-0.06	0.00	**-0.02**	-0.05	-0.01	**-0.05**	-0.11
South America	-0.09	**-0.24**	-0.38	-0.30	**-0.48**	-0.75	-1.16	**-1.78**	-2.63
Brazil	0.00	**-0.12**	-0.40	-0.03	**-0.16**	-0.45	-0.18	**-0.41**	-0.60
Sub-Saharan Africa	0.89	**0.23**	-1.12	0.50	**0.00**	-1.97	0.70	**-0.83**	-4.08
Middle East & North Africa	0.17	**0.04**	-0.09	0.12	**-0.11**	-0.61	0.16	**-0.40**	-2.24
South Africa	0.17	**-0.01**	-0.15	0.15	**-0.03**	-0.22	0.01	**-0.09**	-0.30
Northern Europe	0.13	**-0.15**	-0.62	0.17	**-0.15**	-0.45	0.03	**-0.19**	-0.56
UK & Irland	0.00	**-0.02**	-0.05	0.00	**-0.03**	-0.11	-0.02	**-0.11**	-0.25
Central Europe North	-0.02	**-0.10**	-0.21	-0.03	**-0.11**	-0.21	-0.05	**-0.25**	-0.51
Central Europe South	-0.07	**-0.16**	-0.31	-0.06	**-0.18**	-0.42	-0.13	**-0.54**	-1.41
Southern Europe	-0.02	**-0.07**	-0.15	-0.03	**-0.12**	-0.22	-0.02	**-0.25**	-0.44
Rest of Europe	-0.09	**-0.15**	-0.21	-0.07	**-0.13**	-0.28	-0.05	**-0.17**	-0.31
Rest of FSU	-0.88	**-2.50**	-4.86	-1.60	**-3.99**	-5.49	-4.74	**-7.59**	-15.04
Russia	0.43	**-1.35**	-3.08	-0.56	**-1.67**	-2.90	-1.48	**-4.00**	-5.13
Global	0.04	-0.20	-0.48	-0.05	-0.29	-0.63	-0.31	-0.93	-1.89

In absolute terms (see Table 5), welfare losses could amount to a quarter of a trillion € globally under the 4°C case. At this point, one could compare the welfare losses with the direct damages (Table 2). For the 4°C case, the global direct damages are estimated to be 233 bn € (298 bn € in the 4°C scenario, minus the 65 bn € of the control period). Therefore, the overall welfare losses are approximately 10% higher than the direct losses. Those additional economic damages are due to the adjustments happening in the various markets of the economy.

Table 6: Welfare change (bn€)

Region	1.5C			2.0C			4.0C		
	min	**mean**	max	min	**mean**	max	min	**mean**	max
China	2.6	**-23.5**	-44.1	-11.9	**-33.7**	-63.5	-37.9	**-110.9**	-216.9
South-east Asia	1.4	**-2.6**	-6.3	0.6	**-4.1**	-7.9	-10.5	**-24.2**	-42.1
South-west Asia	-0.6	**-2.4**	-6.8	0.1	**-4.0**	-13.7	-2.8	**-12.9**	-36.3
India	-1.2	**-2.3**	-5.0	-2.5	**-4.0**	-6.9	-8.7	**-13.0**	-23.1
Indonesia	0.2	**0.0**	0.0	0.2	**0.0**	-0.1	0.1	**-0.4**	-0.9
Japan	0.2	**-0.5**	-1.5	0.0	**-0.5**	-1.4	-0.4	**-1.8**	-3.5
Korea	0.4	**-0.2**	-0.6	0.0	**-0.3**	-0.8	0.0	**-1.1**	-2.5
Australia and Oceania	5.0	**-0.1**	-8.8	4.2	**0.3**	-5.6	1.4	**-7.0**	-18.8
USA	0.8	**-1.1**	-3.5	0.4	**-1.6**	-4.8	-3.0	**-5.6**	-8.1
Canada	0.1	**-0.6**	-1.7	0.2	**-0.6**	-1.5	-0.6	**-1.2**	-2.5
Mexico	0.1	**-0.2**	-0.5	0.4	**0.0**	-0.8	0.5	**-0.5**	-3.2
Central America and Caribbean	0.0	**0.0**	-0.1	0.0	**0.0**	-0.1	0.0	**-0.1**	-0.2
South America	-0.5	**-1.2**	-2.0	-1.5	**-2.5**	-3.8	-5.9	**-9.1**	-13.5
Brazil	0.0	**-0.8**	-2.6	-0.2	**-1.1**	-2.9	-1.2	**-2.7**	-4.0
Sub-Saharan Africa	2.8	**0.7**	-3.5	1.6	**0.0**	-6.2	2.2	**-2.6**	-12.9
Middle East & North Africa	1.7	**0.4**	-0.9	1.2	**-1.0**	-5.9	1.5	**-3.9**	-21.7
South Africa	0.3	**0.0**	-0.2	0.2	**0.0**	-0.3	0.0	**-0.1**	-0.4
Northern Europe	0.6	**-0.7**	-2.8	0.7	**-0.7**	-2.1	0.2	**-0.9**	-2.5
UK & Irland	0.0	**-0.3**	-0.8	0.0	**-0.5**	-1.8	-0.3	**-1.9**	-4.1
Central Europe North	-0.5	**-2.5**	-5.1	-0.8	**-2.8**	-5.2	-1.3	**-6.3**	-12.6
Central Europe South	-1.2	**-2.9**	-5.5	-1.1	**-3.3**	-7.6	-2.4	**-9.7**	-25.2
Southern Europe	-0.4	**-1.6**	-3.1	-0.6	**-2.5**	-4.7	-0.4	**-5.2**	-9.4
Rest of Europe	-0.4	**-0.7**	-1.0	-0.3	**-0.6**	-1.3	-0.2	**-0.7**	-1.4
Rest of FSU	-1.6	**-4.4**	-8.6	-2.8	**-7.1**	-9.7	-8.4	**-13.4**	-26.6
Russia	2.3	**-7.3**	-16.7	-3.0	**-9.0**	-15.7	-8.0	**-21.6**	-27.7
Global	12	-55	-132	-15	-80	-174	-86	-257	-520

4 COASTAL FLOODING

Similar to the inland flooding, the costal flood damage assessment consists of three main damage categories: agriculture; industry, commerce and infrastructure; and residential buildings. Agricultural direct damages are accounted for in the model as a change in the productivity of the agricultural sector. Damages to industry, commerce and infrastructure are represented as damage to capital in the economy. Damage to residential structures is represented as an increase in households' subsistence spending.

4.1 FLOOD DIRECT DAMAGE

Table 8 shows the direct damages from coastal flooding for the control or base period (1981-2010), and for three SWLs: 1.5ºC, 2ºC and 4ºC. The SWLs values relate to the minimum, mean and maximum of the climate models' ensemble. At the global level the damage increases from the current 482 bn€ to 543 bn€ at 1.5ºC, 545 bn€ at 2ºC, and 656 bn€ at 4ºC. The uncertainty range suggests that the damage value can vary by up to 20% of the mean value (20% lower than the average in the minimum and 20% in the maximum).

Both in the control period and in the future climate scenarios, Asia accounts for about 45% of the overall global damage, with China representing 40% of the global figure. Furthermore, a similar 46% of the global coastal damage would happen in Europe, with the Central Europe North region accounting for 30% of the global damage. Therefore, two regions (China and Central Europe North) absorb around 2/3 of the overall global damage. Australia and Oceania take about 2% of the global damage, the Americas take 6%, and 1% of the damage occurs in Africa.

Regarding the increase in damage compared to the control period, which is the shock that will be implemented in the economic model, in both the 1.5ºC and 2ºC there is an increase of around 12% compared to the control period, while the 4ºC future would imply an increase of 36%, again a non-linear effect (doubling the temperature change would lead to more than doubling of the additional damage). For some regions under the 4ºC future, the increase is much larger than that of the overall global damage. For instance, USA would register an increase of 70% of the damage (4ºC compared to the control period), Japan and Australia and Oceania an additional 100% damage and Southern Europe a 65% increase.

Regarding the two countries with the highest share in the overall damage, China would see an increase very similar to that of the globe, while the Central Europe North region would experience a lower rise in damage (18% versus 36% in China).

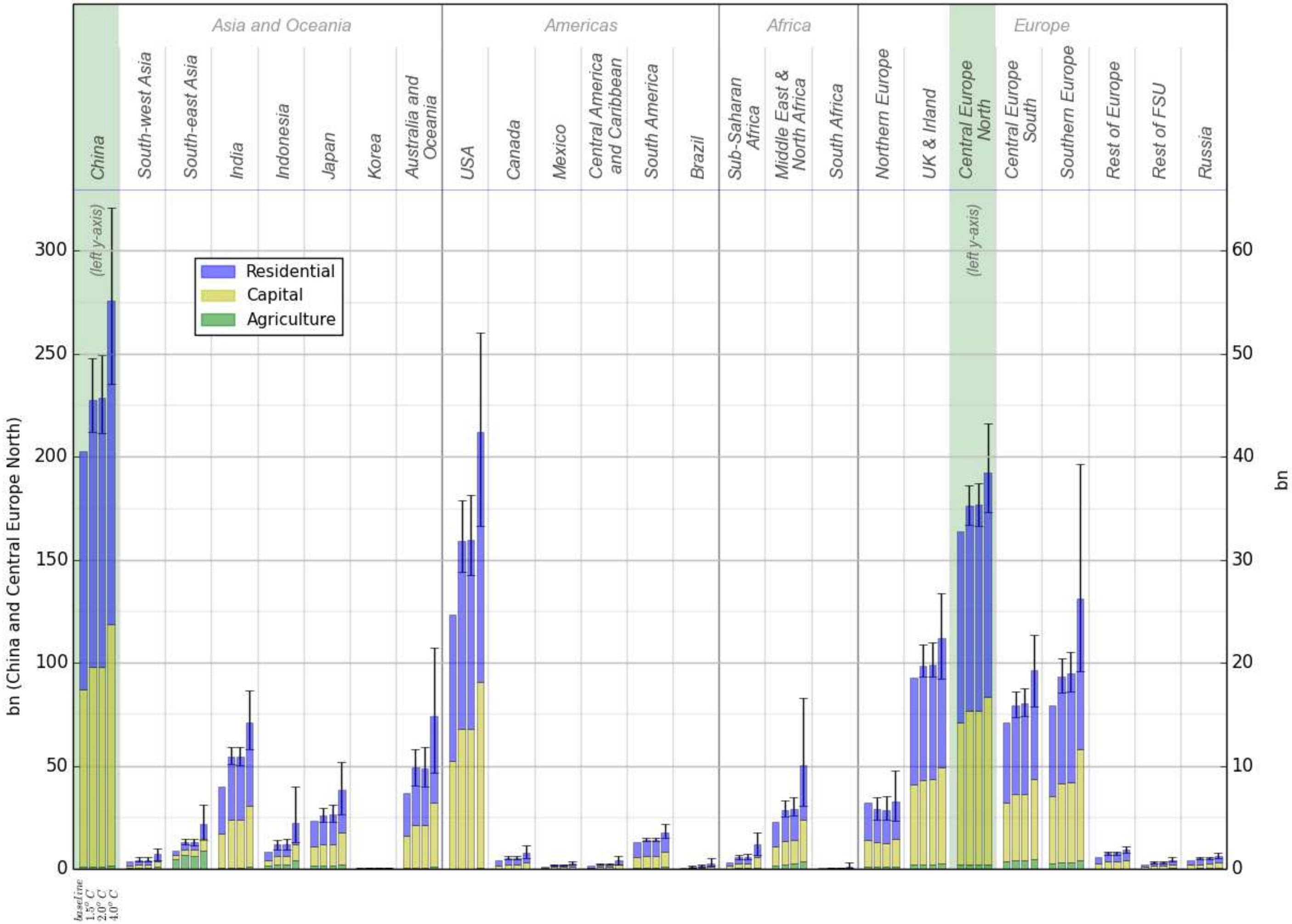
The regional pattern of the additional direct damage (compared to the control period) is quite different from that in each period. Thus, of the overall additional damage under the 4ºC future (175 bn€), 43% would happen in China (75 bn€) and 16% (28 bn€) in the Central Europe North region.

Table 7: Costal flooding damage (bn€)

Region	present	1.5C			2.0C			4.0C		
		min	**mean**	max	min	**mean**	max	min	**mean**	max
China	**202.7**	212.3	**227.7**	247.7	211.5	**228.5**	249.4	235.5	**275.9**	320.9
South-east Asia	**0.7**	0.7	**0.8**	1.1	0.7	**0.8**	1.2	0.8	**1.4**	1.9
South-west Asia	**1.8**	2.4	**2.6**	2.9	2.2	**2.6**	2.9	2.8	**4.3**	6.2
India	**8.0**	10.2	**10.9**	11.8	10.1	**10.9**	11.9	11.6	**14.2**	17.3
Indonesia	**1.6**	1.9	**2.4**	2.8	1.9	**2.4**	2.9	2.6	**4.5**	8.0
Japan	**4.7**	4.5	**5.2**	5.9	4.6	**5.3**	6.2	5.3	**7.7**	10.4
Korea	**0.1**	0.1	**0.1**	0.1	0.1	**0.1**	0.1	0.1	**0.1**	0.1
Australia and Oceania	**7.4**	8.1	**9.9**	11.6	8.0	**9.8**	11.8	9.3	**14.8**	21.5
USA	**24.7**	28.8	**31.9**	35.8	28.5	**32.0**	36.3	33.3	**42.4**	52.1
Canada	**0.8**	0.9	**1.1**	1.3	0.9	**1.0**	1.2	1.0	**1.5**	2.3
Mexico	**0.2**	0.3	**0.4**	0.4	0.3	**0.4**	0.4	0.4	**0.5**	0.7
Central America and Caribbean	**0.3**	0.4	**0.4**	0.5	0.4	**0.4**	0.5	0.5	**0.8**	1.3
South America	**2.6**	2.7	**2.8**	3.0	2.7	**2.8**	3.0	3.0	**3.5**	4.4
Brazil	**0.1**	0.2	**0.3**	0.3	0.2	**0.3**	0.4	0.4	**0.6**	1.0
Sub-Saharan Africa	**0.7**	1.0	**1.1**	1.3	1.0	**1.2**	1.4	1.4	**2.4**	3.5
Middle East & North Africa	**4.6**	5.1	**5.7**	6.6	5.2	**5.8**	6.9	6.2	**10.1**	16.6
South Africa	**0.1**	0.1	**0.1**	0.1	0.1	**0.1**	0.1	0.1	**0.2**	0.6
Northern Europe	**6.4**	4.8	**5.8**	6.9	4.7	**5.7**	7.0	4.7	**6.6**	9.5
UK & Irland	**18.5**	18.7	**19.7**	21.8	18.7	**19.8**	22.0	18.5	**22.4**	26.8
Central Europe North	**163.9**	167.1	**176.4**	186.1	166.7	**176.7**	186.9	173.4	**192.3**	216.1
Central Europe South	**14.2**	14.8	**15.9**	17.3	14.8	**16.1**	17.5	15.7	**19.3**	22.7
Southern Europe	**15.9**	17.1	**18.6**	20.4	17.3	**19.0**	21.1	19.1	**26.2**	39.3
Rest of Europe	**1.2**	1.3	**1.6**	1.7	1.4	**1.6**	1.7	1.6	**1.9**	2.2
Rest of FSU	**0.4**	0.5	**0.7**	0.7	0.5	**0.7**	0.7	0.7	**0.8**	1.2
Russia	**0.9**	0.9	**1.0**	1.1	0.9	**1.0**	1.1	1.0	**1.3**	1.6
Global	482	505	543	590	503	545	595	549	656	788

Figure 5 represents the same information with bars, including also the breakdown for the main three direct damages (agriculture, capital loss and residential). China and the North Central Europe region have a different scale (left-axis in the figure) from the rest. Similarly to river floods, most of the damage is due to residential buildings and capital losses affecting infrastructures. The South-East Asia is the only region where agriculture damages have a similar share to those of the other two damage categories.

Figure 5: Costal flood damage (bn€)



4.2 ECONOMIC IMPLICATIONS

Figure 6, Table 8 and Table 9 represent the impacts on GDP once the CGE model is run. The results refer to the economic impacts relative to the control period. The relative global GDP loss (Table 8) is estimated at 0.08% at 1.5C warming, 0.09% at 2°C and 0.24% at 4°C. In absolute terms, the global GDP loss (Table 9) is estimated at 68bn€ at 1.5°C warming, 71bn€ at 2°C and 195bn€ at 4°C.

China appears to be the most vulnerable region to climate change impacts associated with coastal flooding. Its GDP loss ranges between 0.4% for the 1.5°C and 1.3% for the 4°C case. Other regions relatively sensitive to climate change are India, Indonesia, Australia and Oceania and Central Europe North, where GDP losses are around 0.3 to 0.5% for the 4°C warming level. For the other regions, the impacts are relatively small.

The GDP losses at 2°C are slightly higher comparing to the 1.5°C losses and remain always below 0.5%. From 2°C to 4°C the GDP losses increase by two-to-three times for most of the regions.

Figure 6: Change in GDP (%)

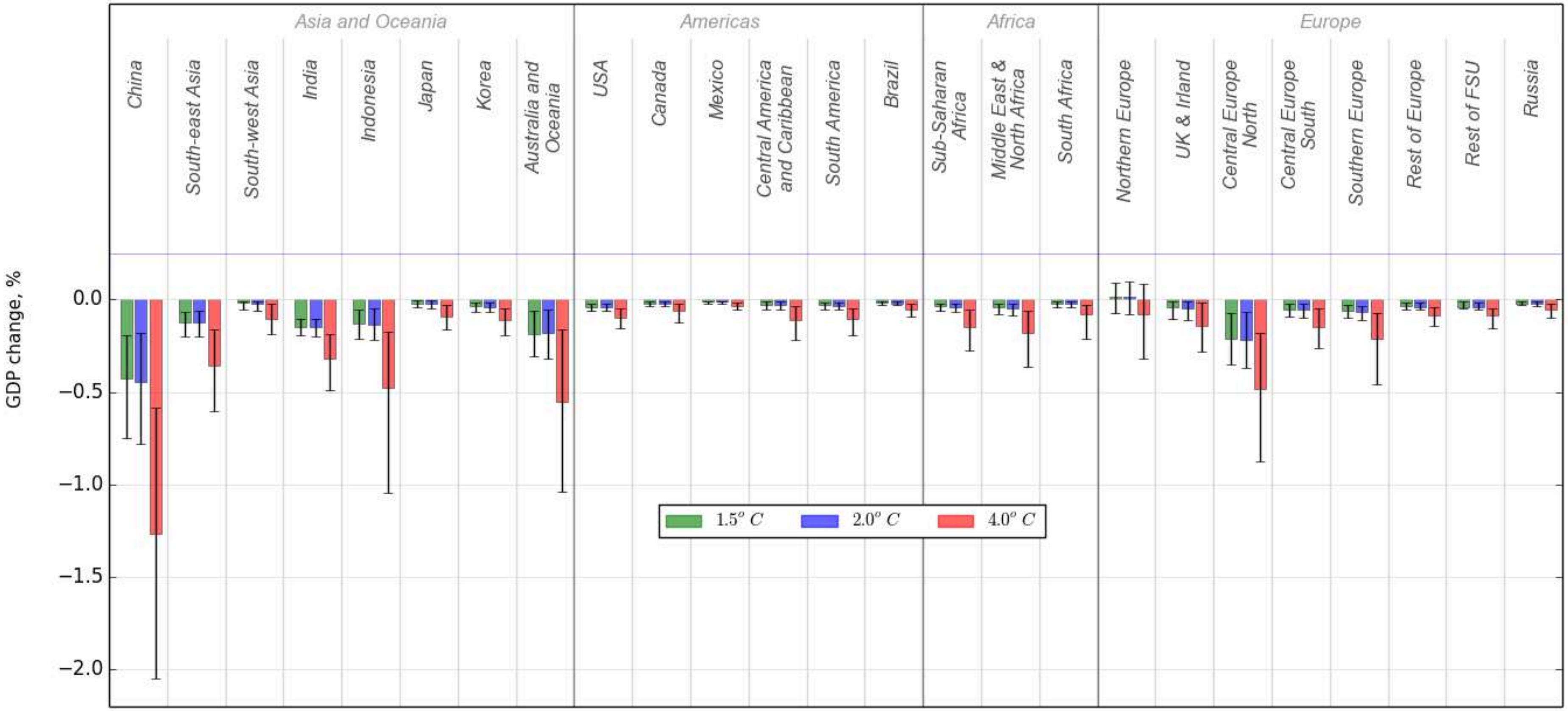


Table 8: Change in GDP (%)

Region	1.5C			2.0C			4.0C		
	min	**mean**	max	min	**mean**	max	min	**mean**	max
China	-0.19	**-0.43**	-0.75	-0.18	**-0.44**	-0.78	-0.58	**-1.27**	-2.05
South-east Asia	-0.07	**-0.12**	-0.20	-0.06	**-0.12**	-0.20	-0.16	**-0.36**	-0.60
South-west Asia	-0.01	**-0.02**	-0.06	-0.01	**-0.02**	-0.06	-0.02	**-0.10**	-0.19
India	-0.11	**-0.15**	-0.19	-0.10	**-0.15**	-0.20	-0.18	**-0.32**	-0.49
Indonesia	-0.05	**-0.13**	-0.21	-0.05	**-0.13**	-0.22	-0.17	**-0.48**	-1.04
Japan	0.00	**-0.02**	-0.04	0.00	**-0.02**	-0.05	-0.03	**-0.09**	-0.16
Korea	-0.02	**-0.04**	-0.06	-0.01	**-0.04**	-0.07	-0.05	**-0.11**	-0.19
Australia and Oceania	-0.06	**-0.18**	-0.31	-0.05	**-0.18**	-0.32	-0.16	**-0.55**	-1.04
USA	-0.02	**-0.04**	-0.06	-0.02	**-0.04**	-0.06	-0.05	**-0.10**	-0.15
Canada	-0.01	**-0.02**	-0.04	-0.01	**-0.02**	-0.04	-0.02	**-0.06**	-0.12
Mexico	-0.01	**-0.01**	-0.02	-0.01	**-0.01**	-0.02	-0.02	**-0.03**	-0.05
Central America and Caribbean	-0.01	**-0.03**	-0.05	-0.01	**-0.03**	-0.06	-0.03	**-0.11**	-0.22
South America	-0.02	**-0.03**	-0.05	-0.01	**-0.03**	-0.06	-0.05	**-0.11**	-0.20
Brazil	-0.01	**-0.02**	-0.03	-0.01	**-0.02**	-0.03	-0.02	**-0.05**	-0.09
Sub-Saharan Africa	-0.02	**-0.04**	-0.06	-0.02	**-0.04**	-0.06	-0.05	**-0.15**	-0.28
Middle East & North Africa	-0.02	**-0.04**	-0.08	-0.02	**-0.05**	-0.09	-0.06	**-0.18**	-0.36
South Africa	-0.01	**-0.02**	-0.04	-0.01	**-0.02**	-0.04	-0.03	**-0.08**	-0.21
Northern Europe	0.09	**0.02**	-0.07	0.09	**0.02**	-0.08	0.08	**-0.08**	-0.32
UK & Irland	-0.01	**-0.04**	-0.10	-0.01	**-0.05**	-0.11	-0.02	**-0.14**	-0.28
Central Europe North	-0.08	**-0.21**	-0.35	-0.07	**-0.21**	-0.37	-0.18	**-0.49**	-0.88
Central Europe South	-0.02	**-0.05**	-0.09	-0.02	**-0.06**	-0.10	-0.05	**-0.15**	-0.26
Southern Europe	-0.03	**-0.06**	-0.10	-0.03	**-0.07**	-0.11	-0.07	**-0.21**	-0.46
Rest of Europe	-0.02	**-0.04**	-0.05	-0.02	**-0.04**	-0.06	-0.04	**-0.09**	-0.14
Rest of FSU	-0.01	**-0.04**	-0.05	-0.02	**-0.04**	-0.05	-0.05	**-0.08**	-0.15
Russia	-0.01	**-0.02**	-0.03	-0.01	**-0.02**	-0.03	-0.02	**-0.06**	-0.10
Global	-0.04	-0.09	-0.15	-0.03	-0.09	-0.15	-0.10	-0.24	-0.43

Table 9: Change in GDP (bn€)

Region	1.5C			2.0C			4.0C		
	min	**mean**	max	min	**mean**	max	min	**mean**	max
China	-6.0	**-13.5**	-23.5	-5.6	**-13.9**	-24.4	-18.4	**-39.8**	-64.3
South-east Asia	-0.7	**-1.4**	-2.1	-0.6	**-1.3**	-2.2	-1.8	**-3.9**	-6.6
South-west Asia	0.0	**-0.1**	-0.3	0.0	**-0.1**	-0.3	-0.1	**-0.5**	-0.9
India	-1.1	**-1.5**	-2.0	-1.1	**-1.5**	-2.1	-1.9	**-3.4**	-5.2
Indonesia	-0.2	**-0.5**	-0.8	-0.2	**-0.5**	-0.8	-0.7	**-1.8**	-4.0
Japan	-0.1	**-0.8**	-1.5	-0.2	**-0.9**	-1.7	-1.1	**-3.4**	-6.2
Korea	-0.1	**-0.3**	-0.6	-0.1	**-0.3**	-0.6	-0.4	**-1.0**	-1.7
Australia and Oceania	-0.6	**-1.7**	-2.8	-0.5	**-1.6**	-2.9	-1.4	**-5.0**	-9.5
USA	-3.0	**-5.0**	-7.6	-2.8	**-5.1**	-7.9	-6.1	**-12.5**	-19.3
Canada	-0.1	**-0.3**	-0.5	-0.1	**-0.2**	-0.4	-0.3	**-0.8**	-1.5
Mexico	-0.1	**-0.1**	-0.2	-0.1	**-0.1**	-0.2	-0.1	**-0.3**	-0.5
Central America and Caribbean	0.0	**-0.1**	-0.2	0.0	**-0.1**	-0.2	-0.1	**-0.4**	-0.7
South America	-0.1	**-0.3**	-0.5	-0.1	**-0.3**	-0.5	-0.4	**-1.0**	-1.8
Brazil	-0.1	**-0.2**	-0.3	-0.1	**-0.2**	-0.4	-0.3	**-0.6**	-1.1
Sub-Saharan Africa	-0.1	**-0.2**	-0.3	-0.1	**-0.2**	-0.3	-0.3	**-0.8**	-1.4
Middle East & North Africa	-0.4	**-0.9**	-1.5	-0.4	**-1.0**	-1.7	-1.1	**-3.5**	-7.1
South Africa	0.0	**-0.1**	-0.1	0.0	**-0.1**	-0.1	-0.1	**-0.2**	-0.5
Northern Europe	0.8	**0.2**	-0.7	0.9	**0.2**	-0.8	0.8	**-0.7**	-3.1
UK & Irland	-0.3	**-1.2**	-2.9	-0.3	**-1.3**	-3.1	-0.5	**-3.9**	-7.9
Central Europe North	-3.5	**-9.6**	-16.2	-3.1	**-9.9**	-16.9	-8.4	**-22.3**	-40.4
Central Europe South	-0.7	**-1.7**	-2.9	-0.7	**-1.8**	-3.2	-1.7	**-5.0**	-8.5
Southern Europe	-1.2	**-2.2**	-3.6	-1.2	**-2.5**	-4.1	-2.7	**-7.9**	-17.2
Rest of Europe	-0.1	**-0.3**	-0.5	-0.2	**-0.3**	-0.5	-0.4	**-0.8**	-1.3
Rest of FSU	0.0	**-0.1**	-0.2	-0.1	**-0.1**	-0.2	-0.2	**-0.3**	-0.5
Russia	-0.1	**-0.2**	-0.3	-0.1	**-0.2**	-0.4	-0.2	**-0.6**	-1.1
Global	-18	-42	-72	-17	-44	-76	-48	-120	-212

Changes in welfare are larger when compared to GDP because the damage to the residential structures is considered to affect households' spending, and therefore welfare, but not directly impacting on the production capacity of the economy (because the overall consumption is the same). Figure 7 and Table 10 and Table 11 present the welfare changes, in a similar way to the GDP effects.

Again, China appears as the country with the highest relative vulnerability to coastal flooding, as was the case of inland flooding. For instance, while under the 1.5°C future the Chinese relative welfare loss is simulated to be ten times bigger than the global one (2.3% and 0.25%, respectively). Under the 4°C future, China would face a welfare loss amounting to 6.7% (versus 0.7% for the world economy). Under the worst case, China would have a welfare loss of 10.7%. Other regions largely affected by the 4°C scenario are India (1% of its welfare), Indonesia (1.3%), Australia and Oceania (1.8%) and Central Europe North (1.4%).

It is also interesting to note that the welfare losses are around 10% higher than direct damages (e.g. for the global economy a welfare loss of 195 bn€ versus a direct damage of 174 bn€), the same way as in the inland flooding analysis.

Figure 7: Change in welfare (%)

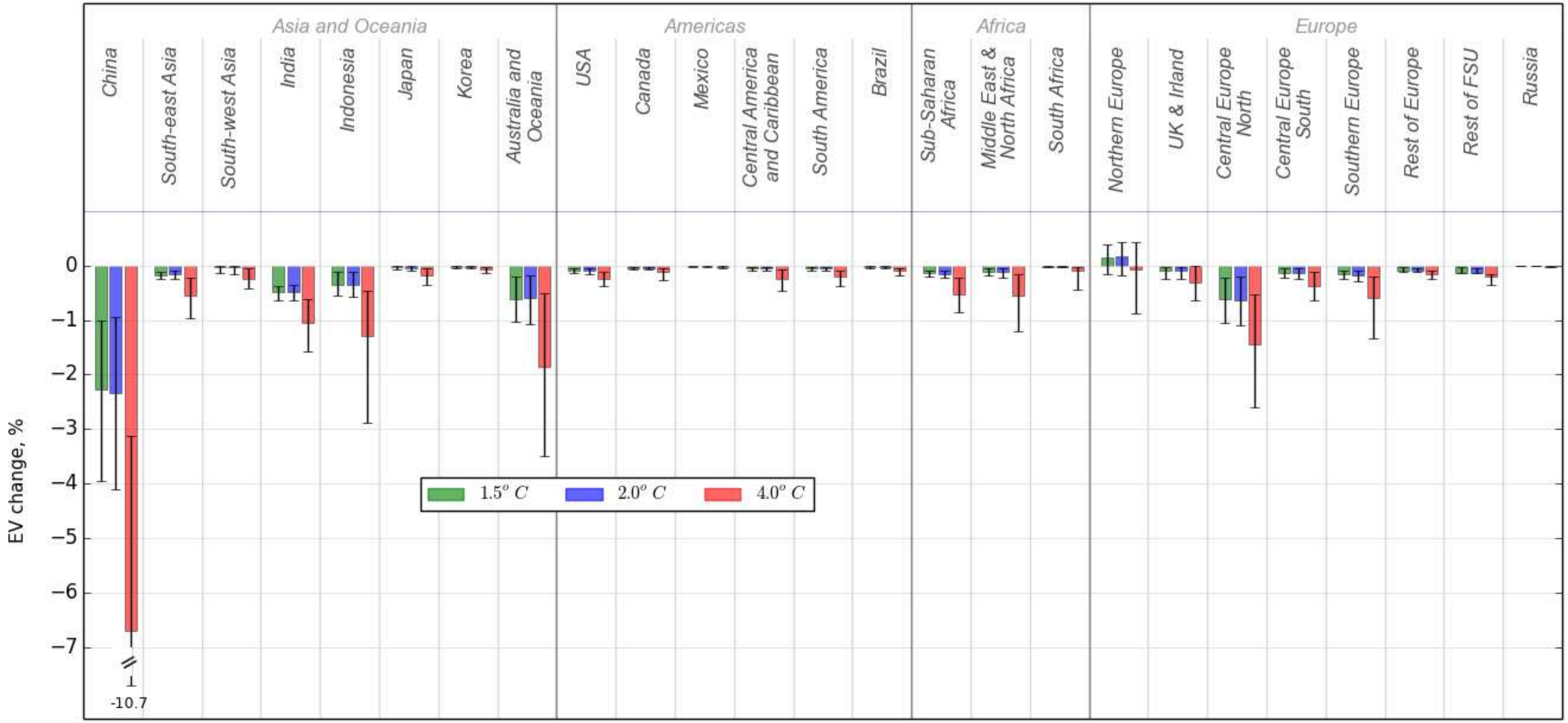


Table 10: Change in welfare (%)

Region	1.5C			2.0C			4.0C		
	min	**mean**	max	min	**mean**	max	min	**mean**	max
China	-1.01	**-2.27**	-3.95	-0.95	**-2.34**	-4.10	-3.12	**-6.68**	-10.71
South-east Asia	-0.12	**-0.18**	-0.25	-0.09	**-0.17**	-0.25	-0.22	**-0.55**	-0.96
South-west Asia	-0.01	**-0.03**	-0.15	-0.01	**-0.04**	-0.16	-0.04	**-0.26**	-0.42
India	-0.37	**-0.49**	-0.63	-0.35	**-0.49**	-0.64	-0.62	**-1.05**	-1.59
Indonesia	-0.13	**-0.35**	-0.54	-0.11	**-0.36**	-0.57	-0.47	**-1.30**	-2.89
Japan	0.00	**-0.04**	-0.08	-0.01	**-0.05**	-0.09	-0.05	**-0.19**	-0.36
Korea	-0.01	**-0.03**	-0.04	-0.01	**-0.03**	-0.05	-0.03	**-0.08**	-0.15
Australia and Oceania	-0.21	**-0.62**	-1.03	-0.17	**-0.60**	-1.07	-0.51	**-1.85**	-3.49
USA	-0.06	**-0.10**	-0.15	-0.06	**-0.10**	-0.16	-0.12	**-0.25**	-0.38
Canada	-0.03	**-0.05**	-0.08	-0.02	**-0.04**	-0.08	-0.04	**-0.13**	-0.26
Mexico	-0.01	**-0.02**	-0.02	-0.01	**-0.02**	-0.02	-0.02	**-0.03**	-0.04
Central America and Caribbean	-0.02	**-0.05**	-0.09	-0.02	**-0.06**	-0.10	-0.07	**-0.24**	-0.46
South America	-0.03	**-0.06**	-0.10	-0.03	**-0.06**	-0.10	-0.10	**-0.21**	-0.39
Brazil	-0.01	**-0.03**	-0.05	-0.01	**-0.04**	-0.05	-0.05	**-0.09**	-0.17
Sub-Saharan Africa	-0.09	**-0.14**	-0.20	-0.10	**-0.16**	-0.23	-0.22	**-0.53**	-0.86
Middle East & North Africa	-0.05	**-0.11**	-0.19	-0.06	**-0.12**	-0.22	-0.16	**-0.55**	-1.20
South Africa	-0.01	**-0.02**	-0.04	-0.01	**-0.02**	-0.04	-0.03	**-0.10**	-0.45
Northern Europe	0.39	**0.15**	-0.15	0.42	**0.16**	-0.17	0.43	**-0.08**	-0.89
UK & Irland	-0.02	**-0.09**	-0.24	-0.02	**-0.10**	-0.26	-0.02	**-0.31**	-0.64
Central Europe North	-0.23	**-0.63**	-1.06	-0.20	**-0.65**	-1.10	-0.54	**-1.43**	-2.59
Central Europe South	-0.05	**-0.13**	-0.22	-0.05	**-0.14**	-0.24	-0.13	**-0.38**	-0.64
Southern Europe	-0.09	**-0.16**	-0.26	-0.10	**-0.18**	-0.30	-0.20	**-0.60**	-1.33
Rest of Europe	-0.04	**-0.10**	-0.12	-0.05	**-0.10**	-0.12	-0.10	**-0.17**	-0.25
Rest of FSU	-0.03	**-0.14**	-0.13	-0.06	**-0.15**	-0.14	-0.15	**-0.21**	-0.35
Russia	-0.01	**-0.01**	-0.02	-0.01	**-0.01**	-0.02	-0.02	**-0.02**	-0.02
Global	-0.11	-0.25	-0.42	-0.10	-0.26	-0.45	-0.29	-0.71	-1.25

Table 11: Change in welfare (bn€)

Region	1.5C			2.0C			4.0C		
	min	**mean**	max	min	**mean**	max	min	**mean**	max
China	-11.8	**-26.3**	-45.8	-10.9	**-27.1**	-47.5	-36.2	**-77.4**	-124.1
South-east Asia	-0.7	**-1.0**	-1.4	-0.5	**-0.9**	-1.4	-1.2	**-3.0**	-5.2
South-west Asia	0.0	**-0.1**	-0.4	0.0	**-0.1**	-0.5	-0.1	**-0.7**	-1.2
India	-2.2	**-2.9**	-3.8	-2.1	**-2.9**	-3.8	-3.7	**-6.2**	-9.4
Indonesia	-0.3	**-0.8**	-1.2	-0.2	**-0.8**	-1.2	-1.0	**-2.8**	-6.3
Japan	-0.1	**-0.8**	-1.6	-0.1	**-0.9**	-1.9	-1.1	**-3.9**	-7.3
Korea	-0.1	**-0.1**	-0.2	0.0	**-0.1**	-0.2	-0.1	**-0.4**	-0.7
Australia and Oceania	-1.0	**-2.9**	-4.8	-0.8	**-2.8**	-5.0	-2.4	**-8.6**	-16.3
USA	-4.9	**-8.0**	-12.0	-4.6	**-8.1**	-12.5	-9.8	**-19.8**	-30.4
Canada	-0.2	**-0.3**	-0.5	-0.1	**-0.3**	-0.5	-0.3	**-0.8**	-1.7
Mexico	-0.1	**-0.1**	-0.1	-0.1	**-0.1**	-0.1	-0.1	**-0.2**	-0.2
Central America and Caribbean	0.0	**-0.1**	-0.2	-0.1	**-0.1**	-0.2	-0.2	**-0.6**	-1.1
South America	-0.2	**-0.3**	-0.5	-0.2	**-0.3**	-0.5	-0.5	**-1.1**	-2.0
Brazil	-0.1	**-0.2**	-0.3	-0.1	**-0.2**	-0.4	-0.3	**-0.6**	-1.1
Sub-Saharan Africa	-0.3	**-0.5**	-0.6	-0.3	**-0.5**	-0.7	-0.7	**-1.7**	-2.7
Middle East & North Africa	-0.5	**-1.1**	-1.8	-0.6	**-1.2**	-2.1	-1.6	**-5.3**	-11.6
South Africa	0.0	**0.0**	-0.1	0.0	**0.0**	-0.1	0.0	**-0.1**	-0.6
Northern Europe	1.8	**0.7**	-0.7	1.9	**0.7**	-0.8	1.9	**-0.4**	-4.0
UK & Irland	-0.4	**-1.5**	-4.1	-0.4	**-1.6**	-4.3	-0.3	**-5.1**	-10.7
Central Europe North	-5.6	**-15.6**	-26.2	-5.0	**-16.0**	-27.3	-13.4	**-35.6**	-64.2
Central Europe South	-0.9	**-2.3**	-4.0	-0.9	**-2.5**	-4.3	-2.2	**-6.8**	-11.5
Southern Europe	-1.9	**-3.4**	-5.5	-2.0	**-3.9**	-6.3	-4.3	**-12.7**	-28.2
Rest of Europe	-0.2	**-0.4**	-0.5	-0.2	**-0.5**	-0.6	-0.4	**-0.8**	-1.1
Rest of FSU	-0.1	**-0.3**	-0.2	-0.1	**-0.3**	-0.3	-0.3	**-0.4**	-0.6
Russia	0.0	**-0.1**	-0.1	0.0	**-0.1**	-0.1	-0.1	**-0.1**	-0.1
Global	-30	-68	-117	-28	-71	-122	-79	-195	-342

5 AGRICULTURAL CROPS

The economic modelling of climate impacts on agricultural crops is based on yield changes computed for four main crops (whet, rice, maize, soybeans). Productivity of other than the four main crops is assumed unchanged. Yield change is modelled as productivity change in the sector producing the agricultural crops.

Table 12 informs about how different GCMs cover the SWLs. The limitations derive from climate data being available only until the end of the 21st century; hence, if a given GCM does not reach a specific SWL in the 21st century it is excluded from further analysis. For 1.5°C and 2°C there is full coverage of the set of climate models. The SWL of 4°C is not reached by one of the models, and 6°C is achieved only by two of the climate models before 2100.

Table 12: Data availability

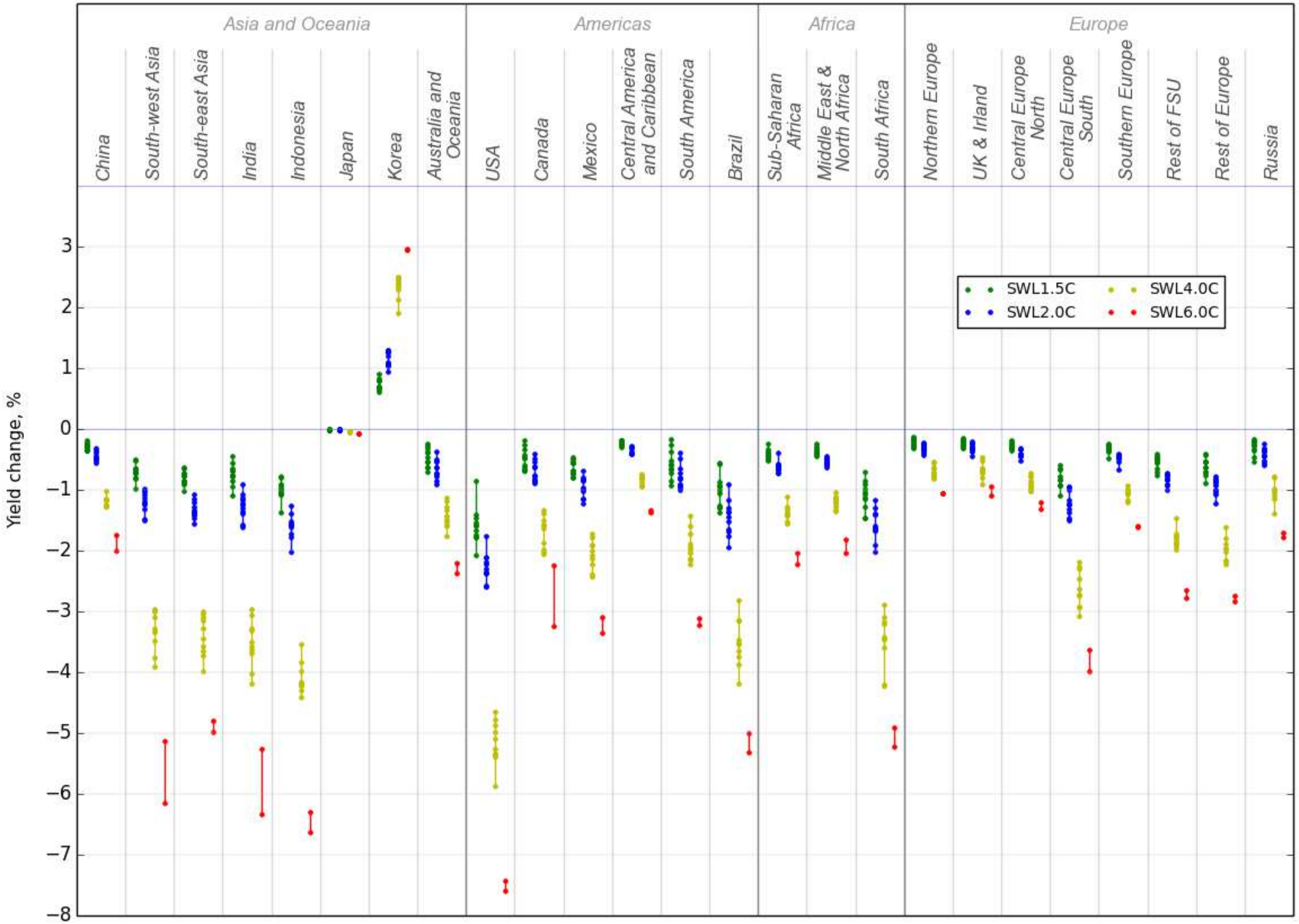
GCM \ SWL	1.5C	2.0C	4.0C	6.0C
ecearth-r1	yes	yes	yes	yes
ecearth-r2	yes	yes	X	X
ecearth-r3	yes	yes	yes	yes
ecearth-r4	yes	yes	yes	X
ecearth-r5	yes	yes	yes	X
ecearth-r6	yes	yes	yes	X
ecearth-r7	yes	yes	yes	X
hadgem3-r1	yes	yes	yes	X
hadgem3-r3	yes	yes	yes	X
hadgem3-r6	yes	yes	yes	X
hadgem3-r8	yes	yes	yes	X

5.1 YIELD CHANGE DATA (DIRECT DAMAGES)

Figure 8 and Table 13 show the percentage change in aggregated crop yields by regions for the different SWLs (relative to the control or reference period). Figure 8 plots the data points for all GCMs separately and it allows assessing distribution and range of the yield change data, while Table 13 presents relevant statistics: mean, minimum and maximum.

The largest reductions in yields (5-7% at 6°C) are projected for the USA and parts of South Asia (both South-East and South-West); also Brazil and parts of Africa (South Africa) can face yields losses of about 5% at 6°C. In Europe, the most affected regions are Central Europe South (up to 4% loss at 6°C) and Rest of FSU and Rest of Europe (2.5% – 3% at 6°C).

Figure 8: Change in agricultural crops production (%)



The yield change loss for the different SWLs changes in a nonlinear fashion. The additional 0.5°C increase from 1.5 to 2°C adds another 50-70% of the yield loss. Then, the additional 2°C (from 2 to 4°C) increases the yield loss by a factor of 2.1-2.8. Finally, the 2°C warming (from 4 to 6°C) worsens the yield reduction by further 20 to 70%.

The only region with positive yield change (0.7% to 3%) is Korea, and Japan shows zero change up until SWL 6°C when it reaches 0.1% reduction.

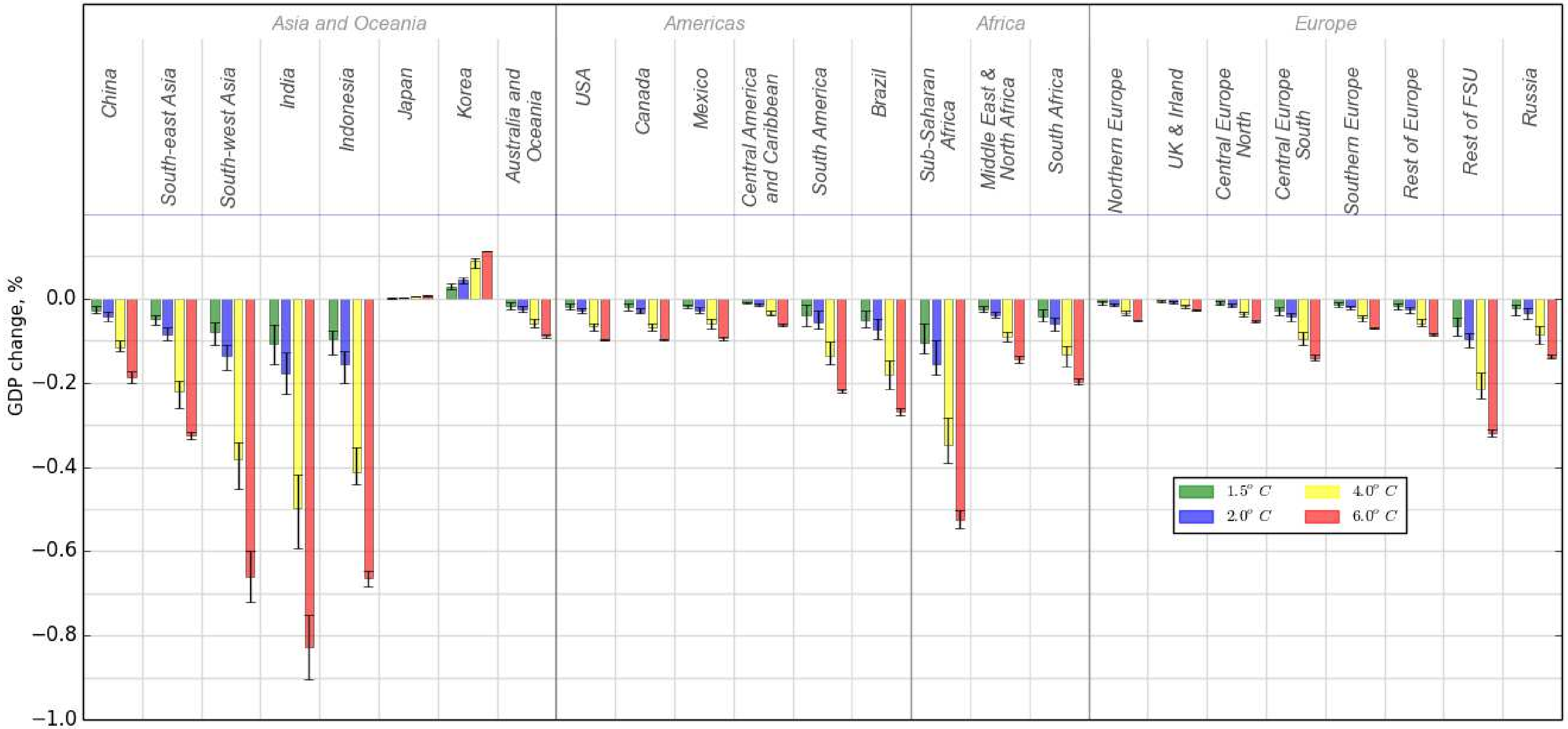
Table 13: Change in agricultural crops production (%)

Region	1.5C			2.0C			4.0C			6.0C		
	min	**mean**	max	min	**mean**	max	min	**mean**	max	min	**mean**	max
China	-0.2	**-0.3**	-0.4	-0.3	**-0.4**	-0.6	-1.0	**-1.2**	-1.3	-1.7	**-1.9**	-2.0
South-east Asia	-0.5	**-0.7**	-1.0	-1.0	**-1.2**	-1.5	-3.0	**-3.3**	-3.9	-5.1	**-5.6**	-6.2
South-west Asia	-0.6	**-0.8**	-1.0	-1.1	**-1.3**	-1.6	-3.0	**-3.4**	-4.0	-4.8	**-4.9**	-5.0
India	-0.4	**-0.7**	-1.1	-0.9	**-1.3**	-1.6	-3.0	**-3.5**	-4.2	-5.3	**-5.8**	-6.3
Indonesia	-0.8	**-1.0**	-1.4	-1.3	**-1.6**	-2.0	-3.5	**-4.1**	-4.4	-6.3	**-6.5**	-6.6
Japan	0.0	**0.0**	0.0	0.0	**0.0**	0.0	0.0	**0.0**	0.0	-0.1	**-0.1**	-0.1
Korea	0.9	**0.7**	0.6	1.3	**1.1**	1.0	2.5	**2.3**	1.9	3.0	**3.0**	2.9
Australia and Oceania	-0.2	**-0.5**	-0.7	-0.4	**-0.7**	-0.9	-1.1	**-1.4**	-1.8	-2.2	**-2.3**	-2.4
USA	-0.9	**-1.6**	-2.1	-1.8	**-2.3**	-2.6	-4.7	**-5.2**	-5.9	-7.4	**-7.5**	-7.6
Canada	-0.2	**-0.5**	-0.7	-0.4	**-0.7**	-0.9	-1.3	**-1.7**	-2.0	-2.2	**-2.7**	-3.2
Mexico	-0.5	**-0.6**	-0.8	-0.7	**-1.0**	-1.2	-1.7	**-2.1**	-2.4	-3.1	**-3.2**	-3.3
Central America and Caribbean	-0.2	**-0.2**	-0.3	-0.3	**-0.4**	-0.4	-0.7	**-0.9**	-0.9	-1.3	**-1.4**	-1.4
South America	-0.2	**-0.6**	-0.9	-0.4	**-0.8**	-1.0	-1.4	**-1.9**	-2.2	-3.1	**-3.2**	-3.2
Brazil	-0.6	**-1.0**	-1.4	-0.9	**-1.5**	-1.9	-2.8	**-3.5**	-4.2	-5.0	**-5.2**	-5.3
Sub-Saharan Africa	-0.2	**-0.4**	-0.5	-0.4	**-0.6**	-0.7	-1.1	**-1.4**	-1.6	-2.0	**-2.1**	-2.2
Middle East & North Africa	-0.2	**-0.4**	-0.4	-0.4	**-0.5**	-0.6	-1.0	**-1.2**	-1.3	-1.8	**-1.9**	-2.0
South Africa	-0.7	**-1.1**	-1.5	-1.2	**-1.6**	-2.0	-2.9	**-3.5**	-4.2	-4.9	**-5.1**	-5.2
Northern Europe	-0.1	**-0.2**	-0.3	-0.2	**-0.3**	-0.4	-0.5	**-0.7**	-0.8	-1.1	**-1.1**	-1.1
UK & Irland	-0.2	**-0.2**	-0.3	-0.2	**-0.3**	-0.5	-0.5	**-0.7**	-0.9	-1.0	**-1.0**	-1.1
Central Europe North	-0.2	**-0.3**	-0.3	-0.3	**-0.4**	-0.5	-0.7	**-0.9**	-1.0	-1.2	**-1.3**	-1.3
Central Europe South	-0.6	**-0.8**	-1.1	-0.9	**-1.2**	-1.5	-2.2	**-2.6**	-3.1	-3.6	**-3.8**	-4.0
Southern Europe	-0.2	**-0.3**	-0.5	-0.4	**-0.5**	-0.7	-0.9	**-1.1**	-1.2	-1.6	**-1.6**	-1.6
Rest of Europe	-0.4	**-0.5**	-0.8	-0.7	**-0.8**	-1.0	-1.5	**-1.8**	-2.0	-2.6	**-2.7**	-2.8
Rest of FSU	-0.4	**-0.6**	-0.9	-0.8	**-0.9**	-1.2	-1.6	**-2.0**	-2.2	-2.7	**-2.8**	-2.8
Russia	-0.2	**-0.3**	-0.5	-0.2	**-0.4**	-0.6	-0.8	**-1.0**	-1.4	-1.7	**-1.7**	-1.8

5.2 Economic implications

The global GDP losses due to reduced agricultural yields are 0.02%, 0.03%, 0.08% and 0.13% for the respective SWLs (Figure 9, Table 14). In absolute terms the GDP reductions are: 11bn€, 17bn€, 41bn€ and 64bn€ (Table 15).

Figure 9: GDP change (%)



In relative terms, the largest percentage GDP reductions are observed in Asia. The GDP effect range from -0.03% (1.5°C) to -0.2% (6°C) in China; -0.05% (1.5°C) to -0.65% (6°C) in South-east and South-west Asia; and, by far the most affected, India with GDP reductions of 0.1% (1.5°C) to 0.83% (6°C).

In the Americas, South America and Brazil are the most affected regions with the GDP losses in a range of 0.05% (at 1.5°C) to 0.25% (at 6°C). In Africa, Sub-Saharan Africa could lose up to 0.1% of its GDP (at 1.5°C) to 0.5% (at 6°C). In Europe, the central Europe South region and the rest of FSU can have GDP reduced by 0.14% and 0.31% respectively at 6°C warming level.

Table 14: GDP change (%)

Region	1.5C			2.0C			4.0C			6.0C		
	min	**mean**	max	min	**mean**	max	min	**mean**	max	min	**mean**	max
China	-0.03	**-0.03**	-0.02	-0.05	**-0.04**	-0.03	-0.13	**-0.12**	-0.10	-0.20	**-0.19**	-0.17
South-east Asia	-0.06	**-0.05**	-0.04	-0.10	**-0.08**	-0.07	-0.26	**-0.22**	-0.20	-0.33	**-0.32**	-0.32
South-west Asia	-0.11	**-0.08**	-0.06	-0.17	**-0.14**	-0.11	-0.45	**-0.38**	-0.34	-0.72	**-0.66**	-0.60
India	-0.15	**-0.11**	-0.06	-0.23	**-0.18**	-0.13	-0.59	**-0.50**	-0.42	-0.90	**-0.83**	-0.75
Indonesia	-0.13	**-0.10**	-0.08	-0.20	**-0.16**	-0.12	-0.44	**-0.41**	-0.35	-0.68	**-0.67**	-0.65
Japan	0.00	**0.00**	0.00	0.00	**0.00**	0.00	0.01	**0.00**	0.00	0.01	**0.01**	0.01
Korea	0.02	**0.03**	0.04	0.04	**0.04**	0.05	0.07	**0.09**	0.10	0.11	**0.11**	0.11
Australia and Oceania	-0.02	**-0.02**	-0.01	-0.03	**-0.03**	-0.02	-0.07	**-0.06**	-0.05	-0.09	**-0.09**	-0.09
USA	-0.03	**-0.02**	-0.01	-0.03	**-0.03**	-0.02	-0.08	**-0.07**	-0.06	-0.10	**-0.10**	-0.10
Canada	-0.03	**-0.02**	-0.01	-0.03	**-0.03**	-0.02	-0.08	**-0.07**	-0.06	-0.10	**-0.10**	-0.10
Mexico	-0.02	**-0.02**	-0.01	-0.04	**-0.03**	-0.02	-0.07	**-0.06**	-0.05	-0.10	**-0.09**	-0.09
Central America and Caribbean	-0.01	**-0.01**	-0.01	-0.02	**-0.01**	-0.01	-0.04	**-0.04**	-0.03	-0.06	**-0.06**	-0.06
South America	-0.06	**-0.04**	-0.01	-0.07	**-0.06**	-0.03	-0.16	**-0.14**	-0.10	-0.22	**-0.22**	-0.21
Brazil	-0.07	**-0.05**	-0.03	-0.10	**-0.08**	-0.05	-0.21	**-0.18**	-0.15	-0.28	**-0.27**	-0.26
Sub-Saharan Africa	-0.13	**-0.10**	-0.06	-0.18	**-0.15**	-0.10	-0.39	**-0.35**	-0.28	-0.55	**-0.52**	-0.50
Middle East & North Africa	-0.03	**-0.03**	-0.02	-0.05	**-0.04**	-0.03	-0.10	**-0.09**	-0.08	-0.15	**-0.14**	-0.14
South Africa	-0.06	**-0.04**	-0.03	-0.08	**-0.06**	-0.04	-0.16	**-0.13**	-0.11	-0.20	**-0.20**	-0.19
Northern Europe	-0.01	**-0.01**	-0.01	-0.02	**-0.01**	-0.01	-0.04	**-0.03**	-0.03	-0.05	**-0.05**	-0.05
UK & Irland	-0.01	**-0.01**	0.00	-0.01	**-0.01**	-0.01	-0.02	**-0.02**	-0.02	-0.03	**-0.03**	-0.03
Central Europe North	-0.01	**-0.01**	-0.01	-0.02	**-0.02**	-0.01	-0.04	**-0.04**	-0.03	-0.06	**-0.05**	-0.05
Central Europe South	-0.04	**-0.03**	-0.02	-0.05	**-0.04**	-0.03	-0.11	**-0.10**	-0.08	-0.15	**-0.14**	-0.13
Southern Europe	-0.02	**-0.01**	-0.01	-0.03	**-0.02**	-0.02	-0.05	**-0.05**	-0.04	-0.07	**-0.07**	-0.07
Rest of Europe	-0.02	**-0.02**	-0.01	-0.03	**-0.03**	-0.02	-0.07	**-0.06**	-0.05	-0.09	**-0.08**	-0.08
Rest of FSU	-0.09	**-0.06**	-0.04	-0.12	**-0.10**	-0.08	-0.24	**-0.21**	-0.18	-0.33	**-0.32**	-0.31
Russia	-0.04	**-0.02**	-0.01	-0.05	**-0.04**	-0.02	-0.11	**-0.08**	-0.07	-0.14	**-0.14**	-0.13
Global	-0.03	-0.02	-0.01	-0.04	-0.03	-0.02	-0.10	-0.08	-0.07	-0.13	-0.13	-0.12

Two regions show increase in GDP: Japan (very small up to 0.01% at 6°C) and Korea (from 0.03% to 0.11% for the range of SWLs). The GDP increase is due to improved yields and higher productivity of the crops sector.

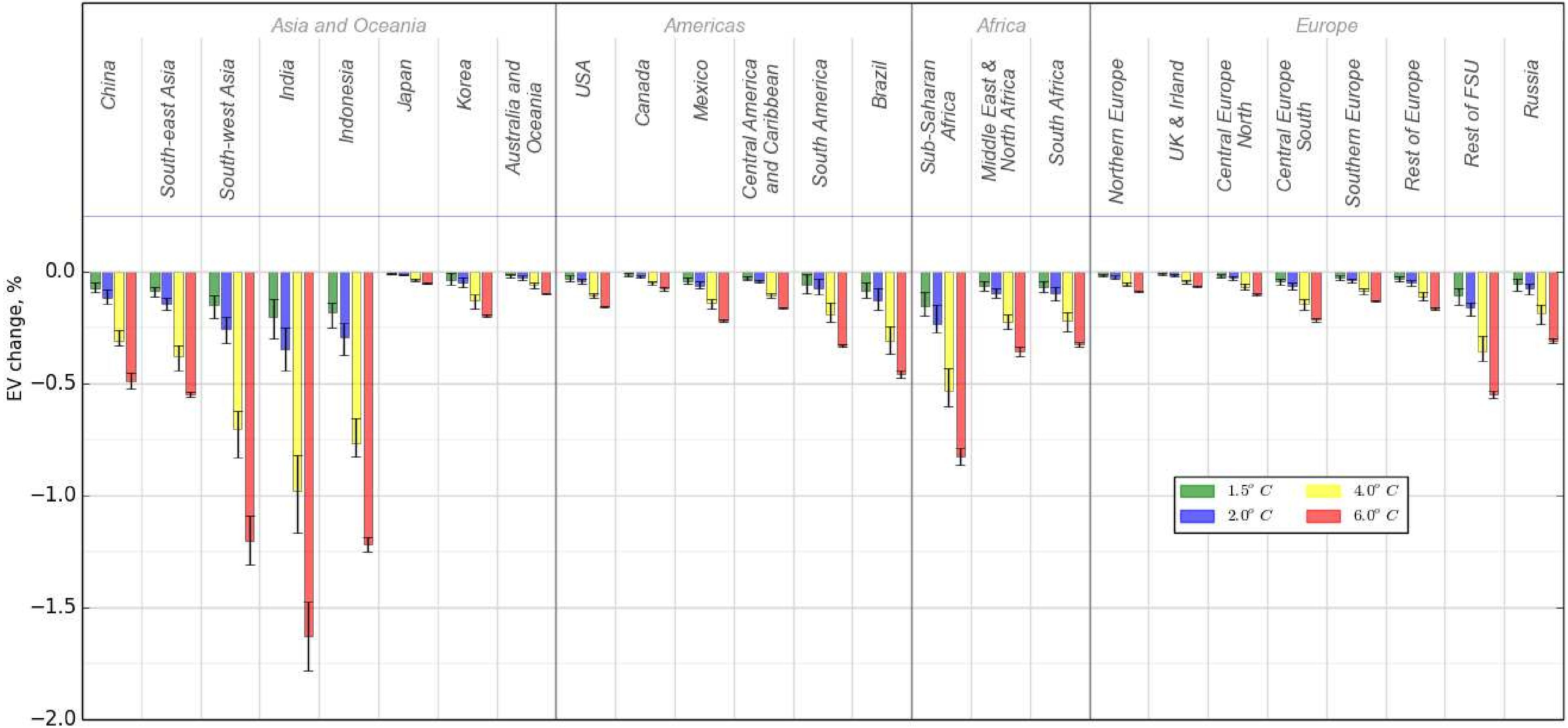
In absolute terms (Table 15), the largest losses occur in the USA: about 20% of the global GDP loss accounts to that region. The USA is followed by India (about 12% of the global loss), China (9%), and Central Europe South (8%).

Table 15: GDP change (bn€)

Region	1.5C			2.0C			4.0C			6.0C		
	min	**mean**	max	min	**mean**	max	min	**mean**	max	min	**mean**	max
China	-1.1	**-0.9**	-0.6	-1.7	**-1.4**	-1.0	-3.9	**-3.7**	-3.1	-6.3	**-5.9**	-5.4
South-east Asia	-0.7	**-0.5**	-0.4	-1.1	**-0.9**	-0.8	-2.9	**-2.4**	-2.1	-3.6	**-3.6**	-3.5
South-west Asia	-0.5	**-0.4**	-0.3	-0.8	**-0.6**	-0.5	-2.2	**-1.8**	-1.6	-3.4	**-3.1**	-2.9
India	-1.6	**-1.1**	-0.7	-2.4	**-1.9**	-1.4	-6.3	**-5.3**	-4.4	-9.6	**-8.7**	-7.9
Indonesia	-0.5	**-0.4**	-0.3	-0.8	**-0.6**	-0.5	-1.7	**-1.6**	-1.3	-2.6	**-2.5**	-2.5
Japan	0.1	**0.1**	0.0	0.1	**0.1**	0.1	0.2	**0.2**	0.2	0.3	**0.3**	0.2
Korea	0.2	**0.3**	0.3	0.3	**0.4**	0.4	0.6	**0.8**	0.9	1.0	**1.0**	1.0
Australia and Oceania	-0.2	**-0.2**	-0.1	-0.3	**-0.2**	-0.2	-0.6	**-0.5**	-0.4	-0.8	**-0.8**	-0.8
USA	-3.3	**-2.5**	-1.3	-4.1	**-3.6**	-2.7	-9.5	**-8.3**	-7.4	-12.6	**-12.3**	-12.1
Canada	-0.3	**-0.3**	-0.1	-0.4	**-0.4**	-0.3	-1.0	**-0.9**	-0.8	-1.2	**-1.2**	-1.2
Mexico	-0.2	**-0.2**	-0.1	-0.3	**-0.3**	-0.2	-0.6	**-0.5**	-0.4	-0.9	**-0.9**	-0.8
Central America and Caribbean	0.0	**0.0**	0.0	-0.1	**-0.1**	0.0	-0.1	**-0.1**	-0.1	-0.2	**-0.2**	-0.2
South America	-0.6	**-0.4**	-0.1	-0.7	**-0.5**	-0.3	-1.5	**-1.3**	-1.0	-2.1	**-2.0**	-2.0
Brazil	-0.8	**-0.6**	-0.3	-1.2	**-0.9**	-0.6	-2.6	**-2.2**	-1.8	-3.3	**-3.2**	-3.1
Sub-Saharan Africa	-0.7	**-0.5**	-0.3	-0.9	**-0.8**	-0.5	-2.0	**-1.8**	-1.4	-2.8	**-2.7**	-2.6
Middle East & North Africa	-0.6	**-0.5**	-0.3	-0.9	**-0.8**	-0.6	-2.0	**-1.8**	-1.5	-3.0	**-2.8**	-2.7
South Africa	-0.1	**-0.1**	-0.1	-0.2	**-0.2**	-0.1	-0.4	**-0.3**	-0.3	-0.5	**-0.5**	-0.5
Northern Europe	-0.1	**-0.1**	-0.1	-0.2	**-0.1**	-0.1	-0.4	**-0.3**	-0.3	-0.5	**-0.5**	-0.5
UK & Irland	-0.2	**-0.2**	-0.1	-0.3	**-0.2**	-0.2	-0.6	**-0.5**	-0.4	-0.8	**-0.8**	-0.7
Central Europe North	-0.6	**-0.5**	-0.3	-0.9	**-0.7**	-0.5	-1.9	**-1.7**	-1.4	-2.6	**-2.5**	-2.4
Central Europe South	-1.3	**-1.0**	-0.7	-1.7	**-1.4**	-1.1	-3.7	**-3.1**	-2.6	-4.8	**-4.6**	-4.4
Southern Europe	-0.7	**-0.5**	-0.3	-1.0	**-0.8**	-0.6	-2.0	**-1.7**	-1.5	-2.7	**-2.6**	-2.6
Rest of Europe	-0.2	**-0.2**	-0.1	-0.3	**-0.2**	-0.2	-0.6	**-0.5**	-0.4	-0.8	**-0.7**	-0.7
Rest of FSU	-0.3	**-0.2**	-0.1	-0.4	**-0.3**	-0.3	-0.8	**-0.7**	-0.6	-1.1	**-1.0**	-1.0
Russia	-0.4	**-0.3**	-0.1	-0.5	**-0.4**	-0.2	-1.2	**-0.9**	-0.7	-1.5	**-1.5**	-1.4
Global	-15	-11	-7	-21	-17	-12	-47	-41	-35	-67	-64	-61

The welfare changes are presented on Figure 10, Table 16 and Table 17. Overall, the welfare changes are comparable to the GDP losses in absolute terms (Table 15 and Table 17), with the exception of Japan and Korea which are discussed further below. In percentage terms, however, the welfare changes are about twice as large as the GDP changes (Figure 9 and Figure 10). This effect results from the fact that yield changes translate into changes in consumer prices and affect households' consumption possibilities, hence welfare. Since private consumption constitutes 40% to 70% of GDP, the percentage change of GDP is correspondingly smaller.

Figure 10: Welfare change (%)



A regional economy is affected not only by performance of domestic crops sector, but also impacted upon by other economies via international trade linkages and the prices they carry. For example, Japan and Korea see reductions in their welfare in spite of a positive yield change and improvement in GDP. This is because of the increase in price of imports which affect consumer prices and lead to reduction in welfare.

Table 16: Change in welfare (EV) (%)

Region	1.5C			2.0C			4.0C			6.0C		
	min	**mean**	max	min	**mean**	max	min	**mean**	max	min	**mean**	max
China	-0.09	**-0.07**	-0.05	-0.15	**-0.12**	-0.08	-0.33	**-0.31**	-0.26	-0.52	**-0.49**	-0.45
South-east Asia	-0.11	**-0.09**	-0.07	-0.17	**-0.15**	-0.12	-0.44	**-0.38**	-0.33	-0.56	**-0.55**	-0.54
South-west Asia	-0.21	**-0.15**	-0.11	-0.32	**-0.25**	-0.20	-0.83	**-0.70**	-0.62	-1.31	**-1.20**	-1.09
India	-0.30	**-0.21**	-0.12	-0.44	**-0.35**	-0.25	-1.16	**-0.98**	-0.82	-1.78	**-1.63**	-1.48
Indonesia	-0.25	**-0.18**	-0.14	-0.37	**-0.29**	-0.23	-0.83	**-0.77**	-0.66	-1.25	**-1.22**	-1.19
Japan	-0.01	**-0.01**	-0.01	-0.02	**-0.02**	-0.01	-0.04	**-0.04**	-0.03	-0.05	**-0.05**	-0.05
Korea	-0.06	**-0.04**	-0.01	-0.07	**-0.05**	-0.03	-0.17	**-0.13**	-0.10	-0.21	**-0.20**	-0.19
Australia and Oceania	-0.03	**-0.02**	-0.01	-0.04	**-0.03**	-0.02	-0.08	**-0.06**	-0.05	-0.10	**-0.10**	-0.10
USA	-0.04	**-0.03**	-0.02	-0.05	**-0.05**	-0.04	-0.12	**-0.11**	-0.10	-0.16	**-0.16**	-0.15
Canada	-0.02	**-0.01**	-0.01	-0.03	**-0.02**	-0.01	-0.06	**-0.05**	-0.04	-0.08	**-0.08**	-0.07
Mexico	-0.06	**-0.04**	-0.03	-0.08	**-0.06**	-0.05	-0.17	**-0.14**	-0.12	-0.23	**-0.22**	-0.21
Central America and Caribbean	-0.04	**-0.03**	-0.02	-0.05	**-0.05**	-0.04	-0.12	**-0.11**	-0.09	-0.16	**-0.16**	-0.16
South America	-0.10	**-0.06**	-0.01	-0.10	**-0.08**	-0.03	-0.23	**-0.19**	-0.14	-0.34	**-0.33**	-0.33
Brazil	-0.12	**-0.09**	-0.05	-0.17	**-0.13**	-0.08	-0.37	**-0.31**	-0.24	-0.47	**-0.46**	-0.44
Sub-Saharan Africa	-0.20	**-0.16**	-0.09	-0.27	**-0.24**	-0.15	-0.60	**-0.53**	-0.43	-0.86	**-0.82**	-0.79
Middle East & North Africa	-0.08	**-0.07**	-0.04	-0.12	**-0.10**	-0.08	-0.26	**-0.23**	-0.19	-0.38	**-0.36**	-0.34
South Africa	-0.09	**-0.07**	-0.04	-0.13	**-0.10**	-0.07	-0.27	**-0.22**	-0.18	-0.34	**-0.33**	-0.31
Northern Europe	-0.02	**-0.02**	-0.01	-0.03	**-0.03**	-0.02	-0.07	**-0.06**	-0.05	-0.09	**-0.09**	-0.08
UK & Irland	-0.02	**-0.01**	-0.01	-0.02	**-0.02**	-0.01	-0.05	**-0.04**	-0.04	-0.07	**-0.07**	-0.06
Central Europe North	-0.03	**-0.02**	-0.01	-0.04	**-0.03**	-0.02	-0.08	**-0.07**	-0.06	-0.11	**-0.10**	-0.10
Central Europe South	-0.06	**-0.05**	-0.03	-0.08	**-0.07**	-0.05	-0.17	**-0.15**	-0.12	-0.23	**-0.22**	-0.21
Southern Europe	-0.04	**-0.03**	-0.02	-0.05	**-0.04**	-0.03	-0.10	**-0.09**	-0.08	-0.13	**-0.13**	-0.13
Rest of Europe	-0.05	**-0.03**	-0.02	-0.06	**-0.05**	-0.04	-0.13	**-0.11**	-0.09	-0.17	**-0.17**	-0.16
Rest of FSU	-0.15	**-0.11**	-0.08	-0.20	**-0.16**	-0.14	-0.40	**-0.36**	-0.29	-0.56	**-0.55**	-0.53
Russia	-0.08	**-0.05**	-0.03	-0.10	**-0.08**	-0.05	-0.24	**-0.19**	-0.15	-0.32	**-0.31**	-0.30
Global	-0.06	-0.04	-0.03	-0.08	-0.06	-0.05	-0.18	-0.16	-0.13	-0.25	-0.24	-0.23

In absolute terms (Table 17), the largest losses occur in the USA: about 20% of the global GDP loss accounts to that region. The USA is followed by India (about 12% of the global loss), China (8%), and Central Europe South (6%).

Table 17: Change in welfare (EV) (bn€)

Region	1.5C			2.0C			4.0C			6.0C		
	min	**mean**	max	min	**mean**	max	min	**mean**	max	min	**mean**	max
China	-1.1	**-0.9**	-0.5	-1.7	**-1.4**	-0.9	-3.8	**-3.6**	-3.0	-6.1	**-5.7**	-5.3
South-east Asia	-0.6	**-0.5**	-0.4	-0.9	**-0.8**	-0.6	-2.4	**-2.0**	-1.8	-3.0	**-3.0**	-2.9
South-west Asia	-0.6	**-0.4**	-0.3	-0.9	**-0.7**	-0.6	-2.3	**-2.0**	-1.8	-3.7	**-3.4**	-3.1
India	-1.8	**-1.2**	-0.7	-2.6	**-2.1**	-1.5	-6.9	**-5.8**	-4.9	-10.5	**-9.6**	-8.7
Indonesia	-0.6	**-0.4**	-0.3	-0.8	**-0.6**	-0.5	-1.8	**-1.7**	-1.4	-2.7	**-2.7**	-2.6
Japan	-0.3	**-0.2**	-0.1	-0.4	**-0.3**	-0.2	-0.8	**-0.7**	-0.6	-1.1	**-1.1**	-1.0
Korea	-0.3	**-0.2**	0.0	-0.3	**-0.2**	-0.1	-0.8	**-0.6**	-0.5	-0.9	**-0.9**	-0.9
Australia and Oceania	-0.1	**-0.1**	0.0	-0.2	**-0.1**	-0.1	-0.3	**-0.3**	-0.2	-0.5	**-0.5**	-0.4
USA	-3.3	**-2.6**	-1.4	-4.2	**-3.7**	-2.9	-9.7	**-8.5**	-7.6	-12.7	**-12.6**	-12.4
Canada	-0.1	**-0.1**	0.0	-0.2	**-0.1**	-0.1	-0.4	**-0.3**	-0.3	-0.6	**-0.5**	-0.5
Mexico	-0.3	**-0.2**	-0.1	-0.4	**-0.3**	-0.2	-0.9	**-0.8**	-0.7	-1.2	**-1.2**	-1.1
Central America and Caribbean	-0.1	**-0.1**	0.0	-0.1	**-0.1**	-0.1	-0.3	**-0.2**	-0.2	-0.4	**-0.4**	-0.4
South America	-0.5	**-0.3**	-0.1	-0.5	**-0.4**	-0.2	-1.2	**-1.0**	-0.7	-1.7	**-1.7**	-1.7
Brazil	-0.8	**-0.6**	-0.3	-1.1	**-0.8**	-0.5	-2.4	**-2.0**	-1.6	-3.1	**-3.0**	-2.9
Sub-Saharan Africa	-0.6	**-0.5**	-0.3	-0.9	**-0.7**	-0.5	-1.9	**-1.7**	-1.4	-2.7	**-2.6**	-2.5
Middle East & North Africa	-0.8	**-0.6**	-0.4	-1.1	**-0.9**	-0.7	-2.5	**-2.2**	-1.9	-3.6	**-3.5**	-3.3
South Africa	-0.1	**-0.1**	-0.1	-0.2	**-0.1**	-0.1	-0.4	**-0.3**	-0.3	-0.5	**-0.5**	-0.5
Northern Europe	-0.1	**-0.1**	0.0	-0.1	**-0.1**	-0.1	-0.3	**-0.3**	-0.2	-0.4	**-0.4**	-0.4
UK & Irland	-0.3	**-0.2**	-0.1	-0.4	**-0.3**	-0.2	-0.9	**-0.7**	-0.6	-1.2	**-1.1**	-1.1
Central Europe North	-0.7	**-0.5**	-0.3	-0.9	**-0.8**	-0.6	-2.0	**-1.7**	-1.4	-2.6	**-2.5**	-2.4
Central Europe South	-1.1	**-0.8**	-0.6	-1.5	**-1.2**	-0.9	-3.1	**-2.6**	-2.2	-4.0	**-3.8**	-3.7
Southern Europe	-0.8	**-0.6**	-0.4	-1.1	**-0.8**	-0.7	-2.1	**-1.9**	-1.6	-2.8	**-2.8**	-2.7
Rest of Europe	-0.2	**-0.1**	-0.1	-0.3	**-0.2**	-0.2	-0.6	**-0.5**	-0.4	-0.8	**-0.8**	-0.7
Rest of FSU	-0.3	**-0.2**	-0.1	-0.3	**-0.3**	-0.2	-0.7	**-0.6**	-0.5	-1.0	**-1.0**	-0.9
Russia	-0.5	**-0.3**	-0.2	-0.6	**-0.4**	-0.3	-1.3	**-1.0**	-0.8	-1.7	**-1.7**	-1.6
Global	-16	-12	-7	-22	-18	-13	-50	-43	-37	-70	-67	-64

6 RESIDENTIAL ENERGY DEMAND

Based on data from global climate models, the daily average temperatures were used to compute heating and cooling degree days. These are used as inputs for the energy model POLES, which is then able to assess the impact of temperature changes on the energy sector. Indeed, heating and cooling needs are impacted by external temperatures, as well as income, energy prices, insulation efforts and improvements in technology efficiency.

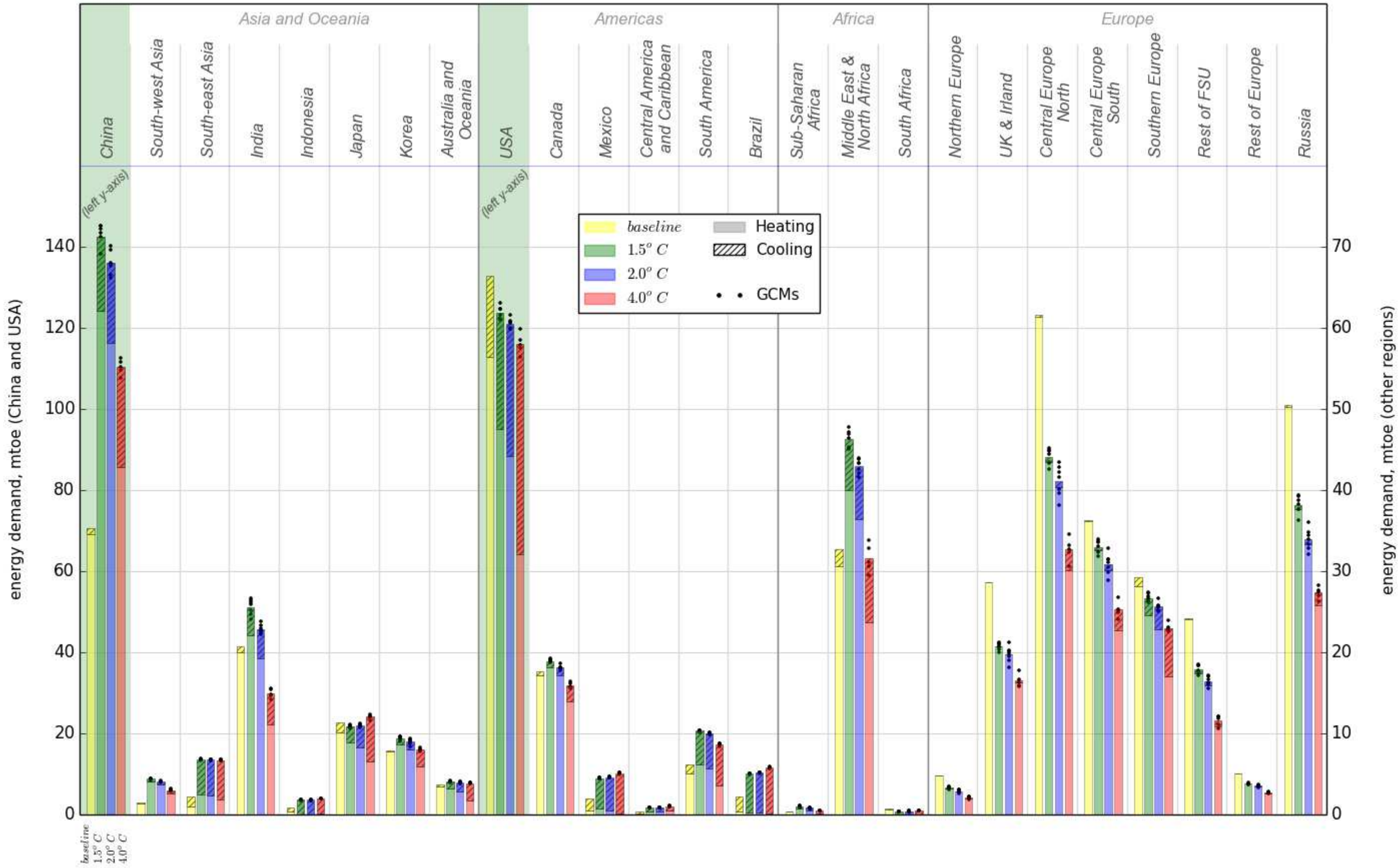
The POLES model computed changes in heating and cooling demand are implemented in the economic model as changes in obliged consumption. If for instance, there is additional cooling demand, that will imply a reduction in welfare because consumers will have to spend the equivalent of the extra cooling demand in other goods.

6.1 ENERGY DEMAND CHANGE (DIRECT DAMAGE)

Figure 11 and Table 18 show regional residential energy demand for heating and cooling for the reference period and the three warming levels (1.5°C, 2°C and 4°C).

The global residential heating and cooling energy demand is at 554 Mtoe at present, and is estimated to increase to 604 Mtoe at 1.5°C warming, then reduce to 574 Mtoe at 2°C warming and further drop below present demand to 487 Mtoe at 4°C.

Figure 11: Change in residential energy demand (Mtoe)



Today the global residential energy demand is dominated by the USA (24% of global use), China (13%), Central Europe North (11%) and Russia (9%). Those share change with warming, and are expected to almost double (at 4°C) for China (23%), remain above 20% for the USA, and drop from current 43% to less than 30% for Europe.

Table 18: Residential energy demand (Mtoe)

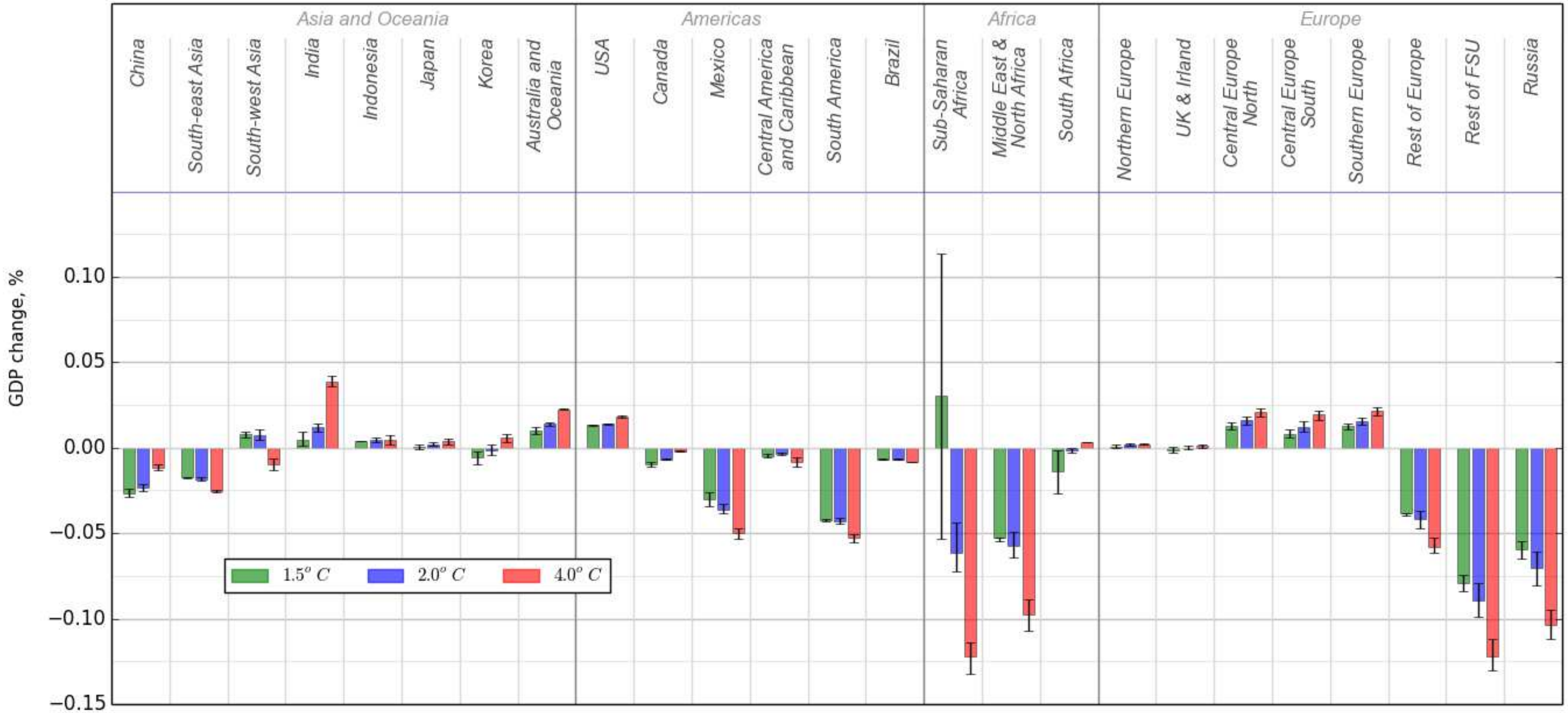
Region	present	1.5C			2.0C			4.0C		
		min	**mean**	max	min	**mean**	max	min	**mean**	max
China	**70.7**	137.1	**142.5**	146.4	131.5	**136.0**	141.8	107.4	**110.4**	112.5
South-east Asia	**1.5**	4.2	**4.4**	4.5	4.0	**4.1**	4.2	2.9	**3.0**	3.2
South-west Asia	**2.3**	6.7	**6.8**	6.9	6.6	**6.8**	6.9	6.6	**6.7**	6.8
India	**20.8**	24.0	**25.6**	26.6	22.2	**22.8**	23.8	14.1	**15.0**	15.7
Indonesia	**0.9**	1.7	**1.8**	1.9	1.8	**1.8**	1.9	1.9	**2.0**	2.0
Japan	**11.3**	10.3	**10.9**	11.3	10.1	**11.0**	11.7	10.5	**12.0**	13.5
Korea	**7.9**	8.9	**9.4**	9.8	8.3	**9.0**	9.6	7.3	**8.0**	8.7
Australia and Oceania	**3.7**	3.7	**4.1**	4.4	3.7	**3.9**	4.2	3.7	**3.9**	4.0
USA	**132.8**	119.9	**123.6**	128.4	117.0	**121.0**	127.2	108.1	**116.1**	125.0
Canada	**17.7**	18.6	**18.9**	19.4	17.6	**18.1**	18.7	14.9	**15.9**	17.0
Mexico	**2.0**	4.3	**4.5**	4.7	4.4	**4.6**	4.8	5.0	**5.1**	5.2
Central America and Caribbean	**0.3**	0.8	**0.8**	0.9	0.8	**0.8**	0.8	0.9	**1.0**	1.1
South America	**6.2**	10.0	**10.3**	10.6	9.8	**10.0**	10.2	8.4	**8.7**	9.0
Brazil	**2.2**	4.9	**5.0**	5.1	5.1	**5.2**	5.3	5.7	**5.8**	5.9
Sub-Saharan Africa	**0.3**	0.9	**1.0**	1.1	0.7	**0.8**	0.9	0.4	**0.5**	0.5
Middle East & North Africa	**32.7**	44.7	**46.2**	47.8	41.4	**42.9**	44.2	29.4	**31.6**	34.0
South Africa	**0.7**	0.4	**0.4**	0.4	0.4	**0.4**	0.4	0.5	**0.5**	0.5
Northern Europe	**4.9**	3.1	**3.3**	3.5	2.6	**2.9**	3.1	1.9	**2.1**	2.3
UK & Irland	**28.6**	19.9	**20.7**	21.2	18.2	**19.7**	21.2	15.5	**16.5**	18.0
Central Europe North	**61.6**	42.4	**44.1**	45.4	37.7	**41.1**	43.9	30.3	**32.7**	36.5
Central Europe South	**36.3**	31.7	**33.0**	34.1	28.4	**30.9**	33.2	23.6	**25.3**	28.2
Southern Europe	**29.3**	26.0	**26.7**	27.6	24.2	**25.6**	27.3	21.3	**23.0**	24.9
Rest of Europe	**24.2**	17.1	**17.9**	18.5	15.5	**16.4**	17.2	10.6	**11.5**	12.1
Rest of FSU	**5.1**	3.7	**3.8**	3.9	3.3	**3.5**	3.7	2.6	**2.7**	3.0
Russia	**50.4**	36.1	**38.2**	39.5	31.8	**33.9**	36.2	26.3	**27.4**	28.6
Global	554	581	604	624	547	574	602	460	487	518

Large increases of up to 200% are foreseen for regions with lower share of global residential energy, such as Asia (West and East), Indonesia, Mexico, Central America and the Caribbean, Brazil and Sub-Saharan Africa.

6.2 Economic implications

As the direct damage is integrated in the model via a welfare change, keeping the overall consumption level constant, there is a minor indirect effect on production or GDP. The global change in GDP is very small and ranges from -0.0019% at 1.5^{o}C to -0.0015% at 4^{o}C (bottom of Table 19), although the regional effects vary widely (Figure 12).

Figure 12: Change in GDP resulting from changed in residential energy demand (%)



The largest GDP reductions are observed for Sub-Saharan Africa (0.12% at 4°C), Middle East and North Africa (0.1% at 4°C), Russia (0.1% at 4°C) and Rest of FSU (0.11% at 4°C). The EU regions are estimated to experience a small positive GDP effect, similar to the USA and Australia and Oceania.

Table 19: Change in GDP resulting from changes in residential energy demand (%)

Region	1.5C			2.0C			4.0C		
	min	**mean**	max	min	**mean**	max	min	**mean**	max
China	-0.024	**-0.027**	-0.029	-0.021	**-0.023**	-0.025	-0.010	**-0.012**	-0.013
South-east Asia	-0.017	**-0.017**	-0.018	-0.019	**-0.018**	-0.017	-0.026	**-0.025**	-0.025
South-west Asia	0.009	**0.008**	0.006	0.004	**0.008**	0.011	-0.013	**-0.010**	-0.006
India	0.009	**0.005**	0.001	0.014	**0.012**	0.010	0.042	**0.039**	0.036
Indonesia	0.004	**0.004**	0.004	0.003	**0.005**	0.006	0.002	**0.005**	0.008
Japan	0.002	**0.001**	-0.001	0.003	**0.002**	0.001	0.005	**0.004**	0.002
Korea	-0.002	**-0.006**	-0.010	0.002	**-0.001**	-0.004	0.008	**0.006**	0.003
Australia and Oceania	0.012	**0.010**	0.008	0.015	**0.014**	0.013	0.022	**0.022**	0.023
USA	0.013	**0.013**	0.013	0.014	**0.014**	0.013	0.019	**0.018**	0.017
Canada	-0.008	**-0.010**	-0.011	-0.006	**-0.007**	-0.007	-0.002	**-0.002**	-0.002
Mexico	-0.034	**-0.030**	-0.026	-0.038	**-0.036**	-0.033	-0.053	**-0.050**	-0.047
Central America and Caribbean	-0.003	**-0.005**	-0.006	-0.003	**-0.003**	-0.004	-0.006	**-0.008**	-0.011
South America	-0.042	**-0.042**	-0.043	-0.044	**-0.043**	-0.041	-0.055	**-0.053**	-0.051
Brazil	-0.006	**-0.007**	-0.007	-0.007	**-0.007**	-0.007	-0.008	**-0.008**	-0.008
Sub-Saharan Africa	-0.053	**0.031**	0.114	-0.072	**-0.062**	-0.044	-0.132	**-0.122**	-0.114
Middle East & North Africa	-0.052	**-0.053**	-0.055	-0.064	**-0.057**	-0.049	-0.107	**-0.097**	-0.089
South Africa	-0.002	**-0.014**	-0.027	0.000	**-0.001**	-0.003	0.003	**0.003**	0.004
Northern Europe	0.002	**0.001**	0.000	0.002	**0.002**	0.001	0.002	**0.002**	0.002
UK & Irland	0.000	**-0.001**	-0.003	0.001	**0.000**	-0.001	0.002	**0.001**	0.000
Central Europe North	0.015	**0.013**	0.011	0.019	**0.016**	0.014	0.023	**0.021**	0.018
Central Europe South	0.011	**0.008**	0.006	0.015	**0.012**	0.009	0.022	**0.020**	0.016
Southern Europe	0.014	**0.013**	0.010	0.018	**0.015**	0.013	0.024	**0.022**	0.019
Rest of Europe	-0.040	**-0.039**	-0.038	-0.047	**-0.042**	-0.037	-0.061	**-0.058**	-0.053
Rest of FSU	-0.084	**-0.079**	-0.075	-0.099	**-0.089**	-0.079	-0.130	**-0.122**	-0.112
Russia	-0.065	**-0.059**	-0.055	-0.080	**-0.071**	-0.061	-0.112	**-0.104**	-0.095
Global	-0.002	-0.002	-0.002	-0.001	-0.002	-0.002	-0.001	-0.002	-0.002

In absolute terms the global GDP loss (Table 20) is about 1bn€ at 1.5°C, 0.8bn€ at 2°C and 0.75bn€ at 4°C.

Table 20: Change in GDP resulting from changes in residential energy demand (bn €)

Region	1.5C			2.0C			4.0C		
	min	**mean**	max	min	**mean**	max	min	**mean**	max
China	-0.75	**-0.84**	-0.90	-0.67	**-0.73**	-0.80	-0.31	**-0.36**	-0.41
South-east Asia	-0.19	**-0.19**	-0.19	-0.21	**-0.20**	-0.19	-0.29	**-0.27**	-0.27
South-west Asia	0.04	**0.04**	0.03	0.02	**0.04**	0.05	-0.06	**-0.05**	-0.03
India	0.10	**0.05**	0.01	0.15	**0.13**	0.10	0.45	**0.41**	0.38
Indonesia	0.01	**0.02**	0.02	0.01	**0.02**	0.02	0.01	**0.02**	0.03
Japan	0.08	**0.03**	-0.02	0.12	**0.08**	0.03	0.20	**0.14**	0.08
Korea	-0.02	**-0.05**	-0.09	0.02	**-0.01**	-0.04	0.07	**0.05**	0.03
Australia and Oceania	0.11	**0.09**	0.07	0.13	**0.13**	0.12	0.20	**0.20**	0.21
USA	1.67	**1.65**	1.63	1.79	**1.76**	1.66	2.39	**2.28**	2.19
Canada	-0.10	**-0.12**	-0.14	-0.08	**-0.09**	-0.08	-0.03	**-0.03**	-0.02
Mexico	-0.31	**-0.27**	-0.24	-0.35	**-0.33**	-0.30	-0.48	**-0.46**	-0.43
Central America and Caribbean	-0.01	**-0.02**	-0.02	-0.01	**-0.01**	-0.01	-0.02	**-0.03**	-0.04
South America	-0.39	**-0.40**	-0.40	-0.41	**-0.41**	-0.38	-0.52	**-0.49**	-0.47
Brazil	-0.08	**-0.08**	-0.08	-0.08	**-0.08**	-0.08	-0.10	**-0.10**	-0.10
Sub-Saharan Africa	-0.27	**0.16**	0.58	-0.37	**-0.31**	-0.22	-0.67	**-0.62**	-0.58
Middle East & North Africa	-1.03	**-1.04**	-1.07	-1.26	**-1.12**	-0.97	-2.10	**-1.91**	-1.74
South Africa	0.00	**-0.04**	-0.07	0.00	**0.00**	-0.01	0.01	**0.01**	0.01
Northern Europe	0.02	**0.01**	0.00	0.02	**0.02**	0.01	0.02	**0.02**	0.02
UK & Irland	0.00	**-0.04**	-0.08	0.03	**0.00**	-0.03	0.06	**0.04**	0.00
Central Europe North	0.69	**0.58**	0.49	0.85	**0.73**	0.63	1.06	**0.98**	0.84
Central Europe South	0.36	**0.27**	0.19	0.50	**0.40**	0.30	0.71	**0.64**	0.53
Southern Europe	0.54	**0.47**	0.39	0.66	**0.58**	0.49	0.89	**0.81**	0.72
Rest of Europe	-0.35	**-0.34**	-0.34	-0.42	**-0.37**	-0.32	-0.54	**-0.51**	-0.46
Rest of FSU	-0.28	**-0.26**	-0.24	-0.32	**-0.29**	-0.26	-0.43	**-0.40**	-0.37
Russia	-0.70	**-0.64**	-0.59	-0.86	**-0.76**	-0.66	-1.20	**-1.12**	-1.02
Global	-0.84	-0.96	-1.07	-0.73	-0.84	-0.93	-0.67	-0.75	-0.89

Because changes in residential energy demand directly affect households' subsistence levels, the impact of the changes on welfare (Figure 13) is much more pronounced when compared with GDP effects (Figure 12). The largest welfare reductions at 1.5°C are in China (0.6%) and Sub-Saharan Africa (1.5%). Other regions' show either mild reductions of about 0.1% or similar increase (mainly the EU regions and the USA) in their welfare (Figure 13and Table 21).

Figure 13: Welfare change from residential energy demand change (%)

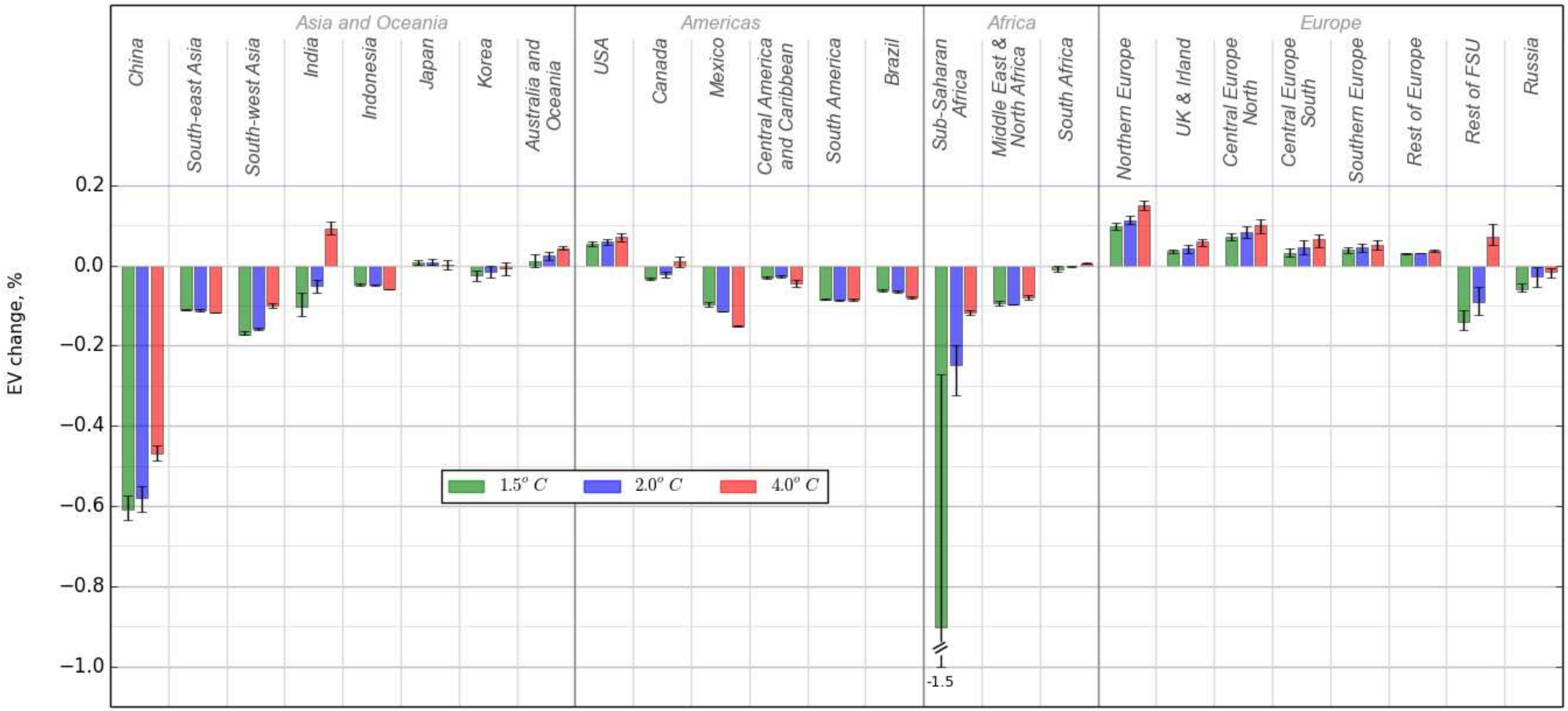


Table 21: Welfare change from residential energy demand change (%)

China	-0.57	**-0.61**	-0.64	-0.55	**-0.58**	-0.62	-0.45	**-0.47**	-0.49
South-east Asia	-0.11	**-0.11**	-0.11	-0.11	**-0.11**	-0.11	-0.12	**-0.12**	-0.12
South-west Asia	-0.17	**-0.17**	-0.17	-0.15	**-0.16**	-0.16	-0.09	**-0.10**	-0.11
India	-0.07	**-0.10**	-0.13	-0.04	**-0.05**	-0.07	0.11	**0.09**	0.08
Indonesia	-0.05	**-0.05**	-0.05	-0.05	**-0.05**	-0.05	-0.06	**-0.06**	-0.06
Japan	0.01	**0.01**	0.00	0.02	**0.01**	0.00	0.01	**0.00**	-0.01
Korea	-0.01	**-0.03**	-0.04	0.00	**-0.02**	-0.03	0.01	**-0.01**	-0.03
Australia and Oceania	0.03	**0.01**	0.00	0.03	**0.02**	0.01	0.05	**0.04**	0.04
USA	0.06	**0.05**	0.05	0.07	**0.06**	0.05	0.08	**0.07**	0.06
Canada	-0.03	**-0.03**	-0.04	-0.01	**-0.02**	-0.03	0.02	**0.01**	0.00
Mexico	-0.10	**-0.10**	-0.09	-0.11	**-0.11**	-0.11	-0.15	**-0.15**	-0.15
Central America and Caribbean	-0.03	**-0.03**	-0.03	-0.03	**-0.03**	-0.03	-0.04	**-0.05**	-0.05
South America	-0.08	**-0.08**	-0.09	-0.08	**-0.09**	-0.09	-0.08	**-0.09**	-0.09
Brazil	-0.06	**-0.06**	-0.07	-0.06	**-0.07**	-0.07	-0.08	**-0.08**	-0.08
Sub-Saharan Africa	-0.27	**-0.90**	-1.54	-0.20	**-0.25**	-0.32	-0.11	**-0.12**	-0.12
Middle East & North Africa	-0.10	**-0.09**	-0.09	-0.10	**-0.10**	-0.10	-0.07	**-0.08**	-0.08
South Africa	0.00	**-0.01**	-0.02	0.00	**0.00**	-0.01	0.01	**0.01**	0.00
Northern Europe	0.11	**0.10**	0.09	0.13	**0.11**	0.10	0.16	**0.15**	0.14
UK & Irland	0.04	**0.04**	0.03	0.05	**0.04**	0.03	0.06	**0.06**	0.05
Central Europe North	0.08	**0.07**	0.06	0.10	**0.08**	0.07	0.11	**0.10**	0.08
Central Europe South	0.04	**0.03**	0.02	0.06	**0.04**	0.03	0.08	**0.07**	0.04
Southern Europe	0.05	**0.04**	0.03	0.05	**0.05**	0.03	0.06	**0.05**	0.04
Rest of Europe	0.03	**0.03**	0.03	0.03	**0.03**	0.03	0.04	**0.04**	0.03
Rest of FSU	-0.11	**-0.14**	-0.16	-0.05	**-0.09**	-0.12	0.10	**0.07**	0.05
Russia	-0.05	**-0.06**	-0.06	0.00	**-0.03**	-0.05	-0.01	**-0.02**	-0.03
Global	-0.01	-0.02	-0.04	0.00	-0.01	-0.02	0.02	0.01	0.00

In absolute terms the global welfare losses stand at 6bn€ for 1.5°C warming, 1.7bn€ for 2°C, and 3.7bn€ for 4°C warming level (Table 22).

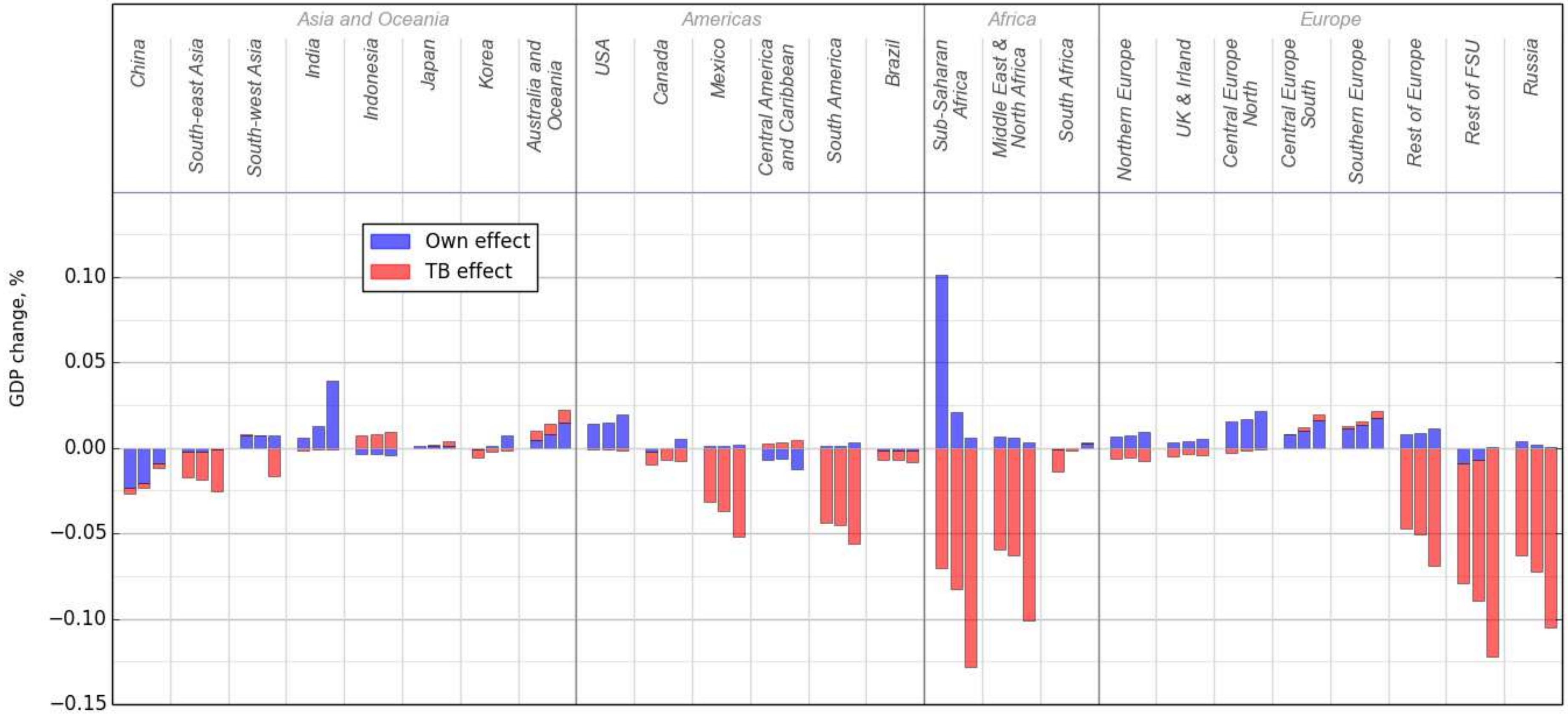
Table 22: Welfare change from residential energy demand change (%)

Region	1.5C			2.0C			4.0C		
	min	**mean**	max	min	**mean**	max	min	**mean**	max
China	-6.6	**-7.0**	-7.4	-6.4	**-6.7**	-7.1	-5.2	**-5.4**	-5.6
South-east Asia	-0.6	**-0.6**	-0.6	-0.6	**-0.6**	-0.6	-0.6	**-0.6**	-0.6
South-west Asia	-0.5	**-0.5**	-0.5	-0.4	**-0.4**	-0.5	-0.3	**-0.3**	-0.3
India	-0.4	**-0.6**	-0.7	-0.2	**-0.3**	-0.4	0.6	**0.5**	0.5
Indonesia	-0.1	**-0.1**	-0.1	-0.1	**-0.1**	-0.1	-0.1	**-0.1**	-0.1
Japan	0.3	**0.1**	0.0	0.3	**0.2**	0.0	0.3	**0.0**	-0.2
Korea	-0.1	**-0.1**	-0.2	0.0	**-0.1**	-0.1	0.0	**0.0**	-0.1
Australia and Oceania	0.1	**0.1**	0.0	0.2	**0.1**	0.1	0.2	**0.2**	0.2
USA	4.9	**4.4**	3.8	5.3	**4.9**	4.1	6.5	**5.7**	4.7
Canada	-0.2	**-0.2**	-0.2	-0.1	**-0.1**	-0.2	0.2	**0.1**	0.0
Mexico	-0.6	**-0.5**	-0.5	-0.6	**-0.6**	-0.6	-0.8	**-0.8**	-0.8
Central America and Caribbean	-0.1	**-0.1**	-0.1	-0.1	**-0.1**	-0.1	-0.1	**-0.1**	-0.1
South America	-0.4	**-0.4**	-0.4	-0.4	**-0.4**	-0.4	-0.4	**-0.4**	-0.4
Brazil	-0.4	**-0.4**	-0.4	-0.4	**-0.4**	-0.4	-0.5	**-0.5**	-0.5
Sub-Saharan Africa	-0.9	**-2.8**	-4.9	-0.6	**-0.8**	-1.0	-0.4	**-0.4**	-0.4
Middle East & North Africa	-1.0	**-0.9**	-0.9	-0.9	**-1.0**	-0.9	-0.7	**-0.8**	-0.8
South Africa	0.0	**0.0**	0.0	0.0	**0.0**	0.0	0.0	**0.0**	0.0
Northern Europe	0.5	**0.4**	0.4	0.6	**0.5**	0.5	0.7	**0.7**	0.6
UK & Irland	0.7	**0.6**	0.5	0.9	**0.7**	0.5	1.1	**1.0**	0.8
Central Europe North	2.0	**1.8**	1.6	2.4	**2.0**	1.7	2.8	**2.5**	2.0
Central Europe South	0.8	**0.6**	0.4	1.1	**0.8**	0.5	1.4	**1.2**	0.8
Southern Europe	1.0	**0.8**	0.7	1.2	**1.0**	0.7	1.4	**1.1**	0.8
Rest of Europe	0.1	**0.1**	0.1	0.1	**0.1**	0.1	0.2	**0.2**	0.1
Rest of FSU	-0.2	**-0.3**	-0.3	-0.1	**-0.2**	-0.2	0.2	**0.1**	0.1
Russia	-0.2	**-0.3**	-0.3	0.0	**-0.2**	-0.3	0.0	**-0.1**	-0.2
Global	-1.9	-6.0	-10.0	1.0	-1.7	-4.7	6.4	3.7	0.3

A regional economy is affected not only by domestic change in energy demand (domestic effect), but it is also impacted upon by other economies via international trade linkages and the prices they carry (transboundary effect, TB effect). For example, even though Russia's domestic residential energy demand reduces over time, its GDP deteriorates because of the drop in international demand for its energy, mainly from Europe.

Figure 15 shows the regional GDP percentage change decomposed into the domestic effect (blue bars) and the transboundary effect (red bars) resulting from changes in rest of the world economies. For some regions, like Russia and the Rest of the FSU, the transboundary effect is much larger than the direct effect. As those economies are large net exporters of fossil fuels, the overall global reduction in energy demand affects them relatively more, reducing their energy exports, which makes their production levels fall relatively more, when compared to other regions.

Figure 14: Transboundary GDP effect for 2ºC warming level

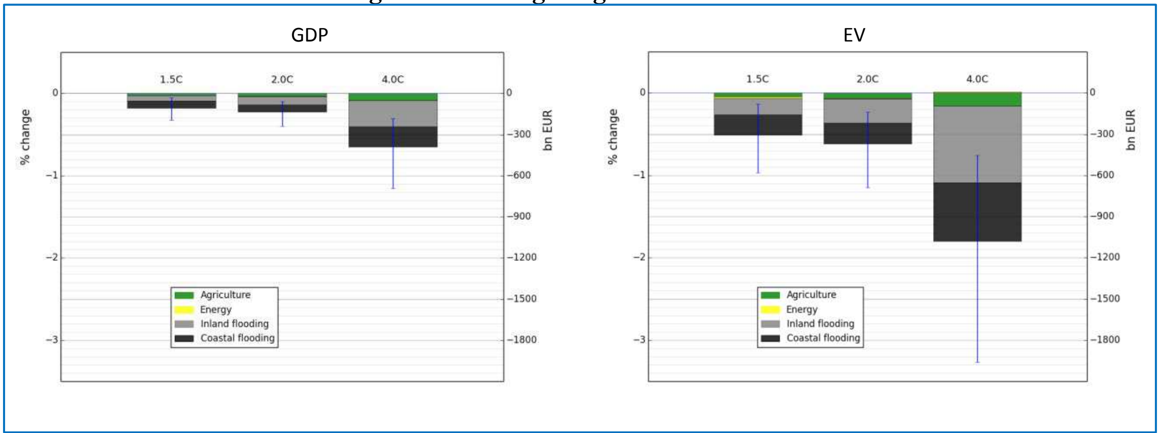


7 OVERVIEW OF THE ECONOMIC ASSESSMENT OF CLIMATE IMPACTS

This section presents an overview of the economic implications of the considered impacts (Inland flooding, coastal damage, energy demand, and agricultural crops).

Figure 15 and Table 23 show changes in global GDP and welfare (EV) for the three warming levels considered. The global GDP reduction is relatively similar for the 1.5°C and 2°C warming (0.18% and 0.22% loss), but significantly larger at 4.0°C warming: 0.65% loss. In money-metric the losses account to 114, 137 and 396 bn€, respectively.

Figure 15: Change in global GDP and welfare



The welfare losses are larger by factor of 2 to 3. The reason of larger welfare losses results from the fact that some damages (eg damage to residential buildings or changes in energy demand) affect level of households' obliged consumption, hence welfare, while GDP levels are only indirectly affected.

The overall welfare loss is estimated at 0.5%, o.6% and 1.8% reductions for the three warming levels or, in absolute terms, at 160, 170 and 491 bn€.

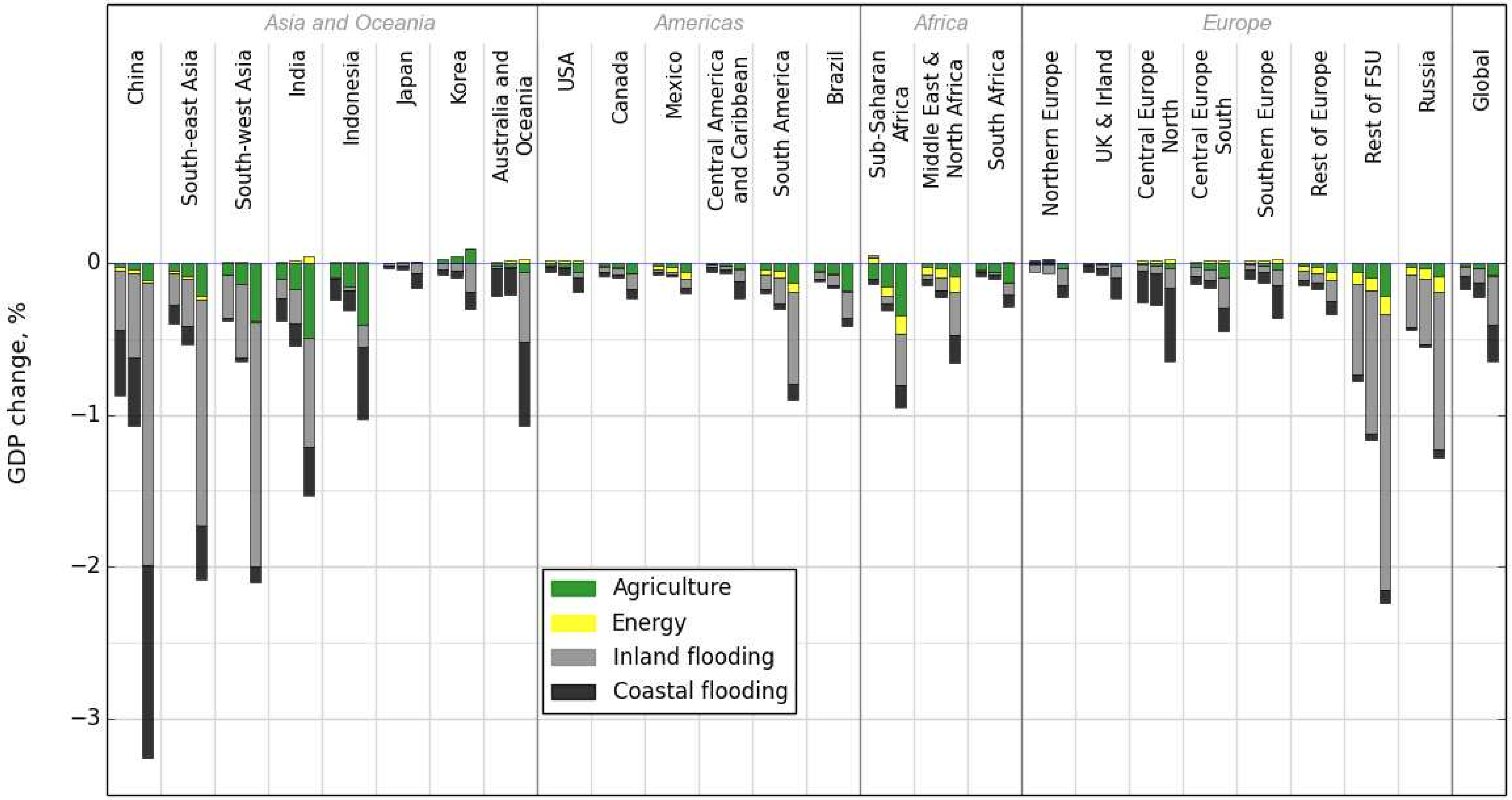
Table 23 represents the changes (both relative and in absolute terms) of GDP and welfare by impact category for all warming levels. Up to 90% of the economic losses account to inland flooding and coastal damage, agricultural damage makes up about 10% of the total damage, while the impact of changes in energy demand is barely noticeable at the aggregate, global level which, however, only masks the regional heterogeneity of results as can be seen from regional results.

Table 23: Change in global GDP and welfare by impact category.

		%			bn€		
		SWL1.5	SWL2.0	SWL4.0	SWL1.5	SWL2.0	SWL4.0
GDP	Crops	-0.022	-0.034	-0.083	-11.1	-16.8	-40.9
	Energy	-0.002	-0.002	-0.002	-1.0	-0.8	-0.8
	Flood	-0.068	-0.099	-0.321	-33.5	-49.1	-158.7
	SLR	-0.085	-0.088	-0.243	-68.3	-70.6	-195.1
	total	***-0.177***	***-0.223***	***-0.648***	***-113.9***	***-137.3***	***-395.5***
EV	Crops	-0.043	-0.065	-0.157	-11.8	-17.7	-43.1
	Energy	-0.022	-0.006	0.013	-6.0	-1.7	3.7
	Flood	-0.199	-0.290	-0.934	-54.6	-79.7	-256.7
	SLR	-0.248	-0.257	-0.710	-68.3	-70.6	-195.1
	total	***-0.512***	***-0.618***	***-1.787***	***-140.6***	***-169.8***	***-491.2***

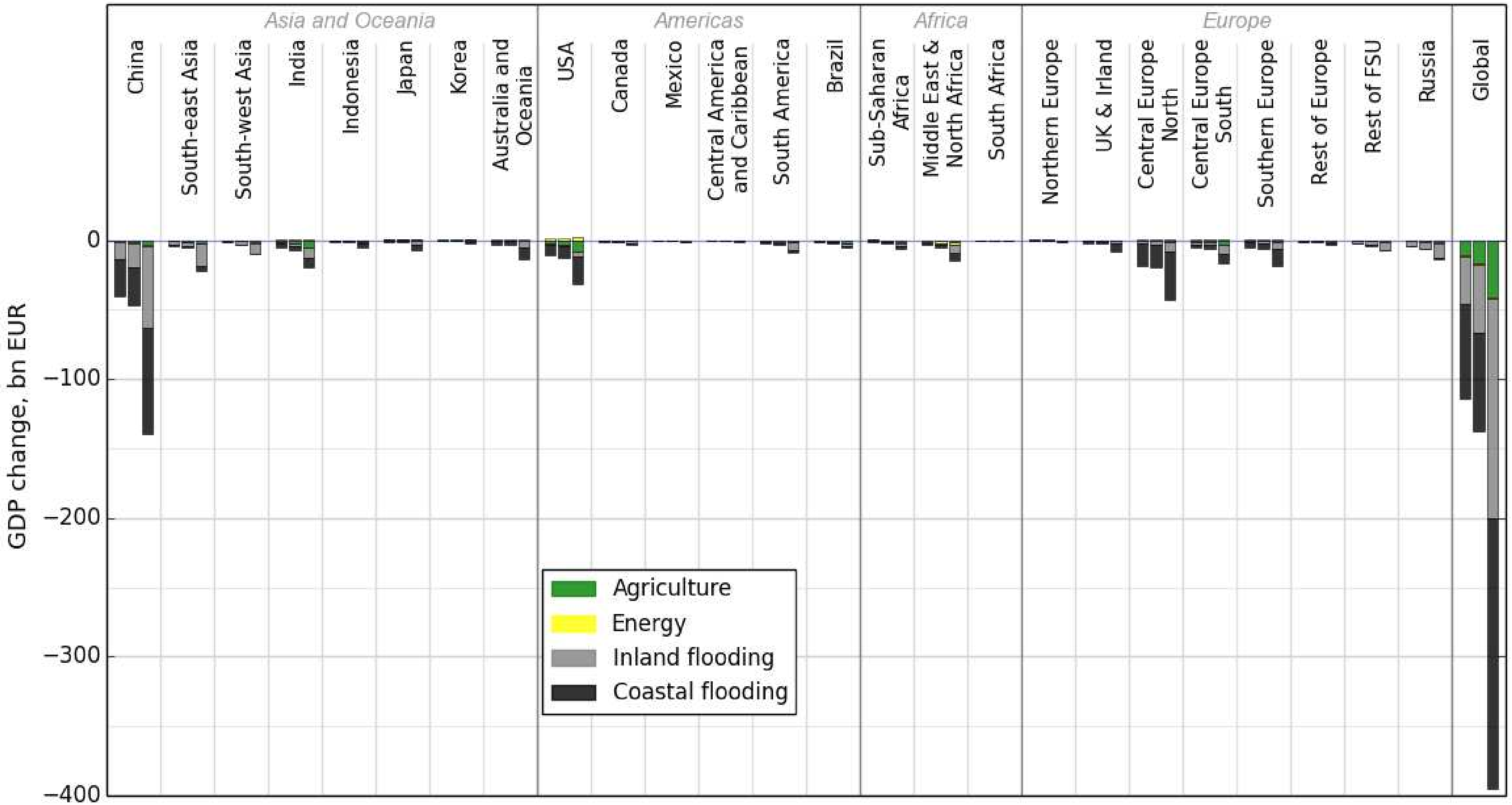
The series of next four graphs (Figure 16 to Figure 19) show regional results for GDP and welfare changes. In relative terms (Figure **19**), the largest GDP reductions are estimated for Asian and Oceanian regions (up to over 3% reduction in China at SWL4.0), South America (about 1% at SWL4.0) and Russia and FSU regions (more than 2% at 4.0°C). Some regions (mainly Europe and the USA) benefit from reduction in net demand for energy (increase in demand for cooling is smaller than reduction in demand from heating) which, at the global level, compensates the increase for residential energy demand in other regions resulting in minor net global effect.

Figure 16: Regional changes in GDP (%)



In absolute terms (Figure 17, bn€) the largest GDP losses occur in China (50bn€ to 150bn€), about a third of the global effect. Large economic implications are also noticed in the USA (about 30bn€) and Central Europe North (45bn€).

Figure 17: Regional GDP changes (bn€)



Welfare changes are presented on Figure 18 (in percentage terms) and Figure 19 (in bn€). When compared to the GDP losses welfare impacts are larger. Also, contributions of different impacts to the total are different. For example, changes in residential energy demand lead to change in households' disposable income (and welfare) rather than to changes in overall regional production activity (GDP). Also, river floods are more likely to affect residential households and alter households' budgets (increase in budget's share spent on damage repair leading to welfare reduction) rather than changes in GDP.

Figure 18: Welfare change (%)

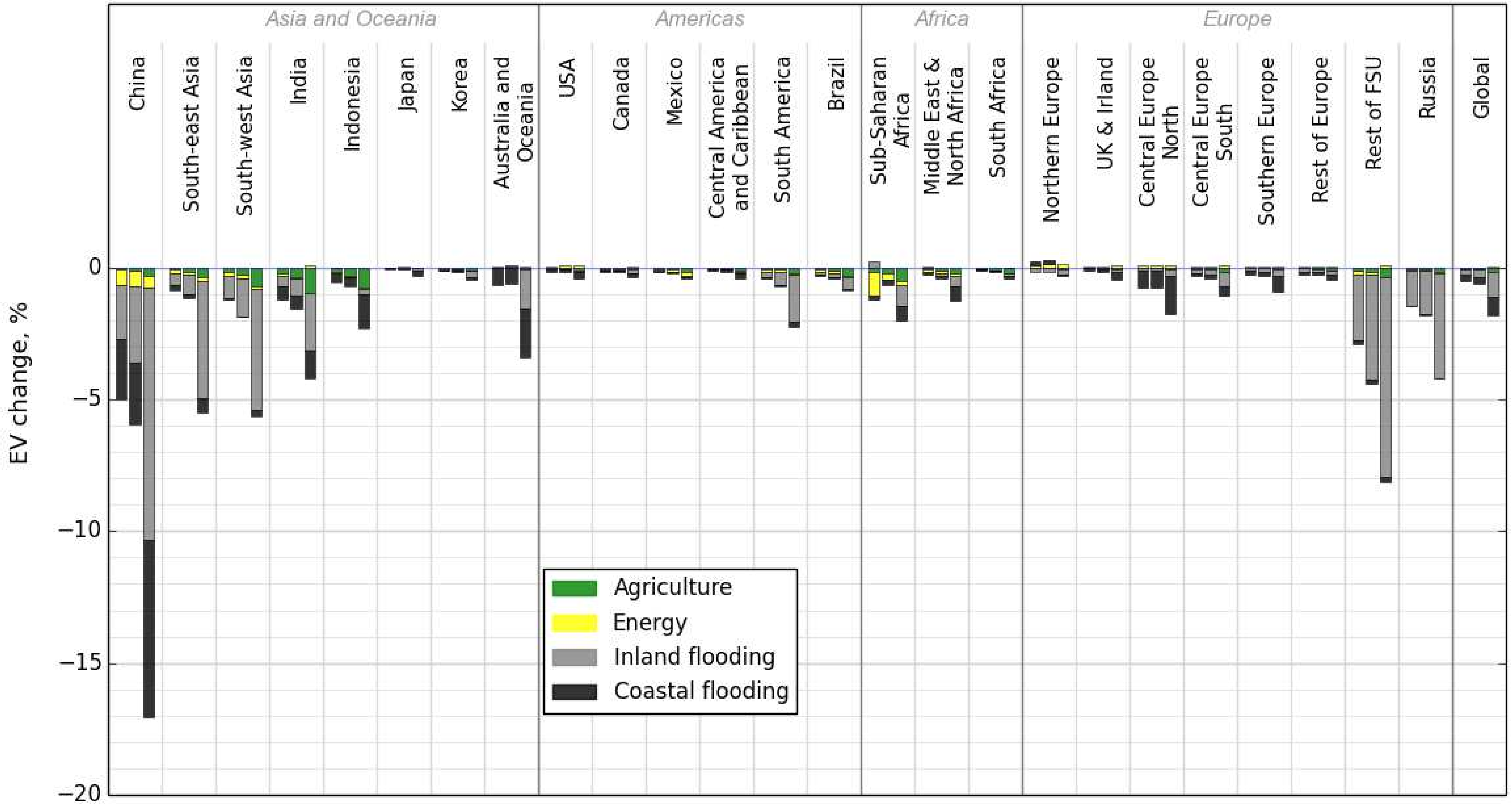
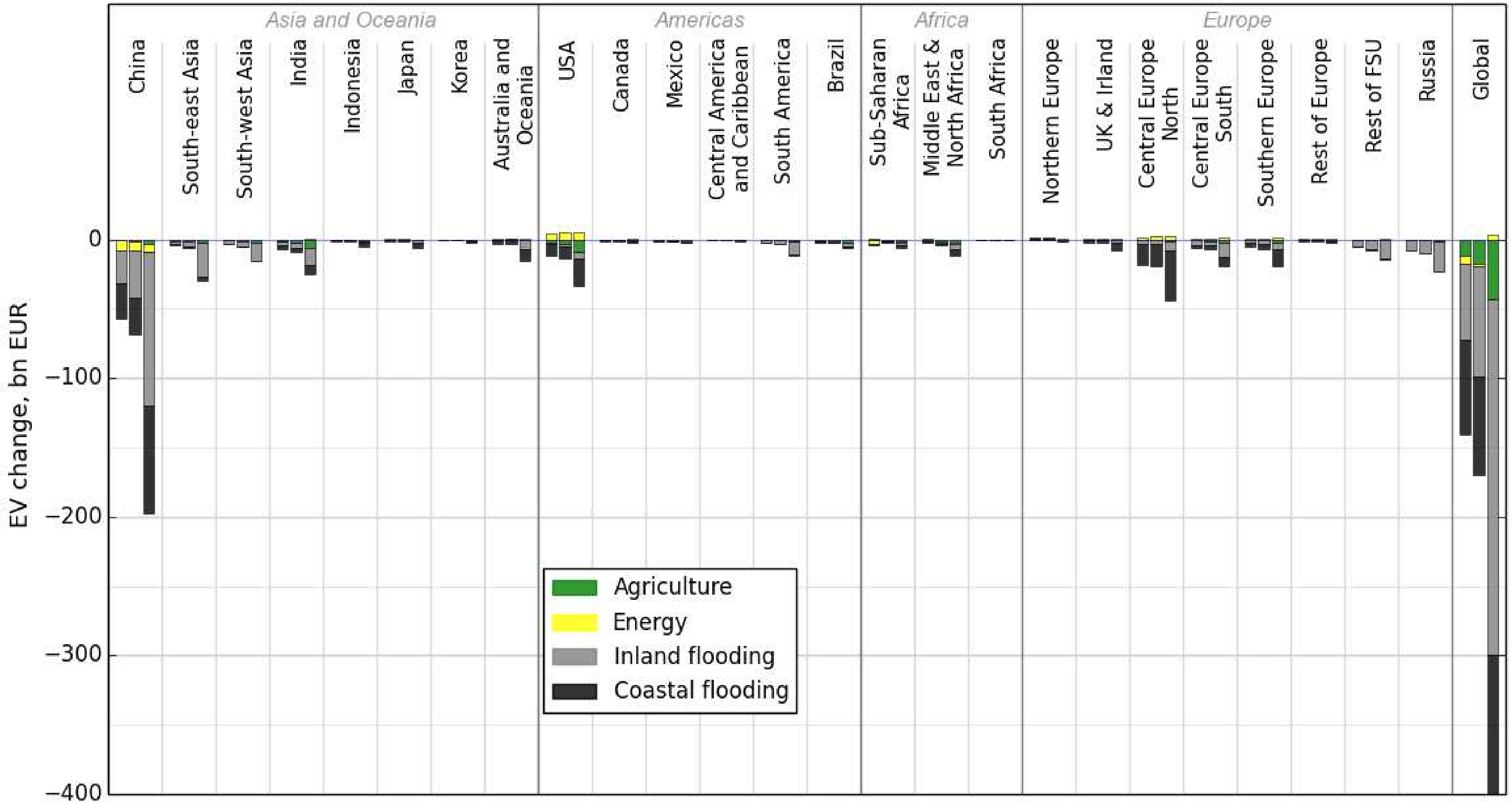


Figure 19: Welfare change (bn €)



8 CONCLUSIONS

Most of the global economic damage (up to 90%) is due to inland flooding and coastal damages. Agricultural damage makes up about 10% of the total damage, while the impact of changes in energy demand is barely noticeable at the aggregate, global level which, however, only masks the regional heterogeneity of results as can be seen from regional results.

From the geographical perspective, the largest climate impacts are simulated to happen in the Asia continent, while Russia and the Rest of the FSU are potentially largely affected by climate change.

Regarding the sensitivity of economic impacts to warming levels, there appears to be a non-linear relationship as impacts rise more than proportionally to higher warming levels.

There is a series of limitations that should be considered when interpreting the results. Firstly, this is not an assessment of the benefits of climate mitigation policy because fundamental impact areas, like the effects on human health or ecosystems are not accounted for in the suggested methodological framework. Furthermore, possible catastrophic climate impacts are not taken into account either in the analysis.

There is also a need to conduct a more systematic uncertainty analysis considering the influence of the many sources of uncertainty in this climate multi-impact integrated assessment.

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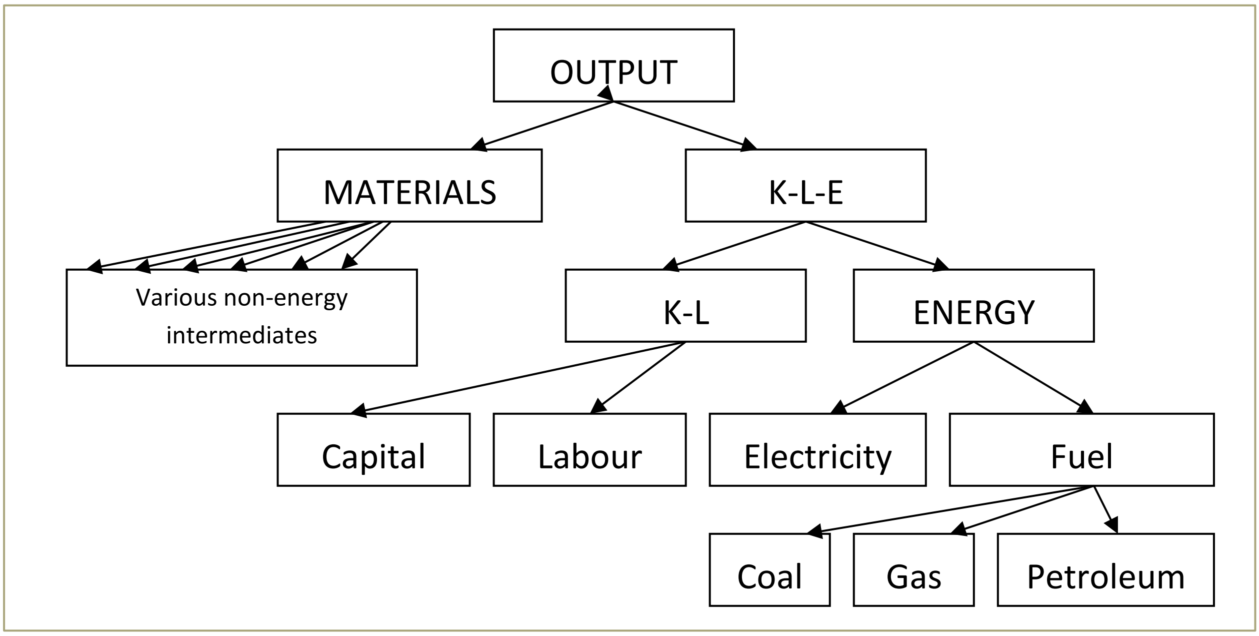
APPENDIX: DESCRIPTION OF THE CAGE-GEME3 MODEL

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 20: 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 24: List of region-codes and geographical aggregation.

Region	***List of countries***
China	China
Japan	Japan
Korea	Korea
Indonesia	Indonesia
Russia	Russia
India	India
USA	USA
Canada	Canada
Mexico	Mexico
Brazil	Brazil
South Africa	South Africa
UK & Ireland	UK, Ireland
Northern Europe	Denmark, Estonia, Finland, Lithuania, Latvia, Sweden
Central Europe (North)	Poland, Netherlands, Luxembourg, Germany, Belgium
Central Europe (South)	Austria, Czech Republic, France, Hungary, Romania, Slovakia, Slovenia, Croatia
Southern Europe	Bulgaria, Cyprus, Spain, Greece, Italy, Malta, Portugal
Australasia	Australia, New Zealand, rest of Oceania
South-west Asia	Bangladesh, Iran, Sri Lanka, Nepal, Pakistan, rest of South Asia
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
Rest of Europe	Albania, Switzerland, Norway, Rest of Eastern Europe, Rest of EFTA, Rest of Europe
South-east Asia	Cambodia, Laos, Mongolia, Malaysia, Philippines, Singapore, Thailand, Taiwan, Vietnam, Rest of East Asia, Rest of Southeast Asia, Rest of the World

Rest of Former Soviet Union	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Ukraine, and other countries from the rest of Former Soviet Union
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
Central. America & Caribbean	Costa Rica, Guatemala, Honduras, Nicaragua, Panamá, El Salvador, Rest of Central America, Caribbean, Rest of North America
Rest of South America	Argentina, Bolivia, Chile, Colombia, Ecuador, Peru, Paraguay, Uruguay, Venezuela, Rest of South America

Table 25: List of sector codes and sectoral aggregation

Agriculture	Bovine cattle, sheep and goats, horses, animal products nec, raw milk, wool, silk-worm cocoons, fishing
Crops	Paddy rice, wheat, cereal, grains nec, vegetables, fruit, nutsv oil seeds, sugar cane, sugar beet, plant-based fibers, crops nec
Forestry	Forestry
Coal Mining	Coal
Crude Oil Extraction	Oil
Natural Gas	Gas, gas manufacture, distribution
Refined Oil	Petroleum, coal products
Electricity	Electricity
Metals	Ferrous metals, metals nec, metal products
Chemicals	Chemical, rubber, plastic products
Energy Intensives	Minerals nec, paper products, publishing, mineral products nec
Electronic equipment	Electronic equipment
Transport Equipment	Motor vehicles and parts, transport equipment nec
Other Equipment	Machinery and equipment nec, manufactures nec
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
Construction	Construction
Transport	Transport nec, water transport, air transport
Market Services	Water, trade, communication, financial services nec, insurance, business services nec, dwellings
Non-market Services	Recreational and other services, public administration, Defense, Education, Health

LIST OF FIGURES

Global assessment of socio-economic impacts from FUND model

October

2017

Disclaimer

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THE TOTAL ECONOMIC IMPACT OF CLIMATE CHANGE: AN APPLICATION OF FUND

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Abstract

I use the latest version of *FUND*, an integrated assessment model, to estimate the total economic impact of climate change. The new version has updated modules for malaria and valuing health risks, and uses recently developed scenarios. The results are in line with previous findings: The impacts of climate change are modest, larger in hotter scenarios and smaller in richer ones. Impacts are concentrated in poorer countries, and dominated by impacts on agriculture and energy. Impacts may be positive, but incremental impacts are negative, justifying greenhouse gas emission reduction.

Key words economic impact; climate change

JEL Classification Q54

1. Introduction

After 30 odd years of climate policy, greenhouse gas emissions are at or near their all-time high (WMO 2017). Politicians have shown themselves to be better at announcing stringent climate policy than at following through (Tol 2017b). It therefore remains imperative to study the impacts of climate change. This paper contributes to that, focusing on human welfare.

I used the latest version of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*), an integrated assessment model that has been used routinely to estimate the impacts of climate change, most notably by the Obama and Trump administrations in their attempts to set a social cost of carbon to guide regulatory cost-benefit analyses for the US federal government (IAWGSCC 2015, 2013, 2010, EPA 2017).

Estimating the economic impact of climate change is heroic, although some have used less complimentary words (Pindyck 2017b, a, 2013, Heal 2017). Emission scenarios show a wide range but may not span all not implausible futures. The carbon cycle is imperfectly understood. Climate models disagree with one another on important details. Impact models disagree more, and impacts are often contingent on trends other than climate change. Economic impact estimates further require that impacts are valued, and that values are aggregated over people living in very different circumstances. None of this is easy, and all of this is necessary for an estimate of the economic impact of climate change.

The paper proceeds as follows. Section 2 presents the model. Section 3 shows the results. Section 4 concludes.

2. FUND

This paper uses version 4.0 of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*). FUND is an integrated assessment model of climate change (Tol 1997, 1998, 1999, 2008, Guo et al. 2006, Anthoff, Hepburn, and Tol 2009, Anthoff, Tol, and Yohe 2009, Waldhoff et al. 2014). The source code, data, and a technical description of the model can be found at http://www.fund-model.org.

The model is specified for sixteen regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. The model runs from 1950 to 3000 in time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module (Tol 2002b, a). The centuries after the 21st are included to assess the long-term implications of climate change, but not discussed here.

Scenarios are defined by the rates of population growth, economic growth, autonomous energy efficiency improvements as well as the rate of decarbonization of the energy use, and emissions of carbon dioxide from land use change, methane and nitrous oxide. The scenarios of economic and population growth are perturbed by the impact of climatic change. Market impacts are a deadweight loss to the economy. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and storms. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the reproductive population. Heat stress only affects the urban population. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane, nitrous oxide and sulphur hexafluoride, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by a five-box model (Maier-Reimer and Hasselmann 1987). The model also contains sulphur emissions (Tol 2006). Radiative forcing is as in the IPCC. The global mean temperature T is governed by a geometric build-up to its equilibrium. In the base case, the global mean temperature rises in equilibrium by 3.0°C for a doubling of ambient carbon dioxide. The dynamics of the global mean sea level are also geometric. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario (Kattenberg et al. 1996).

The climate impact module includes agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, energy consumption, water resources, unmanaged ecosystems, diarrhoea, and tropical and extra tropical storms. Climate change related damages can be attributed to either the rate of change (where damages are calibrated at 0.04 °C/yr) or the level of change (with damage functions calibrated at 1.0 °C). Damages from the rate of temperature change slowly fade, reflecting adaptation. FUND is unique in its class of integrated assessment models by explicitly modelling changes in vulnerability due to e.g. changes in socio economic circumstances. FUND's damage functions are calibrated to match studies that assume optimal adaptation and report residual damages and adaptation costs.

People can die prematurely due to climate change, or they can migrate because of sea level rise. Like all impacts of climate change in FUND, these effects are monetized. Other impact categories, such as agriculture, forestry, energy, water, storm damage, and ecosystems, are directly expressed in monetary values without first estimating impacts in 'natural' units. Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative.

The impacts of climate change on coastal zones, forestry, tropical and extratropical storm damage, unmanaged ecosystems, water resources, diarrhoea, malaria, dengue fever, and schistosomiasis are modelled as power functions. Impacts are either negative or positive with greater climate change, and they do not change sign. The level of coastal protection is based on an internal cost-benefit analysis that includes the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Vulnerability to a given climate change is a function of population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable with increases in these factors, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) are projected to become less vulnerable at least over the long term.

There are regular complaints that the models used to estimate the social cost of carbon are updated only infrequently (Ackerman and Munitz 2016, Ackerman et al. 2009, Ackerman and Munitz 2012, Burke et al. 2016, Pindyck 2013, Cropper et al. 2017). The latest version of FUND has five changes: The baseline and scenarios are updated, the sensitivity of malaria is changed, and the value of a statistical life and its income elasticity are altered. These changes are detailed in Tol (2017a); they have little effect on the outcomes, apart from the scenarios.

3. The impact of climate change

3.1. Scenarios

Figure 1 shows world population as observed (until 2014; data source: World Bank) and as projected according to the FUND scenario and the five Shared Socioeconomic Pathways (SSP; data source: IIASA; the FUND implementation of the SSPs has the average across the models in the IIASA database). The scenarios span a wide range, from 7 billion people in 2100 in SSP1 to 11 billion people in SSP3.

Figure 2 shows average per capita income as observed and projected. The range is wide, but all scenarios are optimistic. People are poorest in SSP3, but incomes still grow from $7,000 per person per year today – living standards as in Gabon or Montenegro today – to $13,000 in 2100 – living standards as in Argentina today. In SSP5, average income goes up to $70,000 per person per year – living standards as in Norway today.

Figure 3 shows world total carbon dioxide emissions from fossil fuel combustion and cement production as observed and as projected. Emissions are highest in FUND, reaching 25 GtC by 2100. Note that SSP5 has higher emissions for most of the century. SSP1 sees the lowest emissions, falling to 5 GtC by the end of the century.

Figure 4 shows the atmospheric concentration of carbon dioxide as projected. The scenarios are ordered as for the emissions, but the range is relatively narrower due to the conservative nature of the carbon cycle. Concentrations in 2100 range from 585 ppm to 800 ppm.

Figure 5 shows the global mean temperature as projected. The order of the scenarios is unchanged, but the range narrows further. The world is 2.8°C to 3.7°C warmer than preindustrial by 2100.

Figure 6 shows global mean sea level rise as projected. As the momentum is so great, the difference between the highest and lowest scenario is only 10 centimetres.

Figure 7 shows the impact of climate change on human welfare as the equivalent income loss. SSP1 is the most optimistic scenario, with positive impacts throughout but falling to 0.1% of GDP by 2100. FUND is the most pessimistic scenario, with impacts reaching -0.7% of GDP by 2100 while continuing to worsen.

The positive impacts are due to two things: agriculture and energy. Carbon dioxide fertilization is positive throughout, and much of the world's most valuable agriculture takes place below its temperature optimum. Warming increases the demand for cooling in summer, but decreases the demand for heating in winter; the latter effect is larger at first.

The positive impacts notwithstanding, Figure 7 shows that the incremental impacts are negative already (in four of the six scenarios) are will be in the near future (in the other two scenarios). This implies that the

The impact graphs show two spikes, in 2000 (in all scenarios) and in 2010 (in the SSPs). This is due to sharp drop in economic growth which, in the model leads to a stop in additional coastal protection and hence an increase in land loss. Such spikes do not occur in the scenarios because projected economic growth is smooth by construction.

Table 1 shows the 2100 values for temperature, per capita income and relative impact. The correlation between temperature and impact is 0.86; the correlation between income and impact is 0.20. Clearly, climate change is a more important determinant of the relative impact of climate change than is economic growth. Economic growth has two effects: It increases emissions and reduces vulnerability to climate change.

3.2. Regions

Figure 8 shows the same information as Figure 7, but now per region, and only for the FUND scenario. The spike around 2000 is still there; this was the economic crisis in Southeast Asia. Net positive impacts are particularly large in China, although rapidly falling towards the end of the century. The former Soviet Union, North Africa, and Subsaharan Africa see the largest net negative impacts.

Figure 9 shows the absolute impacts by region. The largest impacts will be felt in China (positive) and Western Europe (negative).

3.3. Sectors

Figure 10 repeats the information of Figure 9, but absolute impacts are now shown by sector. Agriculture and energy make up most of the impacts. The impact of climate change on agriculture is positive throughout, but beyond its optimum by 2100. The impact on energy starts positive, but turns after 2040 when the extra cooling demand exceeds the reduced heating demand in value.

4. Discussion and conclusion

I present new estimates of the total economic impact of climate change using the latest version of FUND and the latest emission scenarios. In line with previous estimates using this model (Estrada, Tol, and Botzen 2017, Anthoff and Tol 2014, Tol 2013) and the broader literature (Tol 2015b, Howard and Sterner 2017, Nordhaus and Moffat 2017, Tol 2016, 2015a, Arent et al. 2014), the impact of climate change is found to be modest in size. More pronounced climate change is worse, but richer societies suffer less. The impact of climate change is concentrated in poorer countries; and dominated by the impacts on agriculture and energy demand. Climate change may be beneficial to human welfare, but additional climate change is detrimental.

These results come with the usual caveats. Impact assessment are imperfect and incomplete. A focus on the best guess impact comes at the expense of a neglect of tail-risks that are real and important. Valuation is hard, and aggregation of impacts across people is controversial. Some of these issues can be solved with additional research (perhaps financed from a reduction in the budget on assessment), but the controversies around aggregation are intrinsic to the problem while uncertainty is inherent in future projections.

The caveats notwithstanding, this paper highlights that the popular image of climate change as a catastrophe is not supported by the academic evidence. That said, climate change is a problem and reducing greenhouse gas emissions raises welfare.

Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement no 603864. David Anthoff has been of great help in the preparing the paper.

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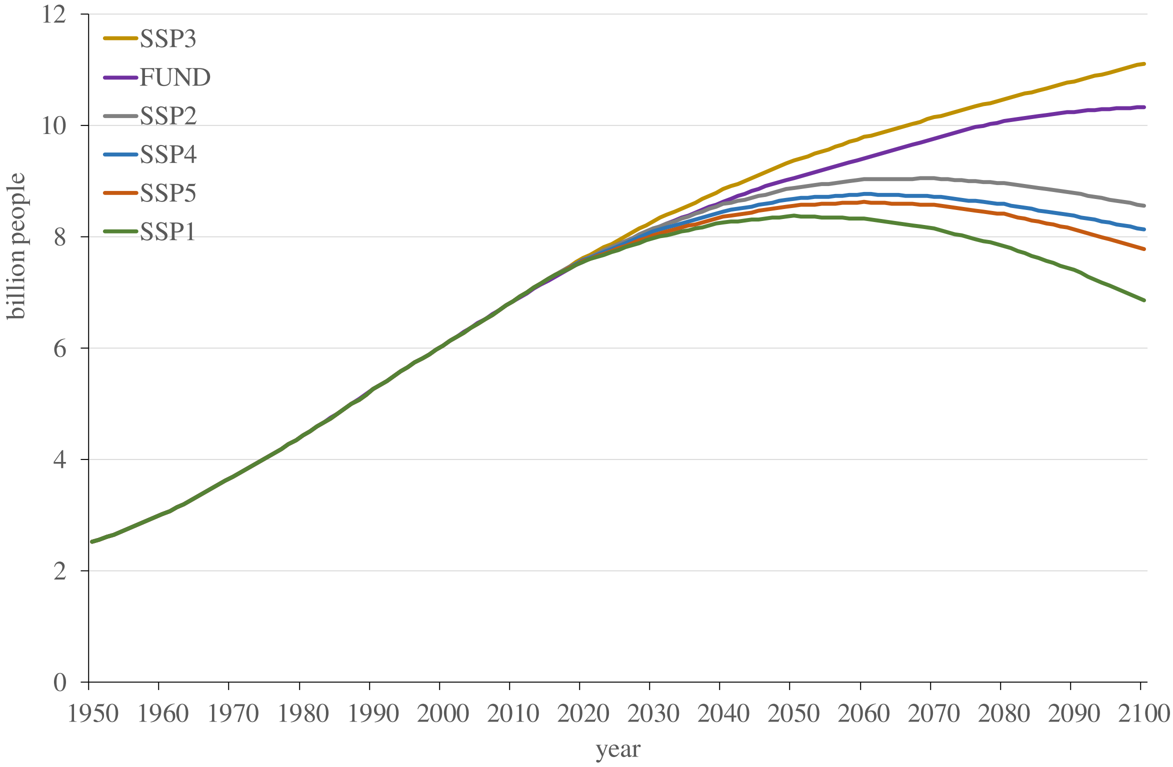

Figure 1. The world population as observed and as projected.

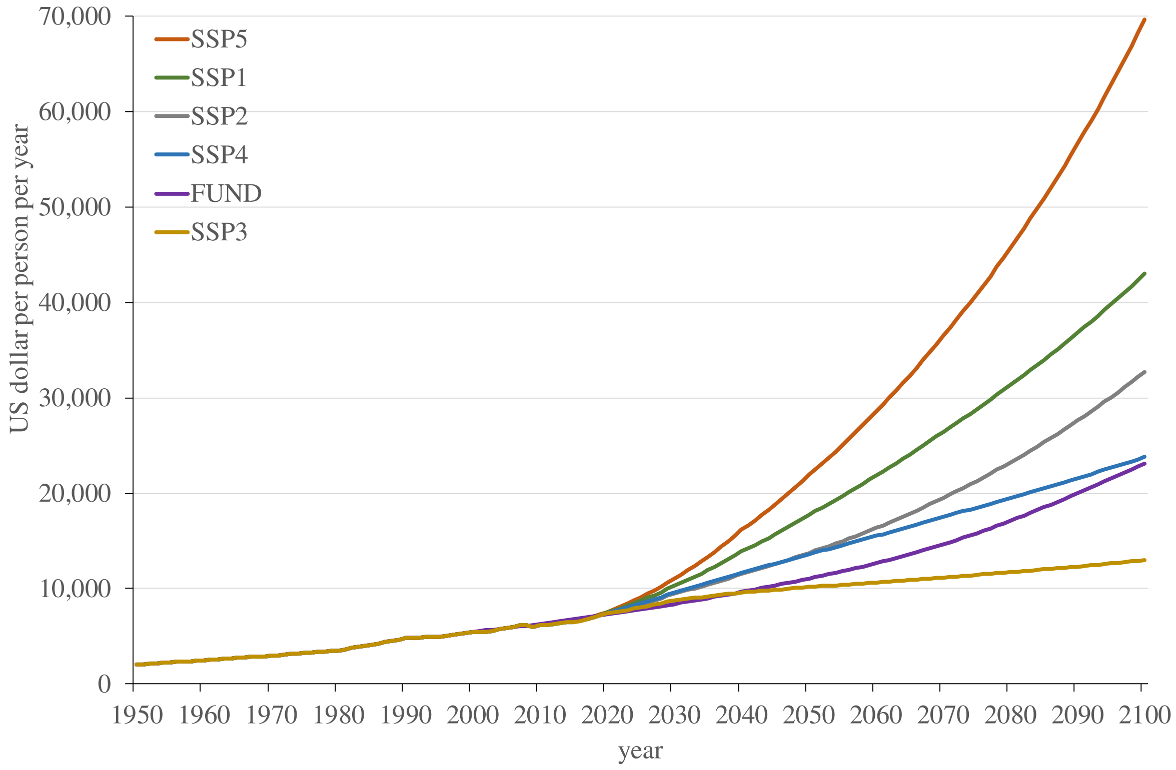

Figure 2. World average per capita income as observed and as projected.

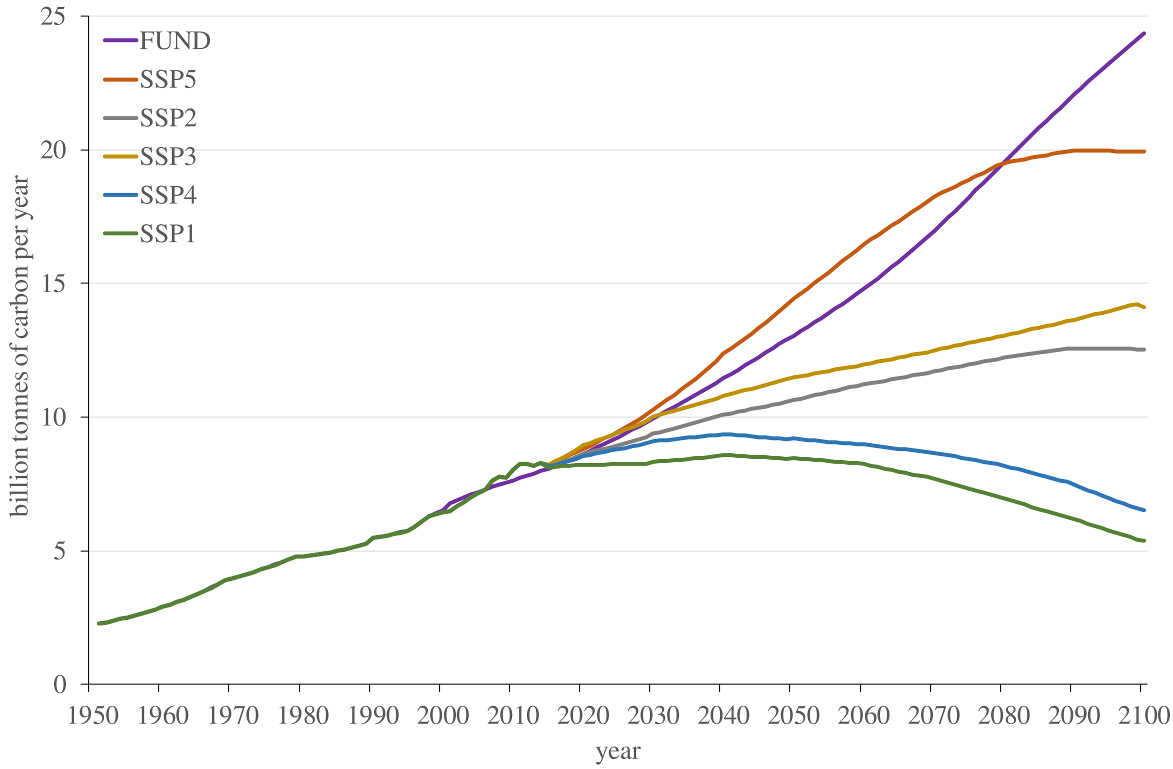

Figure 3. World total carbon dioxide emissions from fossil fuel combustion and cement production as observed and as projected.

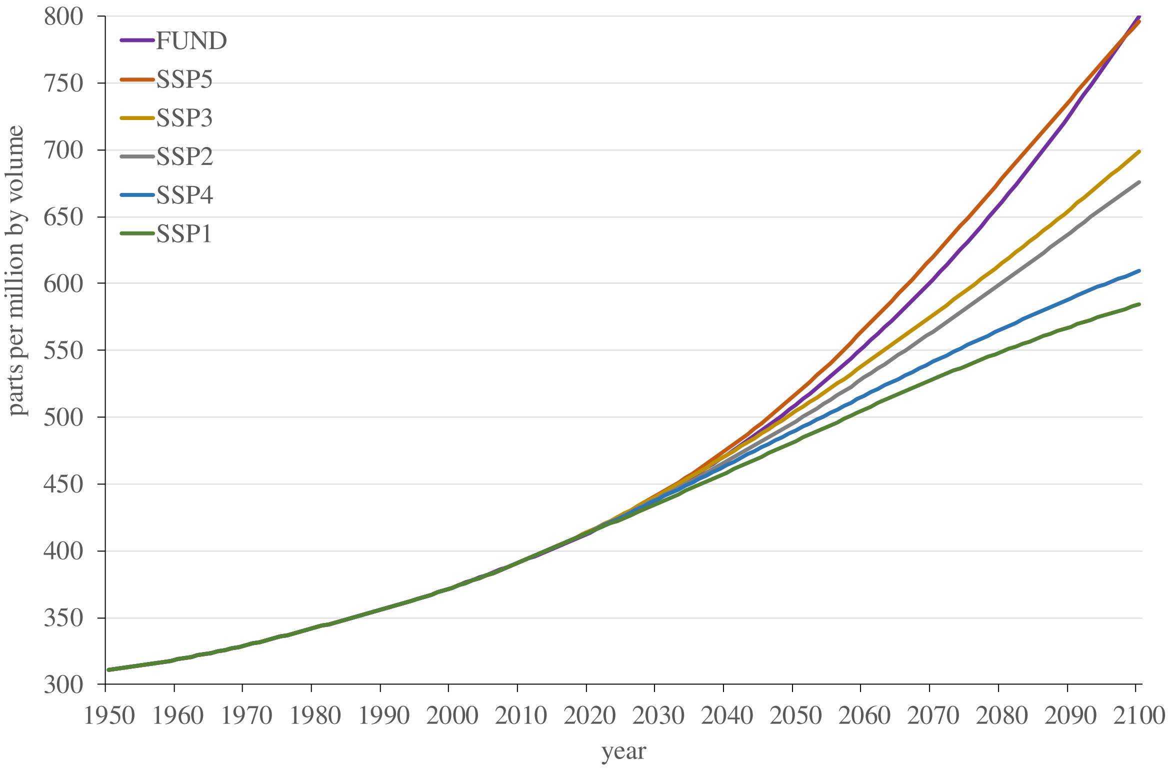

Figure 4. Atmospheric concentration of carbon dioxide as observed and as projected.

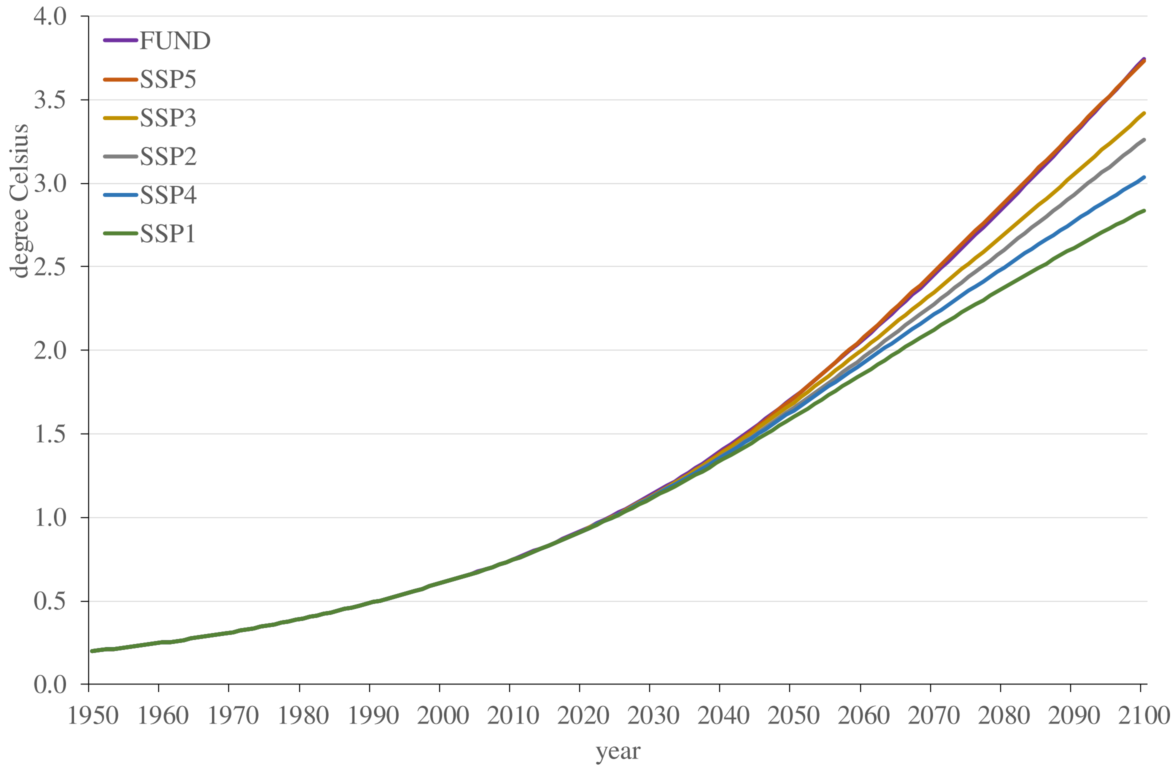

Figure 5. The global annual mean surface air temperature as projected.

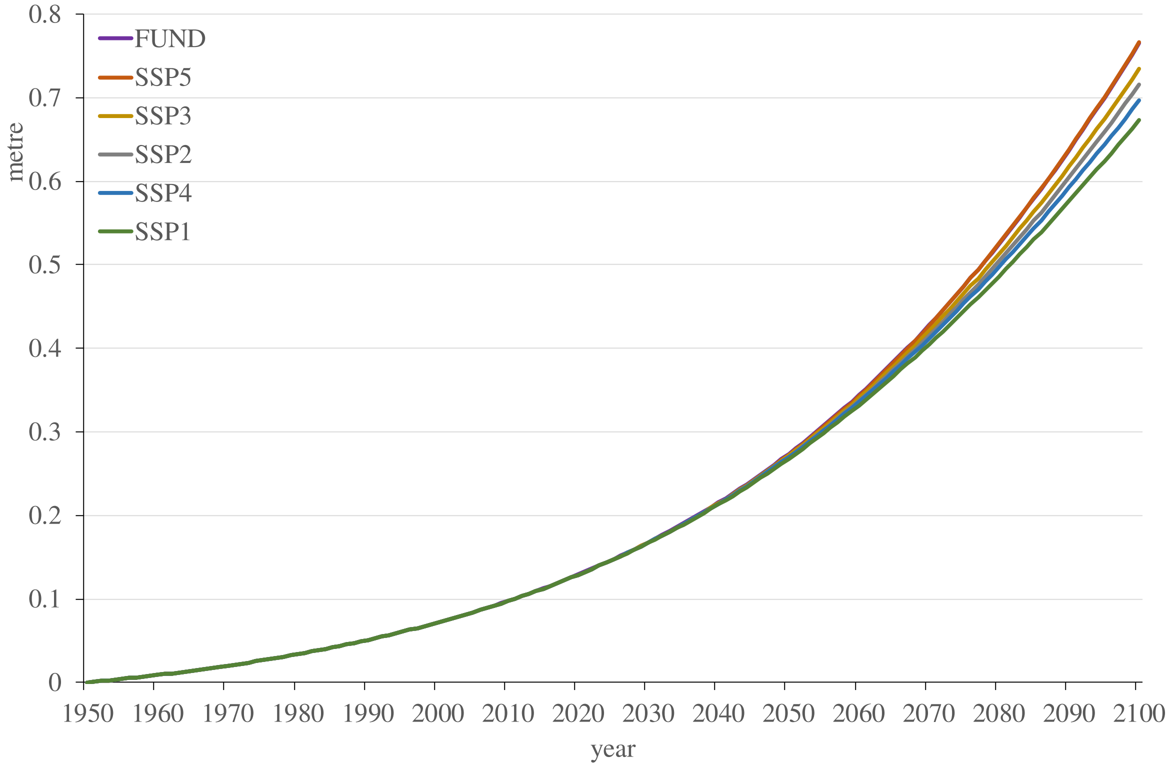

Figure 6. Global average sea level rise as projected.

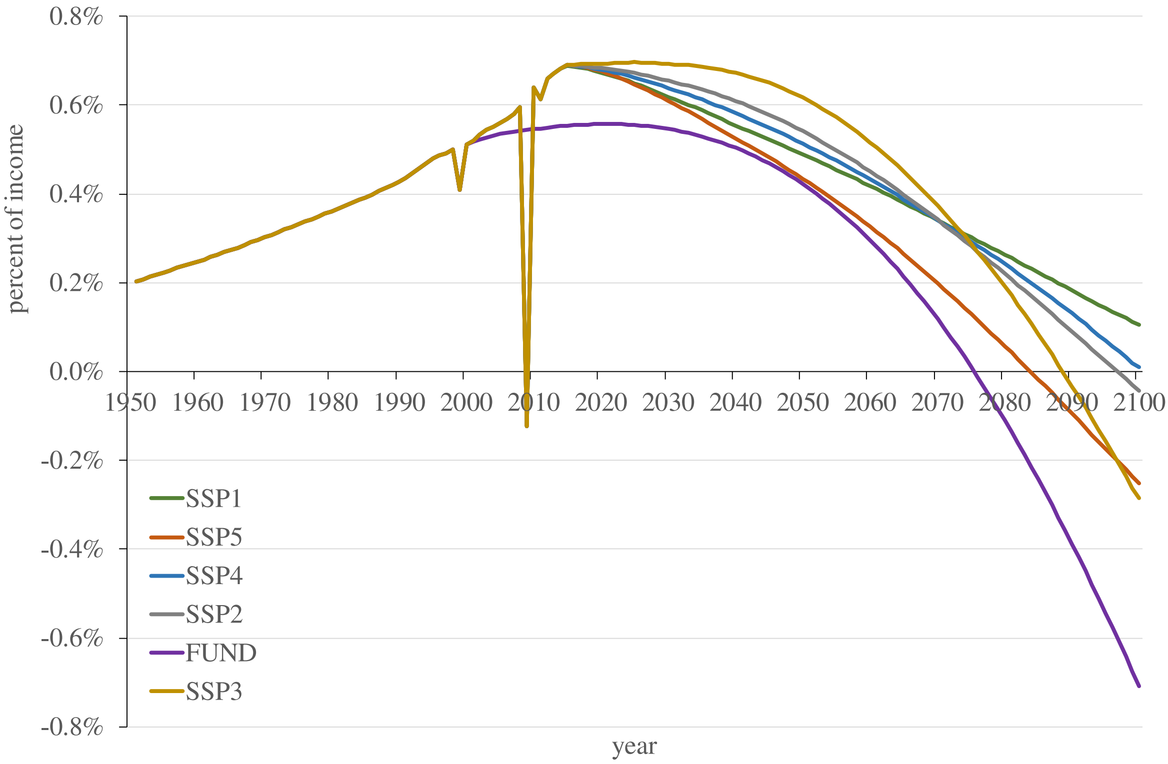

Figure 7. The global average impact of climate change on human welfare as projected.

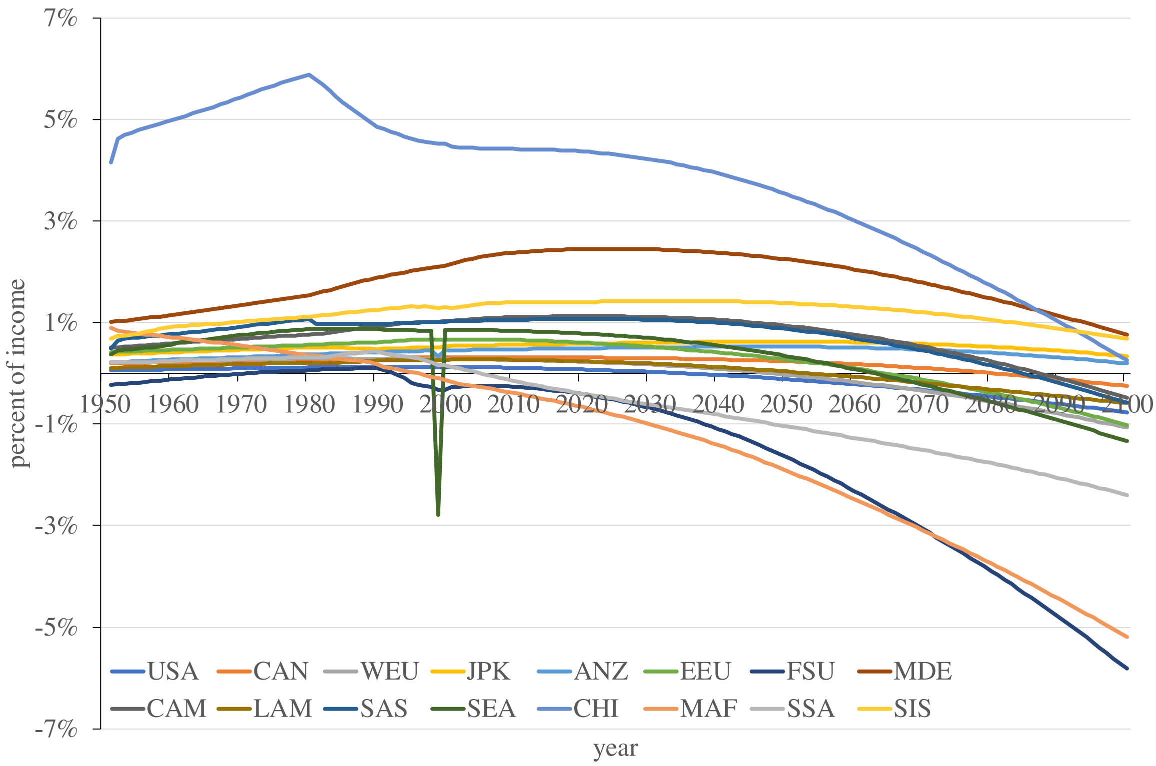

Figure 8. The relative impact of climate change on human welfare by region, as projected.

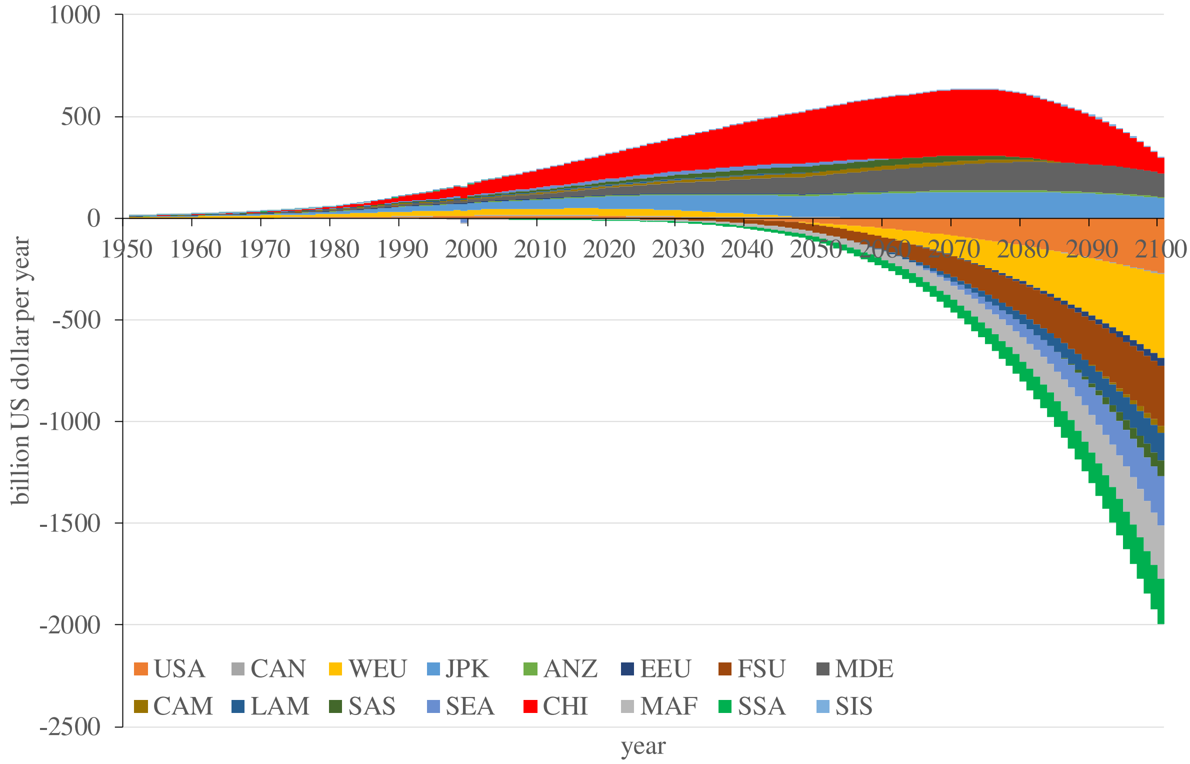

Figure 9. The absolute impact of climate change on human welfare, by region.

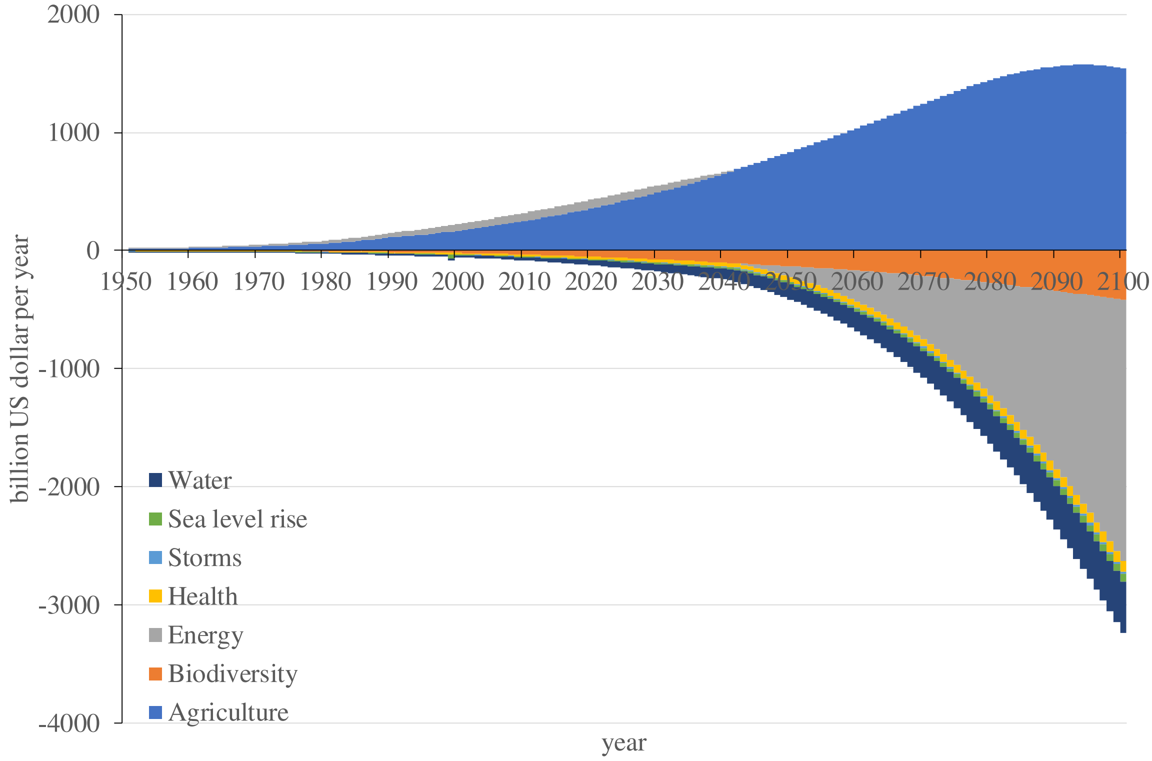

Figure 10. The absolute impact of climate change on human welfare, by sector.

Table 1. Key scenario characteristics for the year 2100.

	Warming (°C)	Income ($/p/yr)	Impact (% income)
FUND	3.75	23114	-0.71%
SSP1	2.84	42979	0.11%
SSP2	3.26	32751	-0.04%
SSP3	3.42	12987	-0.29%
SSP4	3.03	23789	0.01%
SSP5	3.73	69657	-0.25%