Met Office Hadley Centre
Tyndall°Centre for Climate Change Research
Walker Institute
Grantham Institute for Climate Change
An institute of Imperial College London

The economics and climate change impacts of various greenhouse gas emission pathways and a comparison between base line and policy emissions scenarios

AVOID:
Avoiding dangerous climate change

AVOID is a DECC/Defra funded research programme led by the Met Office in a consortium with the Walker Institute, Tyndall Centre and Grantham Institute

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This report should be read in conjunction with two other AVOID reports which complement the research results described here. These reports are:

Workstream 2 Deliverable 1, Report 4:
Report on Costs of Different Paths toward a Low Carbon World, available at:
http://www.avoid.uk.net/resources-researchers.html/AVOID_WS2_D1_04_20091009.pdf

Workstream 2 Deliverable 1, Report 9:
The economic costs of climate change mitigation: results from year 1 of the AVOID programme, available at:
http://www.avoid.uk.net/resources-researchers.html/AVOID_WS2_D1_09_20100809.pdf

This report should be referenced as

Warren R., Arnell N., Berry P., Brown S., Dicks L, Gosling S., Hankin R., Hope C., Lowe J., Matsumoto K., Masui T., Nicholls R., O'Hanley J., Osborn T., Scriecru S., 2010: *The economics and climate change impacts of various greenhouse gas emission pathways and a comparison between base line and policy emissions scenarios.* Work stream 1, Deliverable 3, Report 1 of the AVOID programme (AV/WS1/D3/R01). Available online at www.avoid.uk.net

CONTENTS

1. INTRODUCTION

Deliverable 1 of AVOID-WS1 produced emission scenarios that represented possible future global emission pathways for greenhouse gases during the 21st century. This was detailed in a simple fashion by varying three parameters: the year in which emissions peak globally, the rate of emission reduction (R), and the minimum level to which emissions are eventually reduced (H or L). The scenarios in deliverable 1 show emissions gradually deviating from a baseline, the A1B SRES scenario. Deliverable 1 also produced the global climate change resulting from these various emission scenarios.

Deliverable 2 produced a literature review designed to provide an update on the key advances since the publication of IPCC AR4.

The analysis in deliverable 3 is based upon these scenarios and provides quantitative estimates of (i) the climate change impacts avoided by reducing the emissions relative to the baseline and (ii) the economic implications are of reducing these emissions relative to the baseline.

We calculate impacts averaged over three time periods:
2015-2044 (centred on 2030)
2035-2064 (centred on 2050)
2070-2099 (centred on 2085)

We drive the impacts with the median climate change outcome from the scenarios (from deliverable 1), and we use the downscaling model ClimGen, which is based on a simple pattern scaling approach, to produce climate change patterns on a 50x50km grid. Our default is to use HadCM3 derived pattern scaling. We also carry out two sensitivity studies (i) driving one of the scenarios with the 10% and 90% outcome, in order to understand the effect of uncertainty in climate sensitivity, ocean heat uptake and carbon cycle feedbacks (ii) driving one of the scenarios with an ECHAM4 derived pattern scaling, in order to understand the role of choice of GCM pattern.

The scenarios chosen for analysis in deliverable 3 have peak years of either 2016 or 2030. These scenarios are: 2030.R2.H, 2030.R5.L, 2016.R2.H, 2016.R4.L and 2016.R.Low. The emission profiles of these scenarios in absolute terms and also in terms of % emission reductions with respect to 1990 are shown in the Figure 1 and Table 1a and b below, together with the A1B reference scenario. Also shown for comparison are the baseline scenarios used by the AIM and E3MG economic models.

Many of the impacts and climate models used in AVOID WS1 are linked together in the integrated model CIAS (Warren et al 2008). This enables the avoided impacts from a wide range of scenarios to be deduced.

Figure 1a . Absolute emissions Gt CO_2e in the AVOID reference and policy scenarios

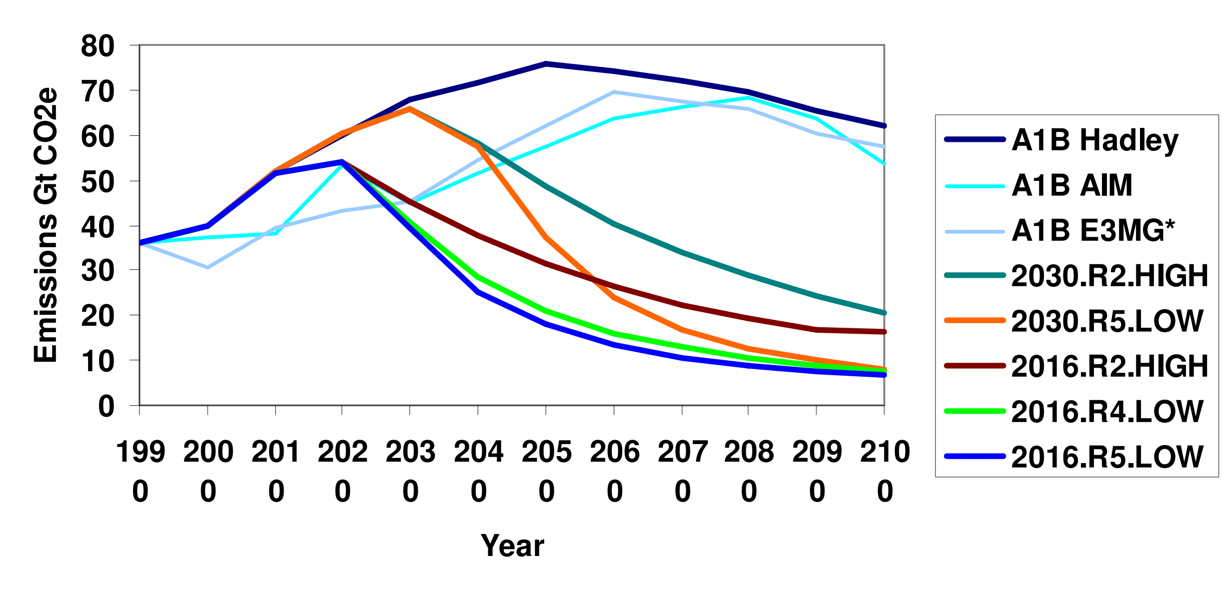

Table 1a. Absolute emissions Gt CO_2e in the AVOID reference and policy scenarios

	SCENARIO							
	A1B Hadley	A1B AIM	A1B E3MG*	2030.R2. High	2030.R5. Low	2016.R2. High	2016.R4 .Low	2016.R5. Low
1990	36.0			36.0	36.0	36.0	36.0	36.0
2000	39.8	37.2	30.5	39.8	39.8	39.8	39.8	39.8
2010	51.8	38.2	39.5	51.8	51.8	51.7	51.7	51.7
2020	59.7	53.1	43.3	60.2	60.2	54.2	54.2	54.2
2030	68.0	44.9	45.1	65.6	65.6	45.1	40.6	39.5
2040	71.7	51.4	54.3	58.2	57.3	37.6	28.3	25.3
2050	76.0	57.4	62.0	48.4	37.3	31.5	20.8	17.9
2060	74.0	63.8	69.4	40.3	23.9	26.4	15.9	13.3
2070	72.2	66.0	67.6	33.9	16.8	22.4	12.8	10.6
2080	69.4	68.4	65.9	28.7	12.6	19.2	10.6	8.9
2090	65.5	63.8	60.2	24.3	9.9	16.7	8.9	7.7
2100	61.9	53.7	57.3	20.7	8.1	16.3	7.7	6.8

Table 1b Percentage Emission Change Relative to 1990

	SCENARIO					
	A1B Hadley	2030.R2 .High	2030.R5. Low	2016.R2. High	2016.R4. Low	2016.R5. Low
1990						
2000	10.4%	10.4%	10.4%	10.4%	10.4%	10.4%
2010	43.7%	43.7%	43.7%	43.5%	43.5%	43.5%
2020	65.7%	66.9%	66.9%	50.4%	50.4%	50.4%
2030	88.8%	82.0%	82.0%	25.3%	12.6%	9.7%
2040	99.0%	61.4%	59.0%	4.3%	-21.4%	-29.9%
2050	110.8%	34.4%	3.6%	-12.5%	-42.3%	-50.3%
2060	105.4%	11.9%	-33.8%	-26.7%	-55.8%	-63.0%
2070	100.2%	-5.9%	-53.4%	-37.9%	-64.6%	-70.6%
2080	92.5%	-20.4%	-65.1%	-46.8%	-70.7%	-75.4%
2090	81.8%	-32.5%	-72.6%	-53.6%	-75.2%	-78.8%
2100	71.8%	-42.6%	-77.6%	-54.7%	-78.6%	-81.2%

2. SUMMARY

2.1 AVOIDED IMPACTS SUMMARY

Avoided global temperature rise

- **Firstly we remind the reader of some of the results obtained by J. Lowe et al in deliverable 1 of AVOID WS1 (Table A). Here we see that in the absence of climate policy it is very likely that global mean temperatures would exceed 3 degrees and there are evens chances that the temperature would rise by 4 degrees relative to pre-industrial times.**

- **The 2030 peaking scenarios (henceforth referred to as 2030R) are insufficient to keep below a 2 degree target and still allow a chance of one in three to four of exceeding 3 degrees C. However they are effective in avoiding a 4C temperature rise.**

- **The 2016 scenarios (henceforth referred to as 2016R) are more effective at keeping below a 3 degree target than the 2030 scenarios, reducing the chances of exceeding it to around one in 10.**

- **Only the 2016 5% scenario approaches what is needed to keep below a 2 degree target, reducing the chances of exceeding it to 45%.**

Avoiding breaching of tipping points

- **The risks of the feedbacks being triggered provides one of the strongest reasons for imposing stringent climate mitigation policies. Under the reference A1B scenario, by the 2080s global temperatures are likely to reach 3-4C above preindustrial levels (see Table A) at which the potential for all these tipping points to be crossed is significant. In particular, the breaching range for the Amazon forest tipping point is 3-4C, so an A1B emissions trajectory would almost certainly trigger this. Many of the other tipping points commence at 3-5C, so it is still likely that an A1B scenario would trigger these. It is therefore clear that ensuring temperatures remain below 3 degrees *with high confidence* is important in this respect.**

- **The 2016R scenario set is far more effective at reducing the risks of triggering these feedbacks than the 2030R scenarios (see Table B below, which draws upon the breaching ranges given in Table 1 of deliverable 2). The 2016R scenarios reduce the chances of being in the breaching range to 1 in 10, whereas the 2030R scenarios only reduce it to 1 in 3 or 4.**

- **The breaches of tipping points that can clearly be avoided by mitigation include the points at which (i) the earth's terrestrial carbon stores in forests and soils are released to the atmosphere, eg in the Amazon and boreal forests (ii) significant melting of the West Antarctic ice sheet occurs (iii) ocean currents and present day features of current climate are disrupted, e.g. the thermohaline circulation in the North Atlantic, the Indian monsoon and the West African monsoon. Items (i) to (ii) act as positive feedbacks, only one of which is included in the climate models used in this report. Thus breaching of these tipping points means that climate change might be accelerated beyond the levels indicated in deliverable 1. The tipping point which would most certainly occur under the A1B reference scenario is the drying of the Amazon forest,**

since the likely outcome of that scenario (3-4C) coincides exactly with that of the breaching range.

- **In the policy scenarios, the breaching of other tipping points for which a breaching range has not been quantified becomes less likely. In particular this includes a key positive feedback, the release of methane from permafrost and ocean clathrates as the earth warms.**

- **Since the breaching range for Greenland ice sheet melt is currently estimated at 1-2C, even the policy scenarios are not sufficient to avoid this. However, it is still true that the rate and severity of the melting would be much less in the policy cases than in the no-policy A1B reference case.**

Avoided impacts of climate change on a range of impacts sectors

- **Of key importance in all impacts sectors will be the reduction in the probabilties of extreme weather events which is delivered by the policy scenarios compared with the reference case, most of which again have not been included in this study. It is indeed possible that the most immediately felt climate change impacts will be those due to increased extreme weather and its impacts upon infrastructure, agriculture and ecosystems. The only extreme weather events that are considered in this study are flooding events (river and coastal) .**

- **Drawing now upon impact modelling calculations, this study finds that the avoided impacts that result from reducing emissions from the baseline A1B scenario to a policy scenario are greater for the 2016R scenarios than the 2030R scenarios in all three of the sectors: water stress, coasts, biodiversity. Thus the date at which emissions peak is more important than the rate of subsequent emissions reduction in determining the avoided impacts. For example, by the 2080s, the 2016R scenarios remove 38-41% of the increases in water stress forcecast under A1B (HadCM3 50% outcome) whereas the 2030R scenarios remove only 33%. In the coastal zone, avoided impacts in terms of people experiencing coastal flooding are large, about 43% by the 2080s in the 2016.R scenarios[1].**

- **Avoided impacts increase with time, being negligible in the 2030s, significant by the 2050s and large by the 2080s. Table C shows the % of impacts that occur under the A1B scenario that are avoided in the 2080s in the five policy scenarios, in each of the sectors studied in this project.**

- **The choice of GCM influences the magnitude of the avoided impacts as much as, or more than, the choice of %ile of climate change outcome, depending on sector. The choice of %ile of climate change outcome is as or more influential than the choice of scenario depending on sector. Hence the uncertainties in our estimates of avoided impacts for each scenario are larger than the difference between the scenarios.**

- **Currently the only sector which has reported regional benefits of climate policies is water stress, and in this sector greatest benefits are in Central America, Africa (N, S and E) and in Europe; also the Middle East, India and the US.**

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[1] There are two caveats to the coastal results. First, the results are only delayed and not avoided due to the long time constant of sea-level rise which will continue for centuries, even with climate stabilisation. This emphasizes that adaptation is critical in coastal zones as recognised in the IPCC AR4 report. Second, adaptation can greatly reduce the impacts through the 21st Century.

- **The PAGE model outputs show that the *<u>date at which global emissions peak is a stronger driver of avoided impacts than is the rate at which emissions are subsequently reduced.</u>***

TABLE A. GLOBAL MEAN TEMPERATURE RISE

	Year	A1B	2016.R (2%H, 4%L, 5%L)	2030.R (2%H, 5%L)
Probability of remaining below 2 degrees	**2100**	**1**	**30, 43, 45%**	**7, 17%**
Probability of exceeding 2 degrees	**2100**	**99**	**70, 57, 55%**	**93, 83%**
Probability of remaining below 3 degrees	**2100**	**7**	**87, 91, 91%**	**63, 76%**
Probability of exceeding 3 degrees	**2100**	**93**	**13, 9, 9%**	**37, 24%**
Probability of remaining below 4	**2100`**	**46**	**98, 99, 99%**	**93, 96%**
Probability of exceeding 4 degrees	**2100**	**54**	**2, 1, 1%**	**7, 4%**

TABLE B. TABLE OF AVOIDED BREACHING OF TIPPING POINTS

SECTOR	Date	Impact (unit)	Breaching range C above pre-industrial levels	Chance of breaching range being reached	Chance of breaching range being reached 2016 (2%H, 4%L, 5%L)	Chance of breaching range being reached 2030.R (2%H, 5%L)
Greenland ice sheet	2100	Probability of irreversible melting	1-2	Almost certain	Reduced further but still likely	Reduced but still likely
Methane release from clathrates	2100	Proability of release	Unclear	Possible	Reduced further	Reduced
West Antarctic Ice Melt	2100	Probability of irreversible melting	3-5	Very likely	Chance reduced to 1 in 10	Chance reduced to 1 in 3 or 4
Atlantic thermohaline circulation	2100	Probability of shutdown	3-5	Very likely	Chance reduced to 1 in 10	Chance reduced to 1 in 3 or 4
El Nino Southern Oscillation (ENSO)	2100	Probability of enhancement	3-6	Very likely	Chance reduced to 1 in 10	Chance reduced to 1 in 3 or 4
Sahara/Sahel & W African monsoon	2100	Probability of disruption	3-5	Very likely	Chance reduced to 1 in 10	Chance reduced to 1 in 3 or 4
Amazon forest/carbon cycle feedback	2100	Probability of dieback	3-4	Extremely likely	Chance reduced to 1 in 10	Chance reduced to 1 in 3 or 4
Boreal forest carbon cycle feedback	2100	Probability of dieback	3-5	Very likely	Chance reduced to 1 in 10	Chance reduced to 1 in 3 or 4

TABLE C. TABLE OF AVOIDED GLOBAL IMPACTS (without any adaptation): % OF IMPACTS AVOIDED UNDER A1B BASELINE SCENARIO IN 21st century (50%ile global climate change outcome of scenarios used, with HadCM3 downscaling pattern)

SECTOR	Impact (unit)	2030s % Impacts Avoided 2016.R (2%H, 4%L, 5%L)	2030s % Impacts Avoided 2030.R (2%H, 5%L)	2050s % Impacts Avoided 2016.R (2%H, 4%L, 5%L)	2050s % Impacts Avoided 2030.R (2%H, 5%L)	2080s % Impacts Avoided 2016.R (2%H, 4%L, 5%L)	2080s % Impacts avoided 2030.R (2%H, 5%L)	2100 % Impacts avoided 2016.R (2%H, 4%L, 5%L)	2100 % Impacts avoided 2030.R (2%H, 5%L)
Water stress	People w. increased stress	0, 0, 0	4, 4	17, 17, 17	9, 9	38, 41, 41	33, 33	45, 47, 50	26, 37
Coastal flooding[2]	People flooded	0, 0, 0	0, 0	19, 20, 20	12, 12	41, 43, 44	30, 33	-	-
Saltmarsh	Area lost					24	21		
Mangrove	Area lost					19	14	25	20
River flood risk	Abslolute	0, -3, -3	5, 5	37, 39, 38	22, 20	61, 65, 66	47, 51	64, 69, 71	47, 57
Increased river flood risk	People exposed	0, -2, -2	6, 6	30, 34, 32	15, 15	41, 47. 48	25, 33	43, 49, 51	26, 35
Biodiversity (European mammals/ plants sample only)	Species crit. endan-gered					88,100,100 mammals 55,66,77 plants	88,88 mammals 44, 44 plants		
Loss agricultrl suitability	Area lost	0, -2, -2	2, 2	16, 17, 17	9, 8	29, 31, 32	19, 22	30, 34, 35	21, 26

Economics in the reference and policy scenarios

- **Whilst the three economic models differ greatly in the assumptions that they make and indeed the questions which they are designed to answer, all three models show that the *date at which global emissions peak is a stronger driver than the rate at which emissions are subsequently reduced for* (i) the induced GDP changes (ii) the carbon taxes, with some exceptions.**
- **In models which assume perfect rationality and foresight and/or assume the economy to be equilibrium with full employment, then mitigation could cause GDP to decrease. In models which do not make these assumptions, mitigation could cause GDP to increase. The overall effect is therefore difficult to quantify, but in either case the effects are small (a few % of GDP lost or gained in 2100) and insignificant when compared with the 600-1200% increase in global GDP forecast between 2000 and 2100 in the SRES A1B reference scenario used in this study.**
- **Estimates of the carbon taxes required to achieve the various policy scenarios differ widely between models.**
- **Avoided impacts, carbon taxes and GDP change increase throughout the 21st century in the models.**

[2] If optimum adaptation is applied in reference and policy scenarios for coastal flooding, the % of impacts avoided by the policy scenarios becomes 9-10% for the 2016R scenarios and 8.7% for the 2030 R scenarios.

3. WATER RESOURCES AND FLOODING

3.1 WATER RESOURCES

3.1.1 How global hydrological models work

This study applies the following steps to estimate the numbers of people that experience an increase in water stress with climate change:

1. Run Mac-PDM.09, a global hydrological model (GHM), at 0.5°x0.5° resolution with present day climate (1961-1990) and changed climates (A1B and the policy scenarios) to simulate 30-year time series of monthly runoff. Calculate average annual runoff from these.
2. Sum the simulated runoff over approximately 1300 global watersheds and small islands to estimate watershed-scale runoff volumes.
3. Determine the watershed population total under the A1B population growth scenario for use with a water resources model.
4. Use the water resources model described in Arnell (2004) to estimate regional water stress, based upon watershed-scale indicators of water stress.

The hydrological model

Global hydrological models (GHMs) model the land surface hydrologic dynamics of continental-scale river basins. Here we apply one such GHM, Mac-PDM.09 ("Mac" for "macro-scale" and "PDM" for "probability distributed moisture model"). Mac-PDM.09 simulates runoff across the world at a spatial resolution of 0.5°x0.5°. It has been described and validated by Arnell (1999, 2003), where it has been shown to simulate average annual runoff reasonably well. Here we apply a revised version of the model in terms of structure, data input formats, and output hydrological indicators. In brief, Mac-PDM.09 calculates the water balance in each 0.5°x0.5° cell on a daily basis, treating each cell as an independent catchment, generating river runoff from precipitation falling on the portion of the cell that is saturated, and by drainage from water stored in the soil. The model parameters are not calibrated - model parameters describing soil and vegetation characteristics are taken from spatial data sets.

The water resources model

The current study uses average annual runoff simulated by Mac-PDM.09 to characterise available water resources using the water resources model described in Arnell (2004). It is necessary to define an indicator of pressure on water resources for the model. Here we use the amount of water resources available per person, expressed as m3/capita/year. This index was used by the PAGE study (Revenga et al. 2000). The water resources model assumes that watersheds with less than 1000m3/capita/year are water stressed, similar to Revenga et al. (2000), where thresholds of both 1700 and 1000m3/capita/year were used. Therefore populations that move into this stressed category are considered to experience an increase in water resources stresses. However, some populations are already within the water stressed category, because present-day resources per capita are less than 1000m3/capita/year. Therefore a more complicated measure combines the number of people who move into (out of) this stressed category with the numbers of people already in the stressed category who experience an increase (decrease) in water stress with climate change. The key element here is to define what characterises a ''significant'' change in runoff, and hence water stress. The water resources model assumes a ''significant'' change in runoff, and hence water stress, occurs when the percentage change in mean annual runoff is more than the standard deviation of 30-year mean annual runoff due to natural multi-decadal climatic variability. Hence the water resources model calculates the millions of people at increased risk to water resources stresses with climate change as the sum of the populations that move into the stressed category (resources less than 1000m3/capita/year) and the numbers of people already in the stressed category who experience an increase in water stress.

3.1.2 What the main results are and what they mean

Five main conclusions can be drawn from the results:

1. ***Choice of policy scenario has very little effect on avoided impacts in the 2030s***
   For instance, for the 2030s time horizon, no regions experience avoided impacts with the policy scenarios that reduce emissions from a 2016 peak, and only 4 regions present avoided impacts for the policy scenarios that reduce emissions from a 2030 peak (Canada, France, Italy and Europe). At most, 8.7 million people globally avoid increases in water stress for the 2030s time horizon. The 2016.R4.L and 2016.R5.L scenarios actually result in a small increase of water stress of 900,000 people relative to the A1B scenario, for Europe. This is because climate change causes some regions to become wetter and so reduces water stress – as such, climate change mitigation will cause some regions to become less wet than they would with climate change, and this can result in an increase in water stress *relative* to the climate change scenario. *These results mean it is unlikely that the benefits of any policy scenario will be clear in the 2030s.*

2. ***Avoided impacts increase with time into the future***
   For any given policy scenario, the avoided impacts increase in magnitude with time into the future. For example, with the 2016.R5.L scenario, the numbers of people globally that avoid increases in water stress increase from -900,000 (2015-2044), to 108.2 million (2035-2064), to 401.3 million (2070-2099). The regions that present the greatest benefits from policy scenarios are North Africa, Southern and East Africa, Central America, and India. *This means that the greatest benefits of any policy scenario will not be realized until the end of the century.*

3. ***Avoided impacts are greater with the 2016-R policy scenarios than they are with the 2030-R policy scenarios***
   For instance, the difference in global avoided impacts between the 2016.R5.L and 2030.R5.L scenarios for 2035-2064 is 52.1 million, and this increases to 73.8 million for 2070-2099. However, the differences within the 2016 scenarios, i.e. 2016.R2.H, 2016.R4.L and 2016.R5.L are minor and do not increase with time into the future. The same is true for the 2 2030-R scenarios. *This means the year at which emissions begin to be reduced has a greater effect on avoided impacts than the annual rate at which emissions are reduced.*

4. ***The range in avoided impacts across percentile of climate change outcome is comparable to the range across policy scenarios***
   For example, the range in avoided impacts for 2070-2099 for the 2016.R5.L policy scenario that uses the 50%, 90% and 10% climate change outcomes is 274.5-401.3 million. This is greater than the range across the 5 policy scenarios for 2070-2099, which is 323.1-401.3. *This implies that model uncertainty is greater than emissions uncertainty.*

5. ***The magnitude of avoided impacts varies greatly between GCM***
   The global avoided impacts are greater with the ECHAM5 GCM (Figures on pp 23-24) than they are with the HadCM3 GCM (Figures on pp 15-17). Avoided impacts with the 2016.R5.L scenario for 2035-2064 are 114.3 million with ECHAM5 and 108.2 million with HadCM3. For 2070-2099 these values increase to 538.5 million and 401.2 million respectively. Furthermore, regional differences can be very large. For instance, avoided impacts for China associated with the 2016.R5.L scenario are 3.5 million for 2035-2064 and 182.9 million for 2070-2099 with ECHAM5. With HadCM3, the avoided impacts are 0.0 and 0.3 million respectively. This inter-GCM difference is greater than the differences between percentiles of climate change outcome

(10%, 50% and 90%) and of the difference between any given policy. *Therefore the magnitude of the avoided impacts is mostly dependent upon GCM*.

3.1.3 Caveats

Mac-PDM.09 assumes that all runoff generated within the grid cell reaches the cell outlet; it does not include transmission loss along the river network or evaporation of infiltrated overland flow, and does not include human intervention. Therefore Mac-PDM.09 tends to overestimate runoff in very dry areas, up to a factor of 3. It is also partly because simulations are sensitive in these regions to the magnitude of the soil moisture capacity distribution parameter, and partly due to inaccuracies in downscaling the monthly rainfall in both time and space (which is not actually done: it is assumed that the entire cell is rained on). However, arguably Mac-PDM.09 provides a reasonable indication of the resources potentially available for use in such areas (many rural communities in dry areas take water from river beds or wetlands). The model does not route water from one grid cell to another. There is not a glacier component, so river flows in a cell do not include any net melt from upstream glaciers. The effects of seasonal freezing and thawing of permafrost are not included in the model.

The amount of water resources available per person, expressed as m3/capita/year, is used as an indicator of pressure on water resources. The advantage of this index is that it does not require assumptions about future water withdrawals. However, it tends to underestimate stresses in areas where there are very large withdrawals (principally for irrigation). Also, it is important to emphasise that the indicators of water resources stress used in this study do not reflect issues such as access to safe drinking water, which is dependent on the availability and quality of local sources and distribution systems rather than the quantity of water available in a catchment.

Australia and the rest of Australasia are the only regions that present no change in water stress, for any scenario. The maps of runoff change show that the coasts of Australia generally see reductions in runoff but the central areas experience increases. The water resources model applied here uses watershed runoff and population to calculate water stress indicators. This means that not all the available gridded runoff values simulated by MacPDM.09 for a given region are used to calculate water resources stresses – a watershed does not typically cover an entire region. This is a limitation of using global water resources models, such as here. It is acknowledged that if a regional or local water resources model was applied the results might be different.

IMPACTS USING 50% (MEDIAN) CLIMATE CHANGE OUTCOME AND ClimGen TUNED to HadCM3: MILLIONS OF PEOPLE AT INCREASED RISK OF WATER RESOURCES STRESSES – 2015-2044

	Climate Change Impacts						Avoided Impacts				
Region	**A1B**	**2016.R2.H**	**2016.R4.L**	**2016.R5.L**	**2030.R2.H**	**2030.R5.L**	**A1B-2016.R2.H**	**A1B-2016.R4.L**	**A1B-2016.R5.L**	**A1B-2030.R2.H**	**A1B-2030.R5.L**
China	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
US	18.7	18.7	18.7	18.7	18.7	18.7	0.0	0.0	0.0	0.0	0.0
Russia	1.2	1.2	1.2	1.2	1.2	1.2	0.0	0.0	0.0	0.0	0.0
Japan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Africa	7.8	7.8	7.8	7.8	7.8	7.8	0.0	0.0	0.0	0.0	0.0
India	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Brazil	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mexico	26.9	26.9	26.9	26.9	26.9	26.9	0.0	0.0	0.0	0.0	0.0
Canada	6.0	6.0	6.0	6.0	0.0	0.0	0.0	0.0	0.0	6.0	6.0
Australia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Indonesia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Korea	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
UK	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
France	19.4	19.4	19.4	19.4	17.1	17.1	0.0	0.0	0.0	2.2	2.2
Italy	13.0	13.0	13.0	13.0	12.9	12.9	0.0	0.0	0.0	0.2	0.2
Germany	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Poland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Saudi Arabia	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0
Rest of South Asia	1.8	1.8	1.8	1.8	1.8	1.8	0.0	0.0	0.0	0.0	0.0
Rest of East Asia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rest of Central Asia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
North Africa	5.6	5.6	5.6	5.6	5.6	5.6	0.0	0.0	0.0	0.0	0.0
West Africa	9.5	9.5	9.5	9.5	9.5	9.5	0.0	0.0	0.0	0.0	0.0
Southern and East Africa	12.5	12.5	12.5	12.5	12.5	12.5	0.0	0.0	0.0	0.0	0.0
Europe	46.7	46.7	47.7	47.7	46.4	46.4	0.0	-0.9	-0.9	0.3	0.3
South America	3.0	3.0	3.0	3.0	3.0	3.0	0.0	0.0	0.0	0.0	0.0
Central America	1.5	1.5	1.5	1.5	1.5	1.5	0.0	0.0	0.0	0.0	0.0
Caribbean	7.0	7.0	7.0	7.0	7.0	7.0	0.0	0.0	0.0	0.0	0.0
Rest of Australasia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	47.2	47.2	47.2	47.2	47.2	47.2	0.0	0.0	0.0	0.0	0.0
Global	228.0	228.0	228.9	228.9	219.3	219.3	0.0	-0.9	-0.9	8.7	8.7

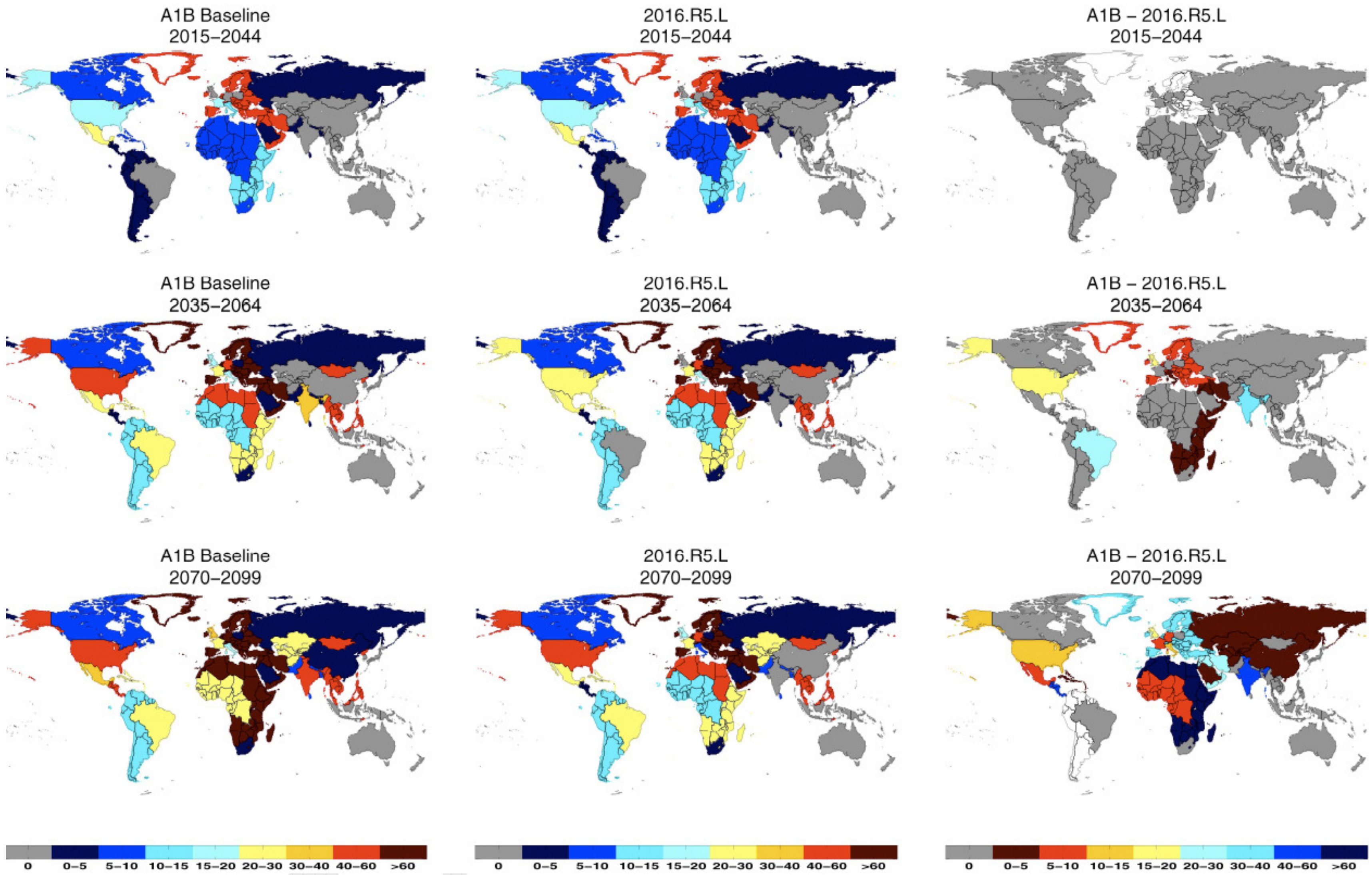
IMPACTS USING 50% (MEDIAN) CLIMATE CHANGE OUTCOME AND ClimGen TUNED to HadCM3: MILLIONS OF PEOPLE AT INCREASED RISK OF WATER RESOURCES STRESSES – 2035-2064

	Climate Change Impacts						Avoided Impacts				
Region	**A1B**	**2016.R2.H**	**2016.R4.L**	**2016.R5.L**	**2030.R2.H**	**2030.R5.L**	**A1B-2016.R2.H**	**A1B-2016.R4.L**	**A1B-2016.R5.L**	**A1B-2030.R2.H**	**A1B-2030.R5.L**
China	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
US	40.6	23.2	23.2	23.2	30.0	30.0	17.4	17.4	17.4	10.6	10.6
Russia	1.1	1.1	1.1	1.1	1.1	1.1	0.0	0.0	0.0	0.0	0.0
Japan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Africa	0.6	0.6	0.6	0.6	0.6	0.6	0.0	0.0	0.0	0.0	0.0
India	33.6	0.0	0.0	0.0	0.0	0.0	33.6	33.6	33.6	33.6	33.6
Brazil	22.5	0.0	0.0	0.0	22.5	22.5	22.5	22.5	22.5	0.0	0.0
Mexico	28.3	28.3	28.3	28.3	28.3	28.3	0.0	0.0	0.0	0.0	0.0
Canada	6.4	6.4	6.4	6.4	6.4	6.4	0.0	0.0	0.0	0.0	0.0
Australia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Indonesia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Korea	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
UK	18.3	0.0	0.0	0.0	18.3	18.3	18.3	18.3	18.3	0.0	0.0
France	24.2	24.2	24.2	24.2	24.2	24.2	0.0	0.0	0.0	0.0	0.0
Italy	18.4	15.3	15.3	15.3	15.3	15.3	3.0	3.0	3.0	3.0	3.0
Germany	53.4	53.4	53.4	53.4	53.4	53.4	0.0	0.0	0.0	0.0	0.0
Poland	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0
Saudi Arabia	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0
Rest of South Asia	4.3	4.3	4.3	4.3	4.3	4.3	0.0	0.0	0.0	0.0	0.0
Rest of East Asia	46.1	46.1	46.1	46.1	46.1	46.1	0.0	0.0	0.0	0.0	0.0
Rest of Central Asia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
North Africa	41.9	41.9	41.9	41.9	41.9	41.9	0.0	0.0	0.0	0.0	0.0
West Africa	13.4	13.4	13.4	13.4	13.4	13.4	0.0	0.0	0.0	0.0	0.0
Southern and East Africa	26.5	22.3	22.3	22.3	22.3	22.3	4.2	4.2	4.2	4.2	4.2
Europe	87.0	78.6	78.6	78.6	82.4	82.4	8.4	8.4	8.4	4.6	4.6
South America	13.6	13.6	13.6	13.6	13.6	13.6	0.0	0.0	0.0	0.0	0.0
Central America	1.7	1.7	1.7	1.7	1.7	1.7	0.0	0.0	0.0	0.0	0.0
Caribbean	22.7	22.7	22.7	22.7	22.7	22.7	0.0	0.0	0.0	0.0	0.0
Rest of Australasia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	117.7	117.0	117.0	117.0	117.7	117.7	0.7	0.7	0.7	0.0	0.0
Global	622.8	514.5	514.5	514.5	566.7	566.7	108.2	108.2	108.2	56.1	56.1

IMPACTS USING 50% (MEDIAN) CLIMATE CHANGE OUTCOME AND ClimGen TUNED to HadCM3:
MILLIONS OF PEOPLE AT INCREASED RISK OF WATER RESOURCES STRESSES – 2070-2099

	Climate Change Impacts						Avoided Impacts				
Region	**A1B**	**2016.R2.H**	**2016.R4.L**	**2016.R5.L**	**2030.R2.H**	**2030.R5.L**	**A1B-2016.R2.H**	**A1B-2016.R4.L**	**A1B-2016.R5.L**	**A1B-2030.R2.H**	**A1B-2030.R5.L**
China	0.3	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.3	0.3
US	55.8	41.7	41.7	41.7	41.7	41.7	14.1	14.1	14.1	14.1	14.1
Russia	1.1	1.0	1.0	1.0	1.0	1.0	0.2	0.2	0.2	0.1	0.1
Japan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Africa	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0
India	42.4	29.0	0.0	0.0	35.4	35.4	13.4	42.4	42.4	7.0	7.0
Brazil	21.3	21.3	21.3	21.3	21.3	21.3	0.0	0.0	0.0	0.0	0.0
Mexico	33.1	26.7	26.7	26.7	26.7	26.7	6.4	6.4	6.4	6.4	6.4
Canada	6.6	6.6	6.6	6.6	6.6	6.6	0.0	0.0	0.0	0.0	0.0
Australia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Indonesia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Korea	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
UK	36.2	19.9	19.9	19.9	36.2	36.2	16.3	16.3	16.3	0.0	0.0
France	29.7	24.5	24.5	24.5	24.5	24.5	5.2	5.2	5.2	5.2	5.2
Italy	16.9	6.1	6.1	6.1	11.9	11.9	10.7	10.7	10.7	5.0	5.0
Germany	61.2	55.3	55.3	55.3	56.0	56.0	6.0	6.0	6.0	5.2	5.2
Poland	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0
Saudi Arabia	0.7	0.3	0.3	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.5
Rest of South Asia	8.7	8.7	8.7	8.7	8.7	8.7	0.0	0.0	0.0	0.0	0.0
Rest of East Asia	44.9	44.9	44.9	44.9	44.9	44.9	0.0	0.0	0.0	0.0	0.0
Rest of Central Asia	22.0	21.8	21.8	21.8	21.8	21.8	0.3	0.3	0.3	0.3	0.3
North Africa	132.9	42.4	42.4	42.4	42.4	42.4	90.5	90.5	90.5	90.5	90.5
West Africa	21.0	13.4	13.4	13.4	14.0	14.0	7.5	7.5	7.5	6.9	6.9
Southern and East Africa	111.2	27.3	27.3	27.3	32.5	32.5	84.0	84.0	84.0	78.7	78.7
Europe	97.1	60.8	60.8	60.8	67.0	67.0	36.3	36.3	36.3	30.1	30.1
South America	12.2	13.7	13.7	13.7	14.0	13.7	-1.5	-1.5	-1.5	-1.9	-1.5
Central America	58.6	1.8	1.8	1.8	4.6	4.6	56.8	56.8	56.8	54.0	54.0
Caribbean	24.8	23.4	23.4	23.4	23.7	23.7	1.4	1.4	1.4	1.1	1.1
Rest of Australasia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	135.0	111.0	111.0	111.0	115.7	111.6	24.0	24.0	24.0	19.3	23.4
Global	974.5	602.2	573.2	573.2	651.4	647.0	372.3	401.3	401.3	323.1	327.5

IMPACTS USING 50% (MEDIAN) CLIMATE CHANGE OUTCOME AND ClimGen TUNED to HadCM3:
MILLIONS OF PEOPLE AT INCREASED RISK OF WATER RESOURCES STRESSES
WITH EXCEPTION TO THE INTERIOR OF GREENLAND, WHITE AREAS EXPERIENCE SUBTLE NEGATIVE AVOIDED IMPACTS (SEE TABLES FOR VALUES)



SENSITIVITY STUDY: 90% OUTCOME OF CLIMATE CHANGE SCENARIO 2016.R5.L AND ClimGen TUNED to HadCM3: MILLIONS OF PEOPLE AT INCREASED RISK OF WATER RESOURCES STRESSES

	2015-2044			2035-2064			2070-2099		
Region	**A1B**	**2016.R5.L**	**A1B-2016.R5.L**	**A1B**	**2016.R5.L**	**A1B-2016.R5.L**	**A1B**	**2016.R5.L**	**A1B-2016.R5.L**
China	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.3
US	18.7	18.7	0.0	42.9	40.6	2.4	72.1	41.7	30.4
Russia	1.2	1.2	0.0	1.1	1.1	0.0	1.1	1.0	0.1
Japan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Africa	7.8	7.8	0.0	6.3	0.6	5.7	5.4	0.5	4.9
India	0.0	0.0	0.0	40.9	33.6	7.3	42.4	35.4	7.0
Brazil	0.0	0.0	0.0	22.5	22.5	0.0	21.3	21.3	0.0
Mexico	26.9	26.9	0.0	35.1	28.3	6.8	33.1	26.7	6.4
Canada	6.0	6.0	0.0	6.4	6.4	0.0	6.6	6.6	0.0
Australia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Indonesia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Korea	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
UK	0.0	0.0	0.0	33.4	18.3	15.0	36.2	36.2	0.0
France	23.0	23.0	0.0	24.2	24.2	0.0	26.8	27.4	-0.6
Italy	16.1	16.1	0.0	21.0	15.3	5.7	16.9	14.2	2.7
Germany	50.8	50.8	0.0	59.2	53.4	5.8	73.0	61.2	11.8
Poland	0.2	0.2	0.0	0.3	0.2	0.1	0.2	0.2	0.0
Saudi Arabia	0.2	0.2	0.0	0.2	0.2	0.0	0.7	0.3	0.5
Rest of South Asia	1.8	1.8	0.0	7.9	4.3	3.6	8.9	8.7	0.1
Rest of East Asia	0.0	0.0	0.0	58.7	46.1	12.6	56.1	44.9	11.2
Rest of Central Asia	0.0	0.0	0.0	15.8	0.0	15.8	28.4	21.8	6.6
North Africa	39.2	39.2	0.0	123.4	41.9	81.5	134.5	125.8	8.7
West Africa	11.9	11.9	0.0	13.9	13.4	0.5	23.7	14.0	9.7
Southern and East Africa	16.4	16.4	0.0	26.5	26.5	0.0	106.9	33.4	73.5
Europe	67.5	67.5	0.0	104.3	87.0	17.3	99.4	85.8	13.6
South America	3.0	3.0	0.0	13.6	13.6	0.0	28.4	14.0	14.4
Central America	1.5	1.5	0.0	4.2	1.7	2.5	60.4	7.7	52.7
Caribbean	20.9	20.9	0.0	23.8	22.7	1.1	24.8	23.7	1.1
Rest of Australasia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	67.6	67.6	0.0	128.8	117.7	11.1	140.9	121.6	19.3
Global	380.8	380.8	0.0	814.5	619.7	194.8	1048.5	774.0	274.5

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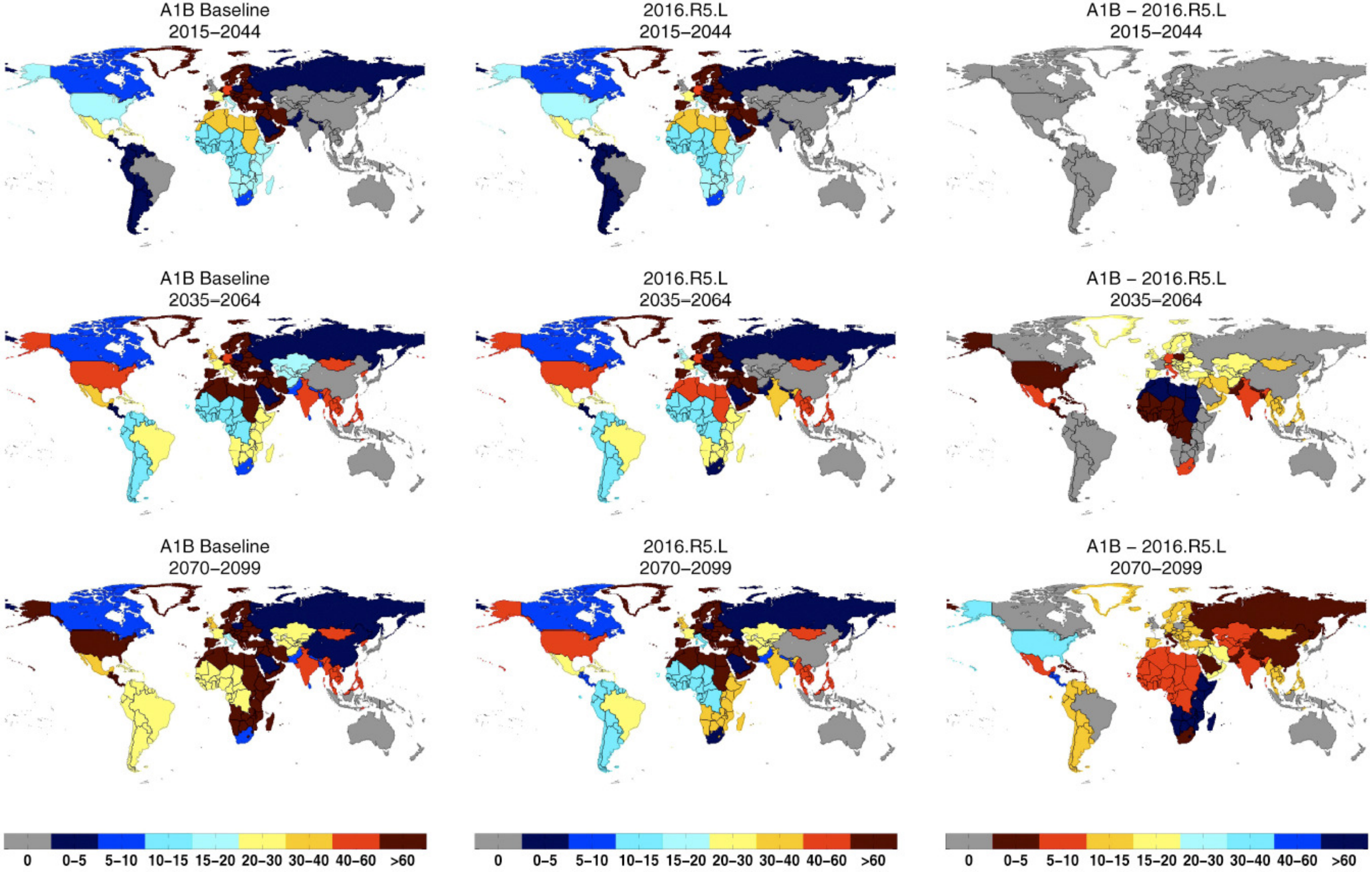

SENSITIVITY STUDY: 10% OUTCOME OF CLIMATE CHANGE SCENARIO 2016.R5.L AND ClimGen TUNED to HadCM3: MILLIONS OF PEOPLE AT INCREASED RISK OF WATER RESOURCES STRESSES

	2015-2044			2035-2064			2070-2099		
Region	**A1B**	**2016.R5.L**	**A1B-2016.R5.L**	**A1B**	**2016.R5.L**	**A1B-2016.R5.L**	**A1B**	**2016.R5.L**	**A1B-2016.R5.L**
China	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
US	18.7	18.7	0.0	23.2	23.2	0.0	44.1	23.8	20.3
Russia	1.2	1.2	0.0	1.1	1.1	0.0	1.0	1.0	0.1
Japan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Africa	7.8	7.8	0.0	0.6	0.6	0.0	0.5	0.5	0.0
India	0.0	0.0	0.0	0.0	0.0	0.0	42.4	0.0	42.4
Brazil	0.0	0.0	0.0	22.5	0.0	22.5	21.3	0.0	21.3
Mexico	26.9	26.9	0.0	28.3	28.3	0.0	33.1	26.7	6.4
Canada	0.0	0.0	0.0	6.4	6.4	0.0	6.6	6.6	0.0
Australia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Indonesia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Korea	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
UK	0.0	0.0	0.0	0.0	0.0	0.0	36.2	0.0	36.2
France	17.1	17.1	0.0	24.2	20.3	3.9	27.4	24.4	3.0
Italy	9.1	9.1	0.0	15.3	11.7	3.6	14.2	6.1	8.1
Germany	0.0	0.0	0.0	53.4	0.0	53.4	61.2	34.5	26.7
Poland	0.0	0.0	0.0	0.2	0.0	0.2	0.2	0.0	0.2
Saudi Arabia	0.2	0.2	0.0	0.2	0.2	0.0	0.7	0.3	0.5
Rest of South Asia	0.4	0.9	-0.5	4.3	4.3	0.0	8.7	8.7	0.0
Rest of East Asia	0.0	0.0	0.0	46.1	46.1	0.0	44.9	44.9	0.0
Rest of Central Asia	0.0	0.0	0.0	0.0	0.0	0.0	21.8	12.4	9.3
North Africa	5.6	5.6	0.0	41.9	8.5	33.4	127.5	42.4	85.1
West Africa	2.9	2.9	0.0	13.4	11.3	2.2	14.0	13.1	0.9
Southern and East Africa	10.1	10.1	0.0	22.3	22.0	0.3	33.4	26.9	6.5
Europe	42.1	42.1	0.0	82.4	47.8	34.5	95.9	42.2	53.8
South America	2.3	3.0	-0.7	13.6	3.6	10.0	12.2	13.7	-1.5
Central America	1.5	1.5	0.0	1.7	1.7	0.0	7.8	1.8	6.0
Caribbean	7.0	7.0	0.0	22.7	22.7	0.0	24.8	23.4	1.4
Rest of Australasia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	39.8	39.8	0.0	117.7	59.4	58.3	133.9	73.5	60.4
Global	192.6	193.9	-1.2	541.6	319.2	222.5	813.9	427.0	386.9

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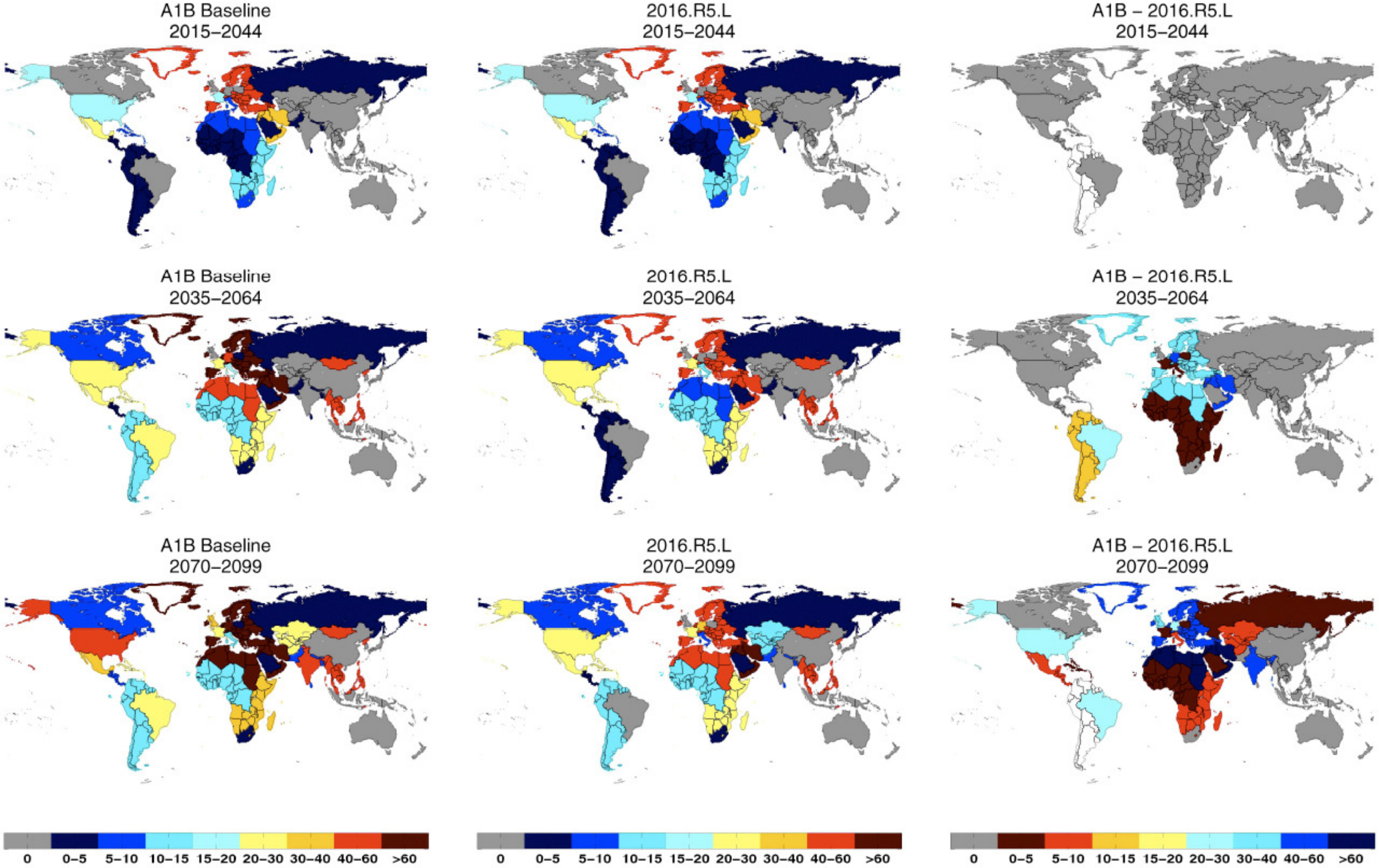
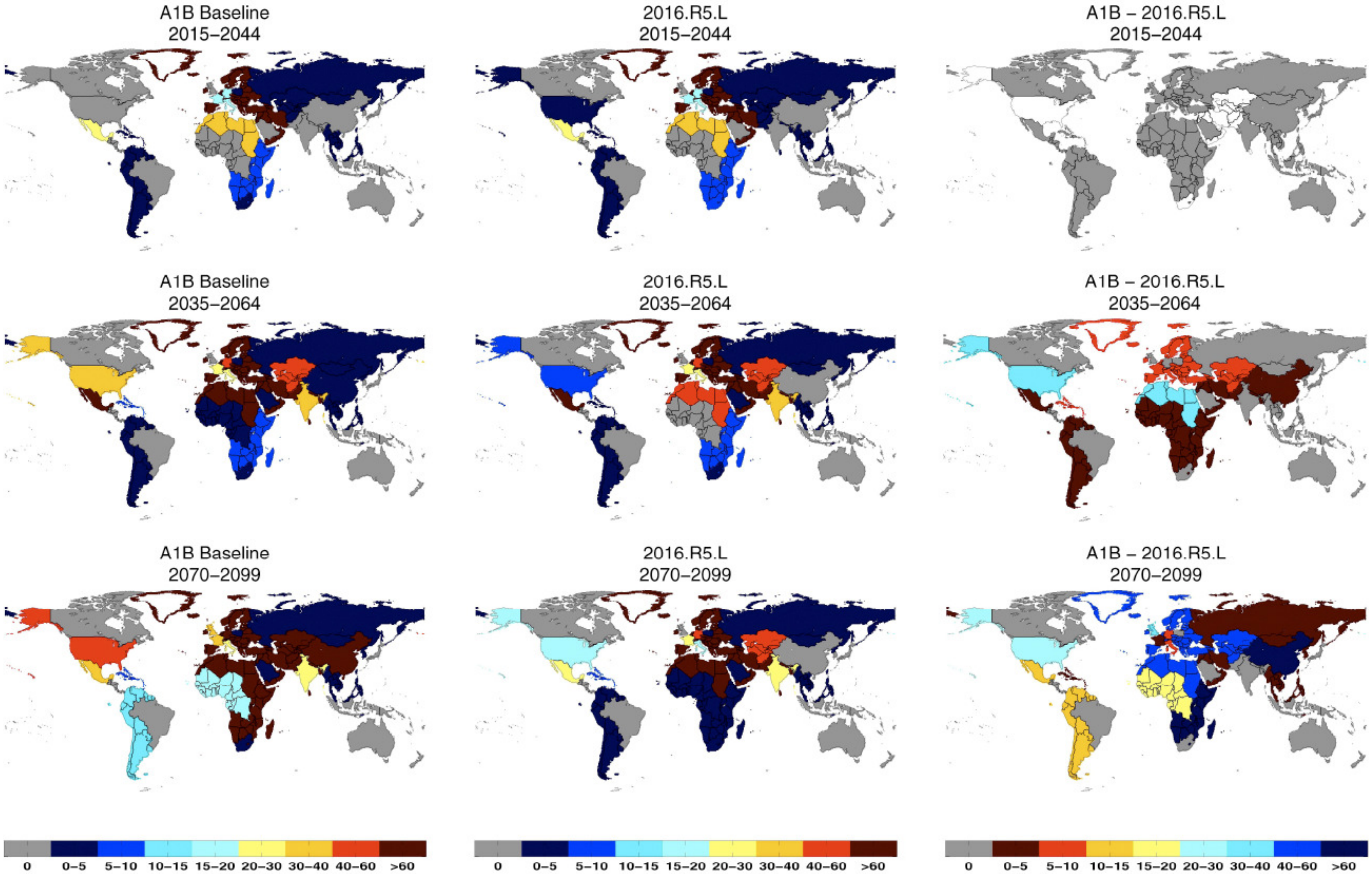
WITH EXCEPTION TO THE INTERIOR OF GREENLAND, WHITE AREAS EXPERINECE SUBTLE NEGATIVE AVOIDED IMPACTS (SEE TABLES FOR VALUES)



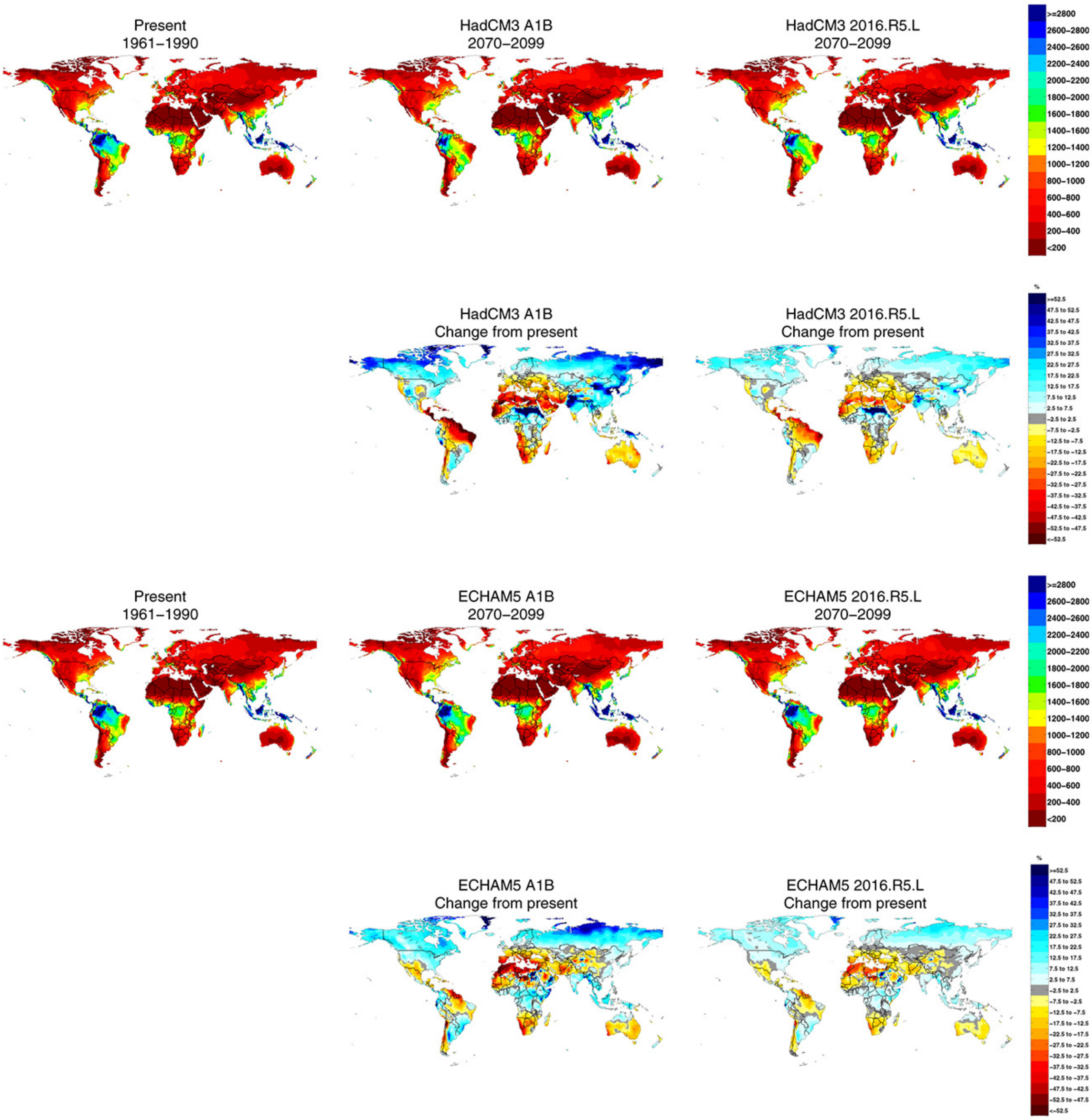
SENSITIVITY STUDY: 50% OUTCOME OF CLIMATE CHANGE SCENARIO 2016.R5.L AND ClimGen TUNED to ECHAM5: MILLIONS OF PEOPLE AT INCREASED RISK OF WATER RESOURCES STRESSES

	2015-2044			2035-2064			2070-2099		
Region	**A1B**	**2016.R5.L**	**A1B-2016.R5.L**	**A1B**	**2016.R5.L**	**A1B-2016.R5.L**	**A1B**	**2016.R5.L**	**A1B-2016.R5.L**
China	0.0	0.0	0.0	3.6	0.0	3.5	183.0	0.0	182.9
US	0.0	2.6	-2.6	38.4	7.4	31.1	41.8	16.3	25.5
Russia	0.1	0.1	0.0	1.1	1.1	0.0	1.2	1.0	0.1
Japan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Africa	0.8	7.8	-7.0	0.6	0.6	0.0	0.5	0.5	0.0
India	0.0	0.0	0.0	31.6	31.6	0.0	29.9	29.9	0.0
Brazil	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mexico	26.7	26.7	0.0	62.7	62.5	0.2	38.0	27.2	10.8
Canada	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Australia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Indonesia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
South Korea	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.3
UK	0.0	0.0	0.0	0.0	0.0	0.0	36.2	0.0	36.2
France	19.5	19.5	0.0	29.3	24.2	5.1	30.7	26.8	3.9
Italy	18.9	18.9	0.0	29.1	21.0	8.0	25.4	15.7	9.7
Germany	19.1	19.1	0.0	53.4	53.4	0.0	61.2	55.3	6.0
Poland	0.2	0.2	0.0	0.2	0.2	0.0	0.2	0.2	0.0
Saudi Arabia	0.0	0.0	0.0	0.4	0.4	0.0	0.5	0.5	0.0
Rest of South Asia	0.0	0.1	-0.1	265.8	265.7	0.1	291.3	291.3	0.0
Rest of East Asia	2.7	2.7	0.0	2.5	2.5	0.0	3.5	2.1	1.4
Rest of Central Asia	0.3	2.7	-2.4	46.3	40.6	5.6	108.2	55.5	52.7
North Africa	38.6	38.6	0.0	80.7	42.8	37.9	130.6	77.9	52.7
West Africa	0.0	0.0	0.0	4.6	0.0	4.6	19.1	0.3	18.7
Southern and East Africa	5.4	5.4	0.0	8.9	6.3	2.6	85.8	2.8	83.0
Europe	72.3	72.3	0.0	94.6	87.0	7.7	119.1	76.2	42.9
South America	0.5	0.5	0.0	1.4	0.6	0.8	11.7	1.4	10.3
Central America	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Caribbean	2.0	2.0	0.0	7.7	2.0	5.7	8.3	8.0	0.3
Rest of Australasia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Middle East	66.3	67.6	-1.3	124.7	123.2	1.5	121.7	120.9	0.9
Global	0.0	286.8	-13.3	887.7	773.3	114.3	1348.4	809.9	538.5

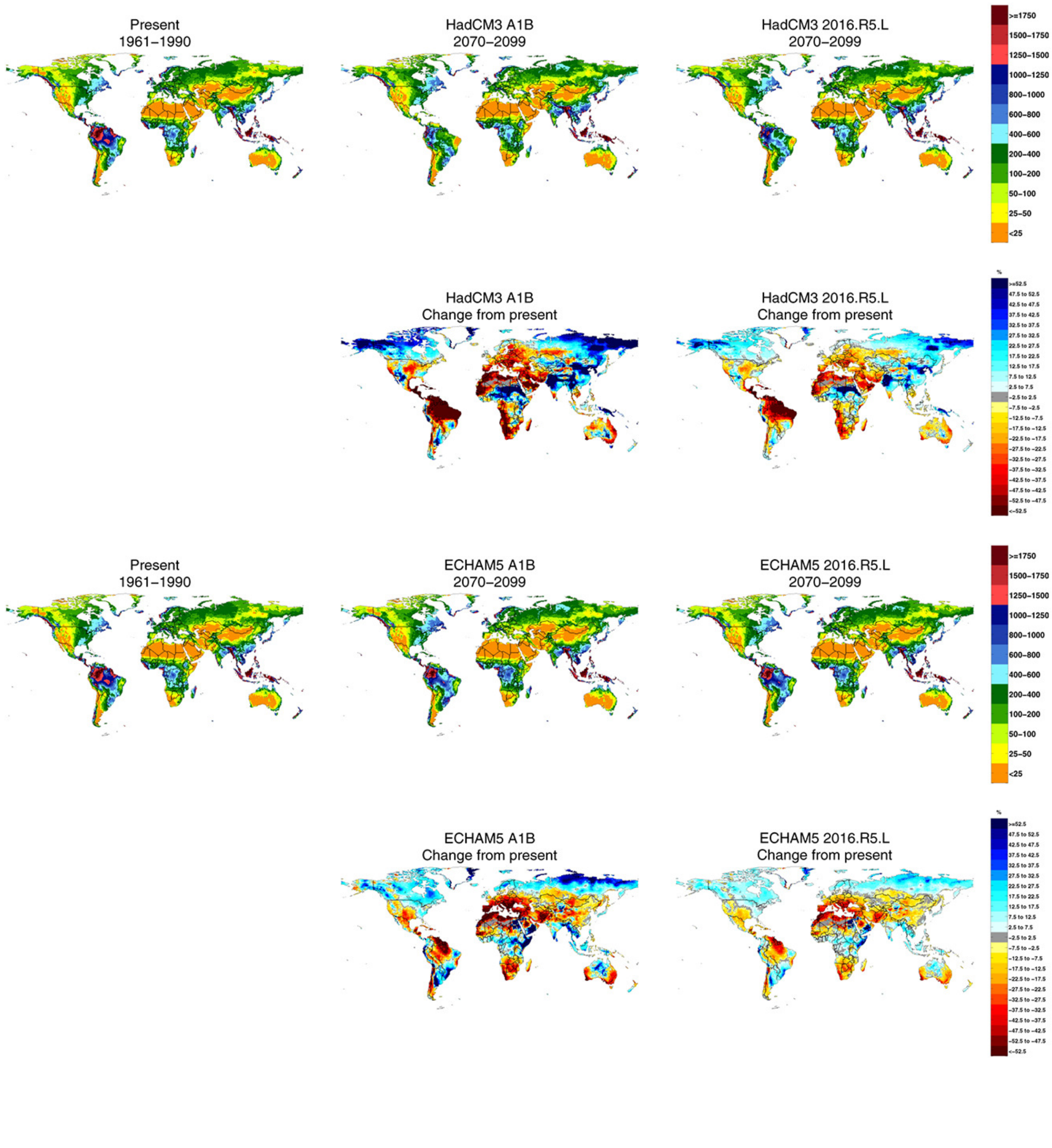
IMPACTS USING 50% (MEDIAN) CLIMATE CHANGE OUTCOME AND ClimGen TUNED to ECHAM5: MILLIONS OF PEOPLE AT INCREASED RISK OF WATER RESOURCES STRESSES WITH EXCEPTION TO THE INTERIOR OF GREENLAND, WHITE AREAS EXPERINECE SUBTLE NEGATIVE AVOIDED IMPACTS (SEE TABLES FOR VALUES)



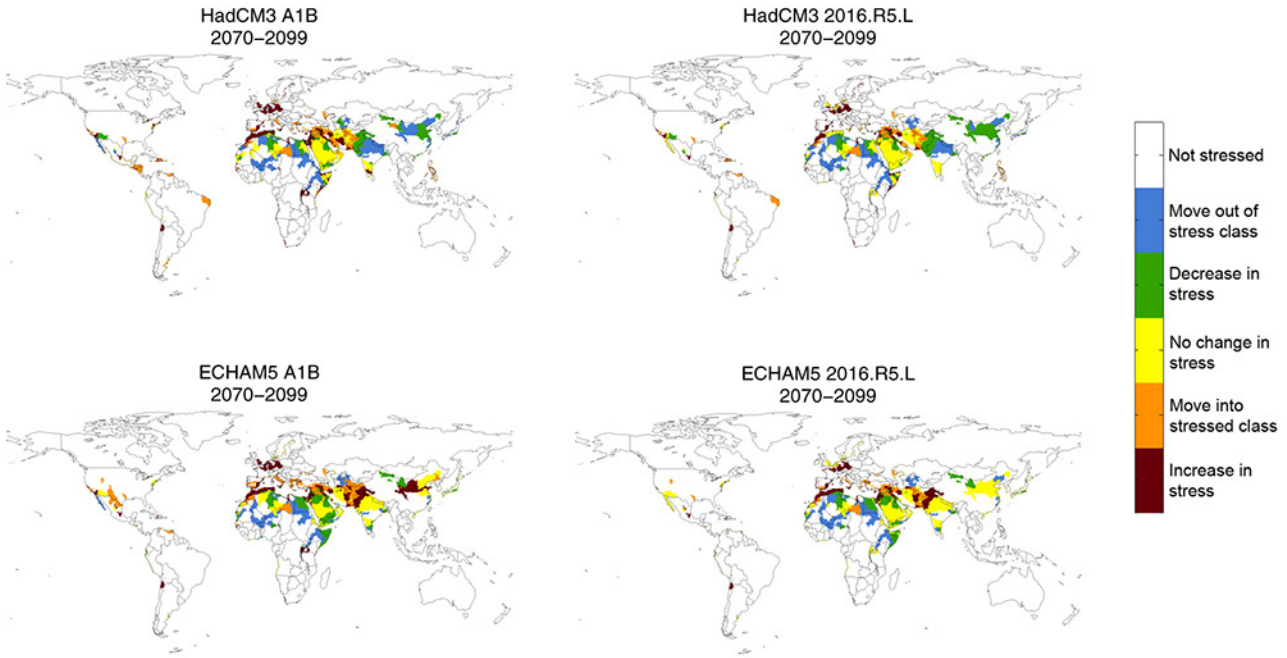
Precipitation. Present and scenario absolute values (1st and 3rd rows) and percentage changes from present (2nd and 4th rows).



Runoff. Present and scenario absolute values (1st and 3rd rows) and percentage changes from present (2nd and 4th rows).



Watersheds and changes in water stress (HadCM3, top; ECHAM5, bottom)



3.1.4 REFERENCES

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Revenga C, Brunner J, Henninger N, Kassem K, Payne N (2000) Pilot Analysis of Global Ecosystems: Freshwater Ecosystems. World Resources Institute and Worldwatch Institute, Washington, DC.

3.2 Implications of climate policy for global fluvial flooding

3.2.1 Methodology and indicators

Two indicators of the impacts of climate change on fluvial flooding have been defined. Both are calculated at the 0.5x0.5^{o} grid-scale level, and aggregated to the regional and global scale. Both are based on changes to the flood frequency curve at the 0.5x0.5 grid scale. The grid flood frequency curve under a defined climate is determined by fitting a generalised extreme value (GEV) distribution to the annual maxima from 30-year time series simulated using Mac-PDM.09 (see section 3 (i)). The differences in flood frequency curves under different climate scenarios are indicative only, for three main reasons:

(i) The hydrological model tends to underestimate the slope of the flood frequency curve (i.e. underestimate the magnitudes of relatively rare floods), largely due to the spatial and temporal resolution at which it works (this is common to most general hydrological models);

(ii) The flood frequency relationship for a grid cell is defined by the simulated hydrological behavioir just in that cell. For large floodplains, the flood frequency relationship at a point will be dependent on the propagation of floods from upstream, and this frequency curve may be different to the "local" frequency curve; in most cases, it is likely to be flatter than the local curve because the slope of the flood frequency curve tends to reduce as catchment size increases.

(iii) The climate scenarios characterise change in mean climate and change in year-to-year variability of total monthly rainfall. They do not characterise change in extreme short-duration flood-producing rainfall. Any changes in apparent river flood characteristics are therefore driven largely by changes in mean climate; the impacts of climate change are therefore likely to be underestimated.

The first indicator characterises the **numbers of people in a region exposed to an increase (or decrease) in flood hazard**. A grid cell has a substantial *increase* in flood hazard if the return period of the flood with a return period T in the absence of climate change reduces (the baseline T-year flood), and has a substantial *decrease* in flood hazard if the return period of the baseline T-year flood increases. The indicator is equal to the population living in grid cells within a region in which flood hazard increases or decreases, with the population expressed as a percentage of total regional population (because not all of the people within a region are exposed to flooding: it is assumed that the proportion of people within a grid cell actually exposed to flooding is equal across all grid cells). Specifically, the indicator reported here is based on the 20-year flood, and defines a substantial change in return period as plus or minus 50%. In other words, the population exposed to an increase in flood hazard live in grid cells in which the future return period of the baseline flood reduces to 10 years or less, and the population living in cells exposed to a decrease in flood hazard live in cells in which the baseline 20-year flood has a return period of 30-years or more under climate change. The impacts *avoided* by climate policy are defined as the percentage difference in exposed population between the policy and the reference (A1b) scenario. "Beneficial impacts" – fewer people exposed to an increase in hazard, or more people exposed to a reduced hazard – are positive, whilst "Adverse impacts" - fewer people exposed to a reduction in hazard, or more people exposed to an increased hazard – are negative.

The second indicator characterises the change in **regional average annual flood risk**, where flood risk[3] is effectively the average annual flood loss. This is calculated by combining for each grid cell

[3] "Risk" does not mean likelihood

the cell flood frequency curve with a generic flood magnitude-damage curve to calculate cell "average annual flood damage". Cell "average annual flood damage" is then multiplied by grid cell population and summed across a region to produce in effect a population-weighted average annual damage. This assumes that the proportion of people exposed to flood is constant across each grid cell. It also assumes that flood damages are proportional to population, not value of exposed assets. Weighting by GDP is feasible and would give different results, but would tend to underestimate the relative impact of flooding in poor regions. The generic magnitude-damage curve fixes damage to be zero at the return period at which damage begins, and 100 at a constant multiple of the flow at which damage begins. In the current analysis, it is assumed that damages begin at the (current) 20-year return period event, that the relationship between magnitude and damage is linear, and that flood protection measures prevent damages occurring in events with a (current) return period of 25 years (standard of service of 25 years). As implemented in this analysis, the indicator assumes no adaptation to changing flood frequencies. Adaptation will of course occur, so the indicator is best interpreted as characterising the sum of impact and adaptation.

The analysis here focuses on the HadCM3 climate model pattern.

3.2.2 Results and implications

- **Mitigation reduces, but does not eliminate, the impact of climate change on global exposure to flood risk, with little effect before 2050** (Figure F1). The magnitude of the effect depends more on the year at which emissions peak than on the rate at which they decline.With the climate model used, reducing emissions from 2016 reduces exposure to increased flood hazard by 2050 by approximately a third (globally), and reducing emissions from 2030 reduces exposure to increased hazard by around 10%. Effects of climate policy on exposure to decreased flood hazard appear to be minimal (in other words, there are – under this climate model pattern – no adverse effects of policy).

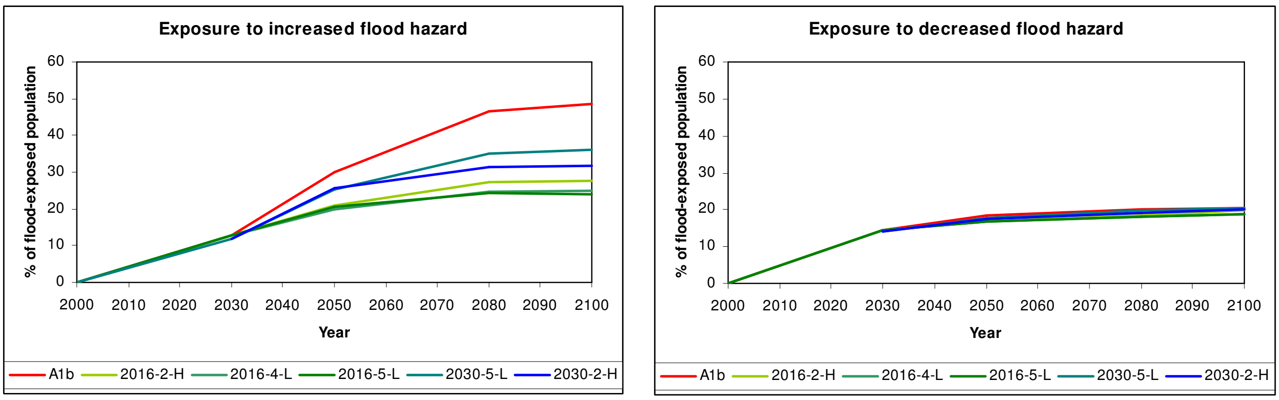


Figure F1: Global exposure to increased or reduced flood hazard (current 20-year flood has a future return period of 10-years or less, or 30-years or more respectively): HadCM3 climate model, A1b population

- **Mitigation reduces the impact of climate change on global flood risk** (Figure F2). The magnitude of effect depends more on the year at which emissions reductions begin than on the rate of decline in emissions. Under this indicator and climate model, reducing emissions from 2016 almost halves the effect of climate change on flood risk by 2050, and reducing emissions from 2030 reduces effects by a quarter.

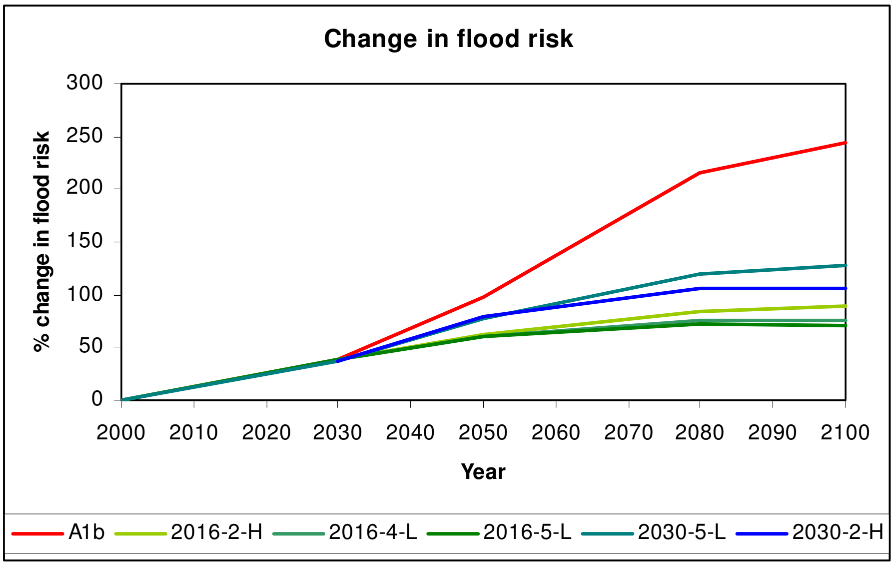


Figure F2: Global change in flood risk (damage begins at current 20-year flood, with protection to 50-year flood): HadCM3 climate model, A1b population

- **The estimated magnitude of the impact of climate change on flood risk, and of the impacts avoided by climate policy, are heavily influenced by assumed climate model** (Figure F3). For example, by 2050 under A1b emissions, the impact of climate change on global flood risk varies between 30 and 100% with four climate models. There is, however, slightly less range in the avoided impacts between climate models (Figure F4). There is also less range between models in estimated change in exposure to flood hazard.

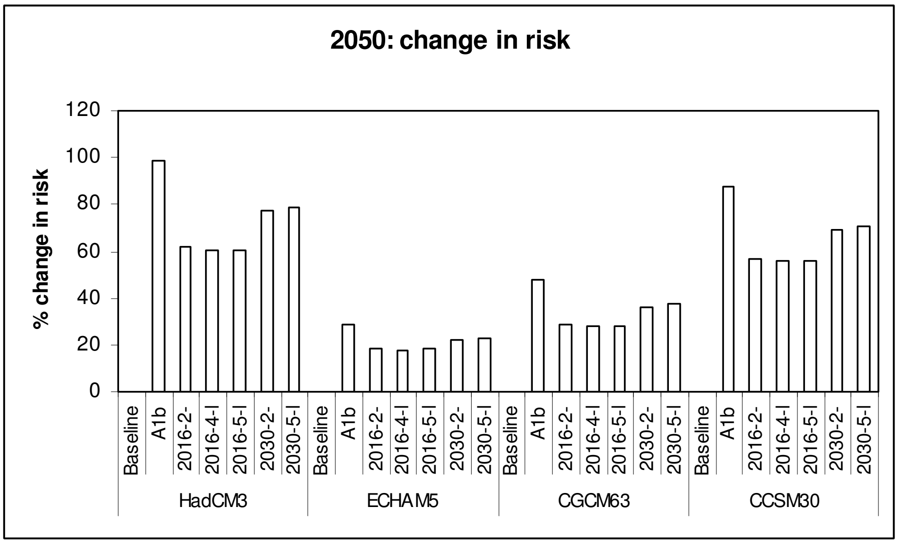


Figure F3: Effect of climate change and climate policy on global flood risk in 2050, under four climate models: change relative to baseline climate

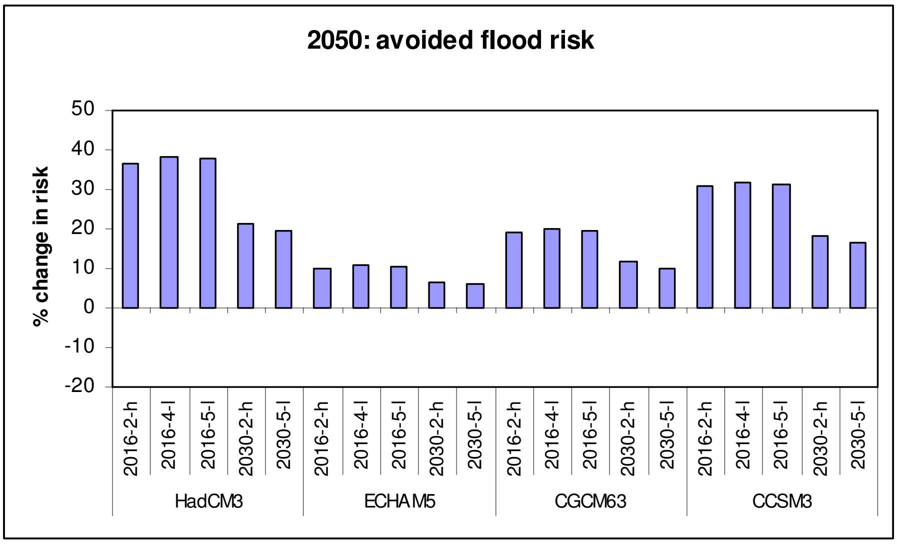


Figure F4: Impacts avoided by climate policy: percentage point change in global flood risk in 2050, compared to impacts under reference emissions.

- **The impacts of climate change, and the effects of climate policy, vary considerably between regions** (Table F1). Most of the increase in flood risk due to climate change – with HadCM3 – occurs in south and east Asia, and in some parts of the world (such as parts of Europe) flood risk decreases. By 2050, policies which reduce emissions from 2016 result in reductions in the numbers of people exposed to increased flood risk of between 3 and 60%, with the smallest avoided impacts in east Asia and the largest avoided impacts in south America. The regional consequences of policy also vary between clmate models (Figure F5). For example, by 2050, policies which reduce emissions from 2016 result in reductions in the numbers of people in China exposed to increased flood hazard of between 26 and 86%, across four different climate models. In other regions, avoided impacts vary considerably more.

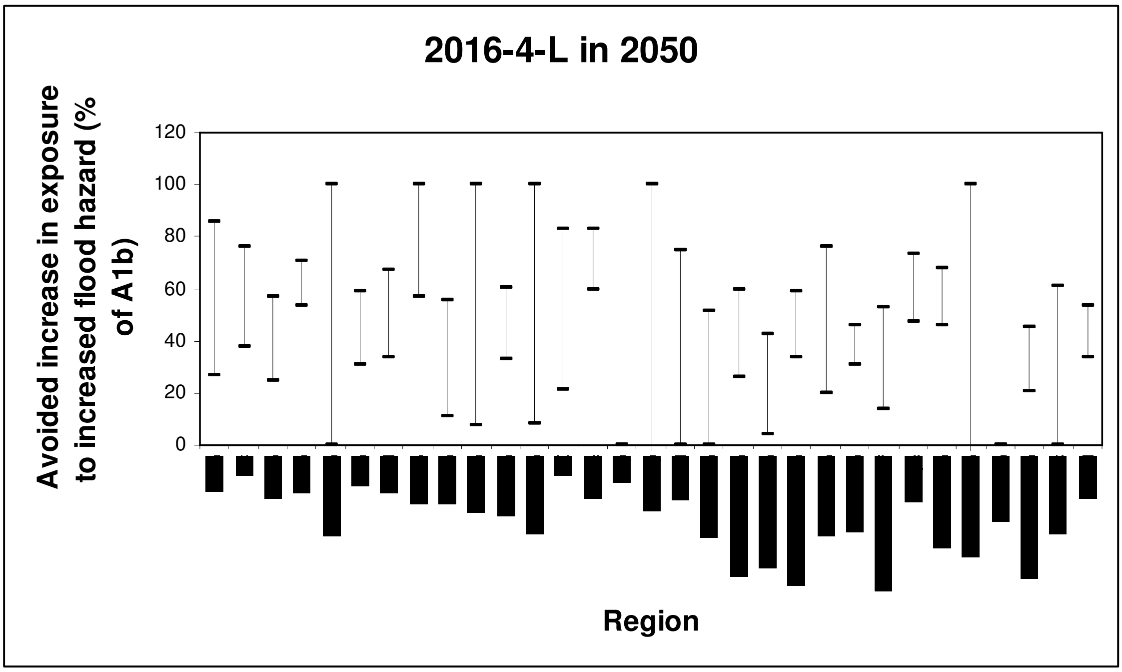


Figure F5: Range in avoided impacts in 2050, under 2016-4-L relative to A1b, across four climate models

Table F1: Regional avoided impacts on flood risk and exposure to flood hazard (HadCM3 climate model). For each indicator, the figures under the A1B column show the effect of A1b relative to no-climate change. For flood risk, the figures under each policy column show the percentage point change in risk relative to the A1B change; for flood exposure, the figures under each policy column show the percentage change in risk relative to the A1b change.

2030	Change in flood risk						Increased exposure to flood hazard						Decreased exposure to flood hazard					
	A1b	2016-2-h	2016-4-l	2016-5-l	2030-2-h	2030-5-l	A1b	2016-2-h	2016-4-l	2016-5-l	2030-2-h	2030-5-l	A1b	2016-2-h	2016-4-l	2016-5-l	2030-2-h	2030-5-l
China	76	0	-2	-2	4	4	21	0	-3	-3	5	5	2	0	-18	-18	-18	-18
US	-6	0	0	0	0	0	1	0	-8	-8	8	8	19	0	10	10	1	1
Russia	-25	0	-1	-1	-2	-2	3	0	-7	-7	11	11	57	0	-8	-8	-15	-15
Japan	54	0	-6	-6	4	4	12	0	10	10	63	63	1	0	360	360	380	380
South Africa	-12	0	1	1	1	1	0	0	0	0	0	0	23	0	-1	-1	-4	-4
India	74	0	0	0	2	2	24	0	-4	-4	3	3	2	0	24	24	24	24
Brazil	0	0	-1	-1	-1	-1	1	0	-54	-54	23	23	34	0	0	0	-3	-3
Mexico	-25	0	1	1	1	1	1	0	0	0	-120	-120	52	0	2	2	2	2
Canada	-9	0	-4	-4	0	0	1	0	0	0	0	0	30	0	-14	-14	6	6
Australia	-14	0	-1	-1	1	1	2	0	0	0	0	0	27	0	18	18	-8	-8
Indonesia	42	0	-4	-4	2	2	8	0	8	8	55	55	4	0	-24	-24	-38	-38
South Korea	226	0	-17	-17	-3	-3	81	0	3	3	1	1	0	0	0	0	0	0
UK	7	0	1	1	7	7	0	0	0	0	0	0	13	0	3	3	-29	-29
France	-7	0	2	2	2	2	1	0	21	21	71	71	22	0	31	31	-11	-11
Italy	-19	0	0	0	0	0	1	0	100	100	100	100	28	0	14	14	9	9
Germany	-35	0	0	0	0	0	0	0	0	0	0	0	46	0	-3	-3	-2	-2
Poland	-28	0	0	0	1	1	0	0	0	0	0	0	46	0	-8	-8	-3	-3
Saudi Arabia	-30	0	0	0	-1	-1	0	0	0	0	0	0	44	0	3	3	8	8
Rest of South Asia	94	0	-2	-2	6	6	28	0	1	1	7	7	1	0	-17	-17	-25	-25
Rest of East Asia	43	0	-2	-2	2	2	11	0	3	3	-1	-1	7	0	8	8	2	2
Rest of Central Asia	5	0	-2	-2	-1	-1	0	0	-100	-100	0	0	11	0	-18	-18	-6	-6
North Africa	-8	0	-1	-1	0	0	4	0	0	0	5	5	35	0	1	1	-5	-5
West Africa	37	0	-1	-1	2	2	9	0	-7	-7	6	6	8	0	-3	-3	0	0
Southern and East A	21	0	-1	-1	1	1	4	0	7	7	27	27	12	0	10	10	-4	-4
Europe	-24	0	0	0	0	0	0	0	50	50	-75	-75	45	0	-2	-2	-4	-4
South America	-8	0	0	0	0	0	2	0	13	13	-7	-7	27	0	-1	-1	-2	-2
Central America	-68	0	0	0	0	0	1	0	100	100	-29	-29	87	0	-1	-1	-3	-3
Caribbean	-51	0	1	1	0	0	0	0	0	0	0	0	86	0	-3	-3	-1	-1
Rest of Australasia	90	0	-1	-1	8	8	35	0	-2	-2	-1	-1	1	0	0	0	50	50
Middle East	-18	0	0	0	0	0	0	0	0	0	0	0	31	0	5	5	3	3
Global	38	0	-1	-1	2	2	13	0	-2	-2	6	6	14	0	1	1	-3	-3

A1b: % change in flood risk, or % exposed to increase/decrease in flood hazard

policy scenarios: figures show change in percentage point change relative to A1b (risk) or percentage change in exposure to hazard

Table F2	Change in flood risk						Increased exposure to flood hazard						Decreased exposure to flood hazard					
2050	A1b	2016-2-h	2016-4-l	2016-5-l	2030-2-h	2030-5-l	A1b	2016-2-h	2016-4-l	2016-5-l	2030-2-h	2030-5-l	A1b	2016-2-h	2016-4-l	2016-5-l	2030-2-h	2030-5-l
China	176	60	63	61	33	30	41	26	27	26	14	12	2	-33	-48	-48	-33	-43
US	1	2	4	4	1	2	8	46	50	49	28	27	34	-15	-14	-21	-19	-10
Russia	-23	4	4	4	3	3	6	24	26	21	13	10	64	2	1	1	5	5
Japan	133	49	52	50	22	26	55	49	54	52	29	27	0	25	25	25	25	25
South Africa	-12	1	1	2	1	2	0	0	0	0	0	0	34	-5	-5	-6	-1	3
India	180	63	66	65	38	35	48	28	31	30	16	14	5	-38	-44	-42	-2	-11
Brazil	23	15	14	15	10	7	19	63	67	65	50	41	34	-2	-2	-1	0	-2
Mexico	-32	-3	-4	-4	0	0	5	57	59	54	17	13	65	-10	-9	-11	-2	-2
Canada	-2	7	6	7	4	3	5	54	56	56	40	21	41	-10	-9	-7	-6	-8
Australia	-9	5	6	5	6	9	3	7	7	7	-4	0	32	-19	-21	-19	20	-17
Indonesia	111	39	45	45	22	21	43	27	55	53	13	17	3	-8	-15	-8	85	46
South Korea	540	169	165	189	68	71	100	3	8	5	0	0	0	0	0	0	0	0
UK	23	7	6	5	8	9	4	17	21	17	-62	-7	8	-53	-29	-35	-5	-67
France	5	8	6	7	4	-2	2	67	83	50	21	42	19	29	12	17	-1	20
Italy	-22	-3	-3	-3	-1	-3	0	0	0	0	0	0	46	-23	-20	-27	-4	-9
Germany	-44	-6	-4	-3	-3	-4	0	0	0	0	0	0	52	0	-3	4	3	-2
Poland	-36	-6	-8	-7	-7	-4	0	0	0	0	0	0	61	-8	-20	-7	-13	-3
Saudi Arabia	-41	-4	-4	-4	-2	-2	0	0	0	0	0	0	70	-11	-11	-11	-6	-5
Rest of South Asia	240	88	92	90	52	50	65	24	26	25	6	7	1	-21	-21	-21	0	0
Rest of East Asia	103	34	35	34	18	16	33	38	40	38	27	26	6	35	43	37	-13	-14
Rest of Central Asia	9	3	3	3	2	1	2	59	53	59	24	18	17	-11	2	2	22	-4
North Africa	-4	5	5	6	2	2	7	26	25	26	10	9	47	-15	-16	-12	-14	-9
West Africa	89	32	31	32	18	16	36	32	39	34	16	15	10	-11	-4	-8	-4	-8
Southern and East Af	57	20	22	21	13	12	20	49	53	51	30	24	14	-9	-4	-8	9	4
Europe	-29	-3	-3	-3	-2	-2	1	-17	50	17	-33	33	56	-8	-14	-10	-7	-7
South America	-6	3	3	3	-1	-1	9	66	68	68	53	49	33	-10	-8	-10	-7	-5
Central America	-78	-2	-4	-4	-1	0	0	100	-600	100	100	100	88	0	-3	-2	0	0
Caribbean	-67	-11	-10	-10	-2	-3	0	0	0	0	0	0	100	-8	-3	-8	-1	-3
Rest of Australasia	249	91	96	92	61	53	70	19	21	20	6	8	0	-100	-100	-100	200	-100
Middle East	-10	3	3	3	2	2	0	0	0	0	0	0	45	-11	-12	-10	-11	-12
Global	98	37	38	38	21	20	30	30	34	32	16	15	19	-9	-10	-10	-5	-6

Table F3

2080	Change in flood risk						Increased exposure to flood hazard						Decreased exposure to flood hazard					
	A1b	2016-2-h	2016-4-l	2016-5-l	2030-2-h	2030-5-l	A1b	2016-2-h	2016-4-l	2016-5-l	2030-2-h	2030-5-l	A1b	2016-2-h	2016-4-l	2016-5-l	2030-2-h	2030-5-l
China	355	195	209	212	141	161	67	43	46	47	29	34	2	-25	-19	-13	-13	13
US	21	22	22	22	17	20	14	37	57	58	30	37	37	-14	-17	-19	-2	-3
Russia	-7	17	18	18	14	15	9	37	42	40	22	26	72	-6	-8	-7	-5	-6
Japan	257	143	150	149	98	112	81	47	52	53	10	26	0	150	150	100	150	100
South Africa	-5	6	7	8	7	8	10	100	100	100	92	99	46	-12	-22	-24	1	-21
India	422	261	275	279	194	219	75	37	44	45	18	28	6	-15	-33	-27	-4	-9
Brazil	90	71	77	76	54	61	45	67	74	77	43	58	34	0	1	0	1	1
Mexico	-20	12	12	12	11	12	9	56	55	54	39	36	67	-4	-4	-5	-3	-4
Canada	15	20	20	21	15	13	13	63	69	75	52	56	51	-25	-26	-31	-22	-17
Australia	7	23	23	22	15	17	4	23	23	20	20	20	32	5	-6	13	9	24
Indonesia	271	168	181	181	130	146	81	50	58	56	27	33	2	169	144	175	75	163
South Korea	1140	634	662	693	433	495	100	1	0	0	0	0	0	0	0	0	0	0
UK	70	46	57	51	39	38	22	79	77	80	69	72	5	109	-50	28	-9	-32
France	46	45	42	44	30	38	26	92	94	94	85	88	13	28	62	37	28	30
Italy	-15	8	5	7	6	8	0	0	0	0	0	0	48	-16	-13	-3	-6	3
Germany	-37	7	5	6	9	10	0	0	0	0	0	0	54	-4	-4	-1	7	11
Poland	-33	-1	-2	-4	3	2	0	0	0	0	0	0	58	-2	-2	-7	13	5
Saudi Arabia	-48	-8	-9	-9	-3	-6	0	100	100	100	100	100	72	-6	-8	-8	-1	-1
Rest of South Asia	518	298	324	327	212	245	82	21	26	25	12	19	1	0	0	0	0	7
Rest of East Asia	221	130	135	139	92	108	47	41	49	50	19	32	7	-20	-30	-23	1	-16
Rest of Central Asia	21	16	16	16	11	11	3	43	50	57	27	33	20	-10	-9	-3	-2	-5
North Africa	9	20	18	19	12	14	8	29	31	35	14	20	50	-8	-13	-17	-10	-13
West Africa	196	117	124	126	88	98	59	43	49	50	27	33	11	-17	-16	-13	-7	-15
Southern and East Af	124	76	80	83	57	64	41	61	65	68	42	49	16	-11	-3	-6	1	-5
Europe	-25	2	2	2	4	2	3	62	85	77	65	50	57	-6	-7	-7	1	-4
South America	14	19	19	19	15	18	21	63	79	80	33	57	34	-12	-14	-9	-7	-10
Central America	-78	0	0	-1	3	2	0	0	0	0	0	0	84	2	2	4	4	6
Caribbean	-79	-11	-15	-14	-7	-10	0	0	0	0	0	0	100	-1	-2	-1	-2	-1
Rest of Australasia	633	408	426	432	290	343	83	15	18	20	7	9	0	0	0	0	0	0
Middle East	22	27	28	28	20	24	14	100	100	100	100	100	41	-10	-11	-12	-5	-6
Global	216	132	141	143	97	110	47	41	47	48	25	33	20	-8	-10	-10	-2	-5

Table F4

2100	Change in flood risk						Increased exposure to flood hazard						Decreased exposure to flood hazard					
	A1b	2016-2-h	2016-4-l	2016-5-l	2030-2-h	2030-5-l	A1b	2016-2-h	2016-4-l	2016-5-l	2030-2-h	2030-5-l	A1b	2016-2-h	2016-4-l	2016-5-l	2030-2-h	2030-5-l
China	404	228	252	257	165	201	72	42	48	49	29	36	2	7	-27	-13	0	47
US	28	27	29	29	21	25	15	50	55	61	36	42	37	-7	-15	-16	-1	-4
Russia	-1	21	25	25	17	22	10	37	43	47	22	24	72	-13	-7	-8	-4	-6
Japan	318	187	206	211	147	167	92	44	49	57	24	29	0	25	25	25	25	0
South Africa	1	13	14	14	9	14	14	100	100	100	88	100	45	-25	-14	-20	-13	-15
India	506	327	350	359	248	293	78	38	43	46	19	26	5	-16	-26	-28	10	0
Brazil	116	93	100	102	71	83	47	62	74	76	29	46	34	3	3	3	3	3
Mexico	-17	15	17	15	12	13	10	55	55	59	32	44	68	-5	-9	-6	-6	-5
Canada	22	25	27	26	19	24	14	64	70	70	49	54	51	-20	-26	-27	-25	-19
Australia	11	20	24	27	20	16	5	-61	41	41	39	39	34	-22	-18	-9	-2	-15
Indonesia	322	214	229	232	163	189	86	54	55	61	22	34	1	70	180	290	170	160
South Korea	1207	668	716	729	442	542	100	1	1	0	0	0	0	0	0	0	0	0
UK	82	60	65	70	48	52	31	87	88	84	80	84	5	55	20	-47	28	-28
France	58	54	54	53	35	51	18	84	86	92	-8	84	8	119	151	158	91	83
Italy	-13	8	8	6	7	7	1	-20	0	100	100	100	42	-11	-6	0	-1	15
Germany	-35	7	8	6	9	10	1	86	29	-214	100	43	52	-2	8	-2	2	14
Poland	-27	8	3	4	6	6	0	0	0	0	0	0	55	13	2	5	10	12
Saudi Arabia	-48	-8	-9	-9	-3	-4	1	100	100	100	100	100	71	0	-5	-7	0	1
Rest of South Asia	604	362	398	410	261	319	86	24	27	29	14	21	1	0	0	0	7	7
Rest of East Asia	260	160	174	176	120	143	49	35	48	53	16	36	6	10	-15	-15	27	7
Rest of Central Asia	24	17	21	20	13	15	4	57	68	66	48	55	20	-4	-4	-6	-3	-3
North Africa	13	25	26	25	18	21	9	35	38	39	22	27	46	0	-6	-5	-3	-4
West Africa	235	148	159	163	113	134	62	44	50	53	24	34	11	-8	-16	-14	-6	-10
Southern and East Af	146	95	102	104	72	84	45	59	68	69	36	53	16	-12	-5	-4	3	-10
Europe	-21	7	6	7	8	7	4	87	87	90	66	68	57	-1	-7	-6	-1	-1
South America	22	28	27	27	19	25	23	64	82	82	39	59	36	-7	-20	-20	-13	-10
Central America	-78	1	0	-1	1	2	0	0	0	0	0	0	86	-2	0	-1	2	-4
Caribbean	-84	-16	-16	-19	-9	-15	0	0	0	0	0	0	100	-4	0	-2	0	-1
Rest of Australasia	776	516	556	568	392	465	91	19	22	25	13	15	0	-33	33	-100	133	-100
Middle East	41	40	43	44	30	37	26	100	100	100	100	100	39	-5	-15	-14	-6	-8
Global	245	157	170	174	116	139	49	43	49	51	26	35	21	-4	-8	-8	-2	-3

4. AGRICULTURE AND FOOD PRODUCTION

4.1 Avoided change in land suitable for crops

4.1.1 Methodology and indicator

Climate change has the potential to alter the extent of land suitable for cultivation. Crops are dependent on climate – typically temperature, moisture availability and day-length - but land suitability is also influenced by topography and soil properties. This analysis uses a generic index of land suitability for cultivation developed by Ramankutty et al. (2002), and assesses both how the index varies with climate change, and the effects of climate policy.

The index has two main components (Ramankutty et al., 2002), and in this analysis is calculated at a spatial resolution of $0.5x0.5^{o}$. The climate suitability part is a function of mean annual growing degree days above $5^{o}C$ and the ratio of actual to potential evaporation. In this analysis, this is calculated from current and future climate data. The soil suitability part is a function of soil organic carbon content and soil pH. In this analysis, soil organic carbon content and pH are taken from the ISRIC WISE soil data base (v1.0: Batjes (1996)), and are assumed constant. Soil organic carbon content is projected to decrease under climate change, which would decrease land suitability further *(this effect can be incorporated in later simulations).*

The land suitability index does not account for actual production, but rather indicates whether the characteristics of the land allow for cultivation. In practice, only just over 40% of the land which could be cultivated is actually currently under cultivation (Ramankutty et al., 2002). Changes in the land suitability index therefore only give a broad indication of changes in cultivation potential.

The analysis here focuses on (i) change in the area of land suitable for cultivation (where land is suitable when the index is greater than 0.1) and (ii) change in the suitability of land for cultivation (where the suitability index changes by more than 5%). Most of the analysis is based on regional climate changes as simulated by HadCM3.

4.1.2 Key results

- **Climate change tends to increase land suitability at high latitudes (due to higher temperatures), but decrease suitability in many dry tropical and subtropical regions (due to lower moisture availability).** The net effect is to increase the area of land potentially suitable for cultivation (except under high temperature increases).

- **Climate policy reduces the effect of climate change on land suitability**. Figure 1 shows change (decreases and increases) through the 21st century in the global area of land suitable for cultivation. Policies with an emissions peak in 2016 reduce the area which becomes unsuitable by approximately 40% in 2050, and by over 60% by 2080. Policies with an emissions peak in 2030 have a smaller, but still substantial, effect. Policies have less effect on the area of land which becomes suitable for cultivation. Climate policies have less (proportional) effect on overall suitability for cultivation (Figure 2) than on area suitable for cultivation.

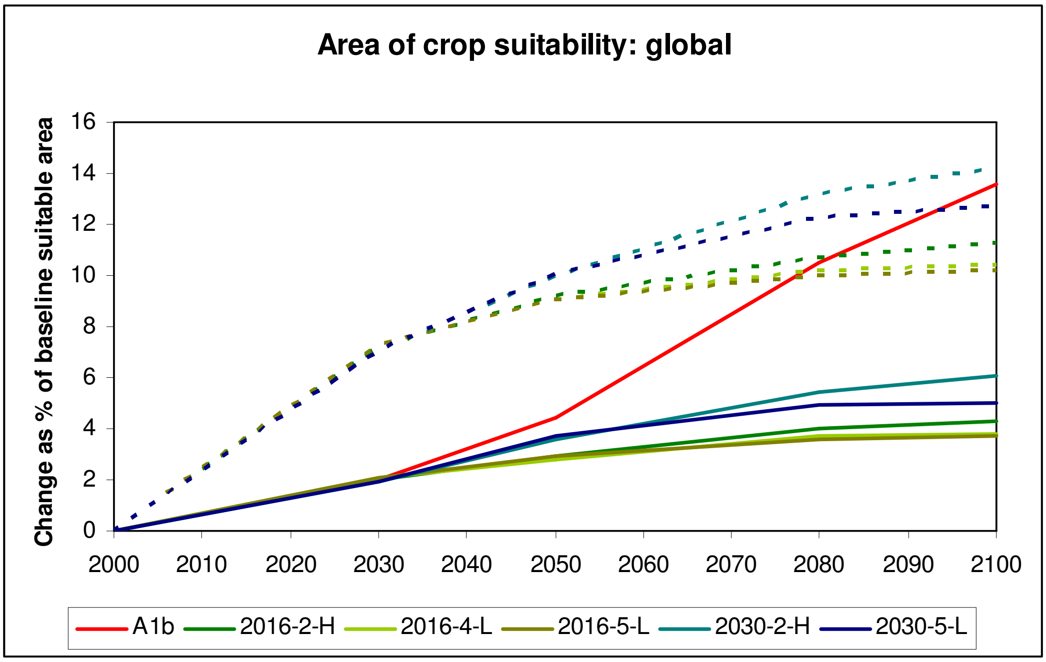


Figure 1: Change in global area of crop suitability (HadCM3 pattern), expressed as a percentage of area of crop suitability in the absence of climate change. Solid lines: area no longer suitable for crops; dashed lines; area which becomes suitable for crops.

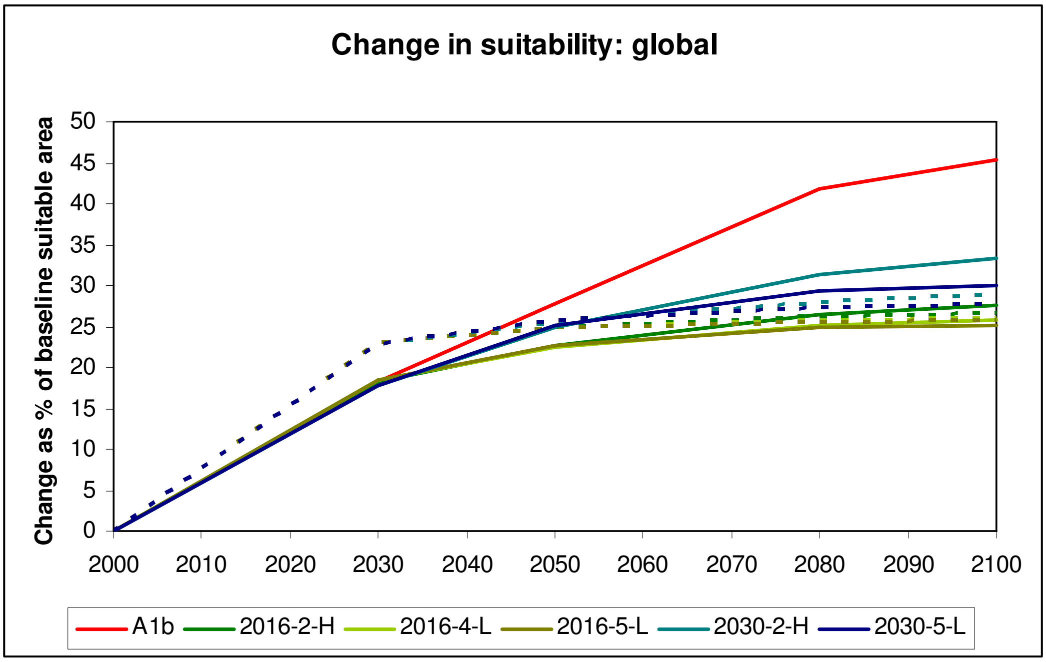


Figure 2: Effect of climate change on suitability of land for cultivation (HadCM3 pattern), expressed as a percentage of area of crop suitability in the absence of climate change. Solid lines: area where suitability index decreases by more than 5%; dashed lines; area where suitability index increases by more than 5%.

- **There is a strong regional variability in avoided changes in land suitability**. Dry regions are most adversely affected by climate change, and obtain the greatest relative avoided impacts. This is shown in Figure 3, which reproduces Figure 1 for southern and eastern Africa.

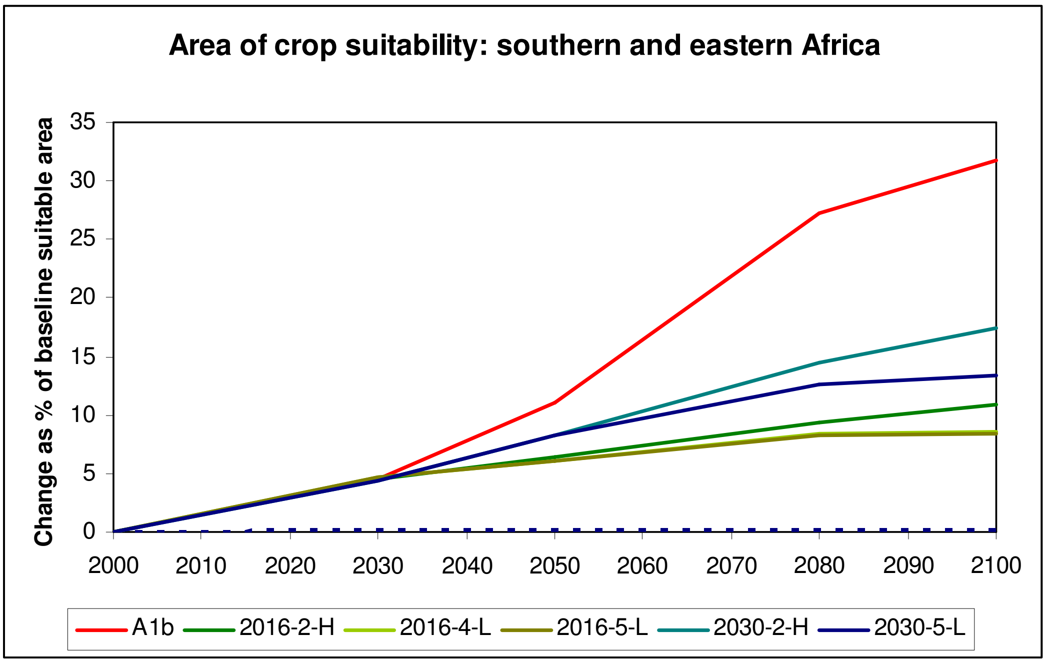


Figure 3: Change in area of crop suitability in southern and eastern Africa (HadCM3 pattern), expressed as a percentage of area of crop suitability in the absence of climate change. Solid lines: area no longer suitable for crops; dashed lines; area which becomes suitable for crops.

- **The absolute magnitude of the effect of climate change and climate policy on land suitability differs between climate models, but the general direction of effect is consistent.** Figure 4 shows the proportion of current land suitable for cultivation with a decline in suitability in 2050, under five climate models.

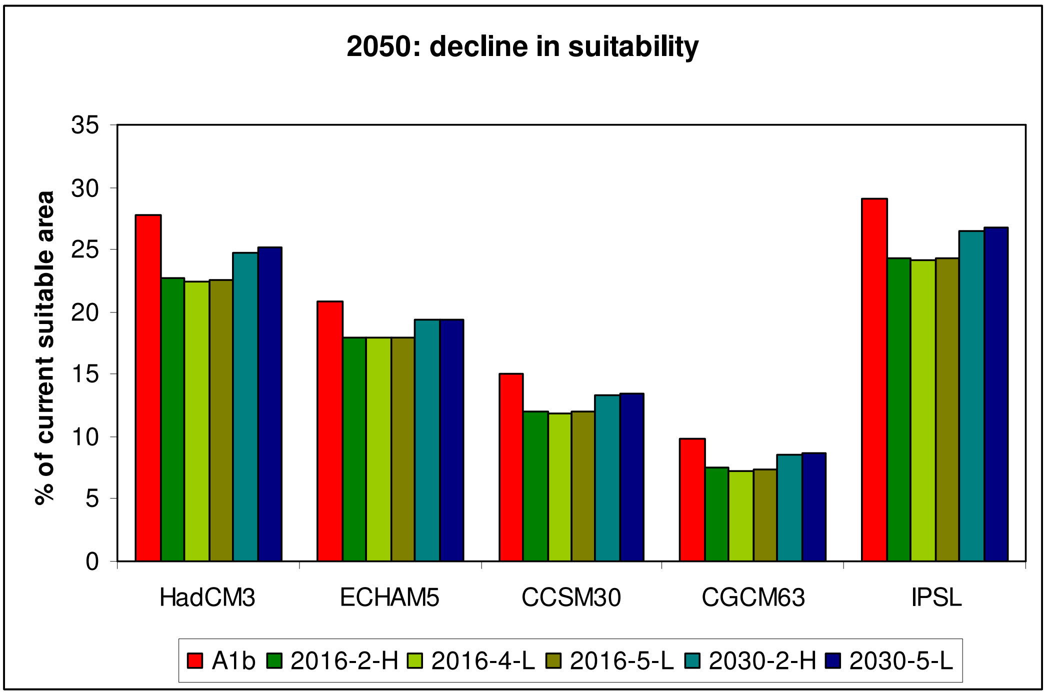


Figure 4: Percentage of land suitable for cultivation with a decline in suitability: 2050, five climate model patterns

4.1.3 References

Batjes, N.H. (1996) Documentation to ISRIC-WISE global data set of derived soil properties on a ½ by ½° grid (Version 1.0). Working Paper and Preprint 96/05, International Soil Reference and Information Centre (ISRIC), Wageningen.

Ramnkutty, N., Foley, J.A., Norman, J. & McSweeney, K. (2002) The global distribution of cultivable lands: current patterns and sensitivity to possible climate change. *Global Ecology and Biogeography* 11, 377-392.

4.2 Avoided impacts on food production

4.2.1 Methodology and indicators

The effects of climate policy on food production are indexed by simulating changes in productivity and production of soybean. Soybean is a major global crop, producing both protein and oil. Much of the protein is used in animal feed. Soybeans grow in climates with hot summers, and although are native to east Asia, over half of global production takes place in North and South America.

The yield (*productivity*) of soybean is simulated using the GLAM crop growth model (see Challinor et al., 2004 for a description of the groundnut version of the model), working at a spatial resolution of 0.5x0.5^{o}. GLAM simulates the yield of three different maturity groups/varieties, under rainfed or irrigated conditions, and incorporates the effect of CO_2 enrichment on plant growth. The model works on a daily time step, and simulates 30 years of data; the indicator used here is the mean yield across all 30 years. The analysis here focuses on rainfed production, and it is assumed that at each location the most productive of the three varieties is grown. No explicit adaptation to climate change is assumed - sowing and harvesting dates are assumed to remain unchanged from the baseline – although expansion of production into previously unsuitable areas is simulated.

Changes in *production* due to climate change are estimated by assuming that the same area is planted in each grid cell in which production is feasible, and calculating total regional "production" under a climate scenario with "production" in the absence of climate change. In reality, of course, different areas are grown in each grid cell, but the effects of this on change in regional production are likely to be small. The changes in potential production, however, are to be regarded as indicative only - they also do not take changes in market demand for the product.

4.2.2 Key results

- **Climate change leads to a general reduction in soybean yield and production, and mitigation reduces slightly this decrease in production**. Figure 1 shows change in yield per hectare in 2050 under A1b, A1b-2016-5-L and A1b-2030-5-L, relative to yield with current (1961-1990) climate. Whilst there are some areas of increase in productivity and an expansion into some areas (e.g. parts of India), productivity declines, as does total global production (Figure 2). Under A1b, total production decreases by approximately 25% compared to the situation without climate change. Mitigation reduces the decrease slightly.

- **The consequences of climate policy on production reflect a complex relationship between climate change and CO_2 concentration.**. A policy with peak emissions in 2030 has a similar effect on potential production in 2050 than a policy with emissions peaking in 2016 (Figure 2), even though the effect of the policy on climate change (as indexed by temperature and rainfall change) is smaller. This is because CO_2 concentrations in 2050 are higher under the 2030 peak than under the 2016 peak, and the effect of these higher concentrations offset the effect of the greater amount of climate change. This complex relationship changes through the 21st century as the relative contributions of CO_2 enrichment, higher temperatures and altered rainfall change. By 2080 (Figure 2), the greater beneficial effect of policies peaking in 2016 rather than 2030 are apparent.

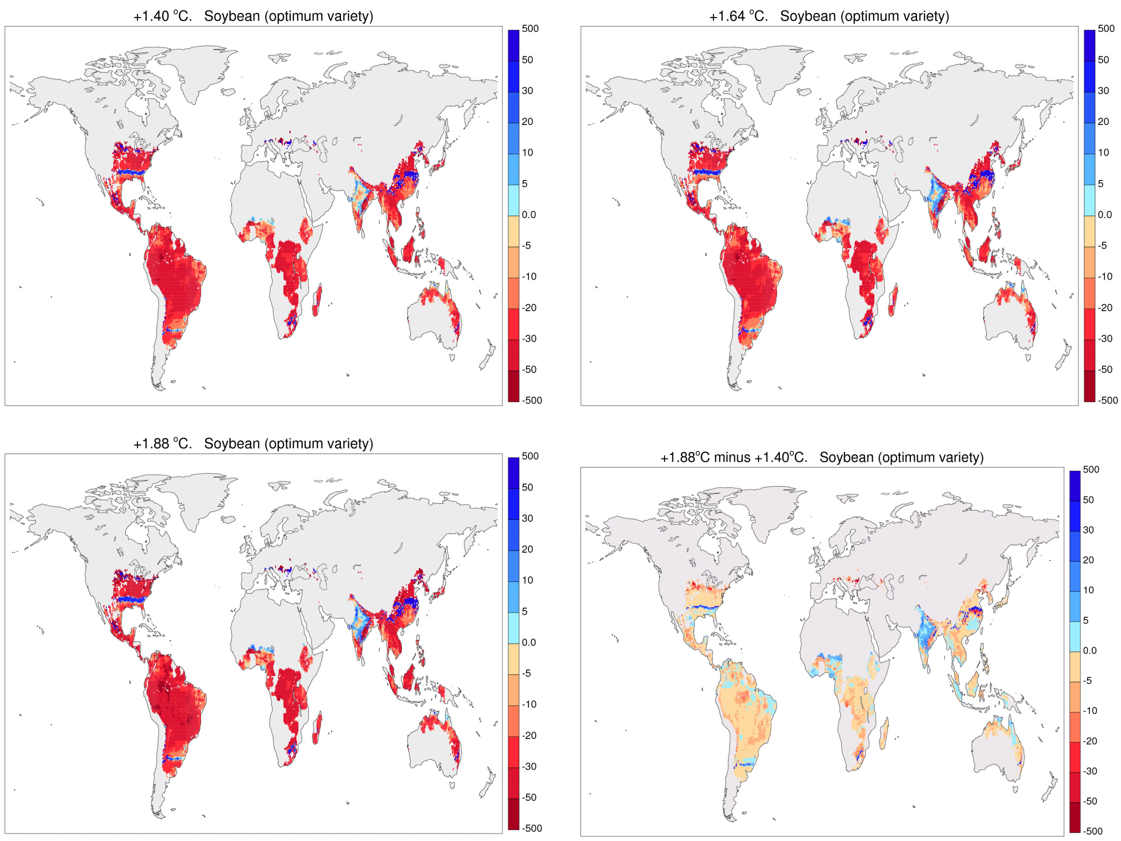


Figure 1: Change in soybean productivity (yield in kg/hectare) in 2050, relative to situation without climate change. A1b (bottom left), A1b-2016 (top left), A1b-2030 (top right), and difference between A1b and A1b-2016 (bottom right).

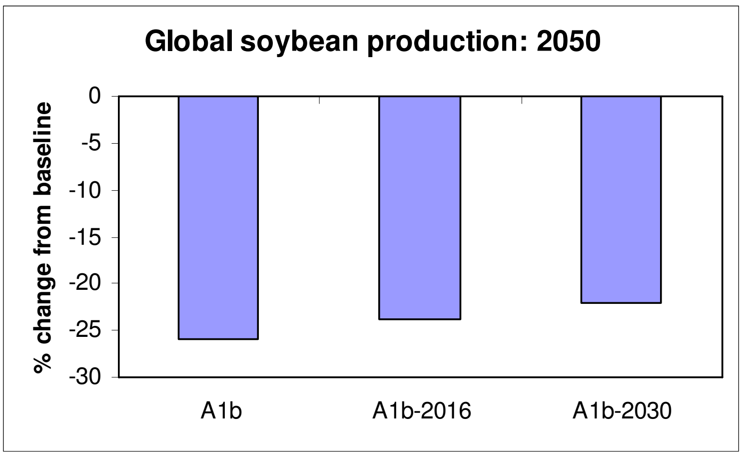


Figure 2: Indicative change in global production of soybean maturity group 3 in 2050 (HadCM3 climate model pattern).

Challinor, A.J., Wheeler, T.R., Craufurd, P.Q., Slingo, J.M. and Grimes, D.I.F. (2004) Design and optimisation of a large-area process-based model for annual crops. *Agricultural and Forest Meteorology*, 124, 99-120.

4.3 Global scale impacts on aquatic ecosystems under defined climate policies

4.3.1 Methods

Additional AVOID future climate scenario runs were examined within the 'vulnerability analysis' framework for aquatic ecosystems. This is an indicator-based country-by-country analysis, based on the IPCC/Millennium Ecosystem Assessment vulnerability assessment framework, (Adger 2000; IPCC, 2001) to determine the sensitivity of marine and freshwater fisheries sectors to climate change, thereby identifying climate change vulnerability 'hot spots' (Allison et al., 2009).

Estimates of country-level (AVOID region) vulnerability were developed based upon two components:

- Potential Impact (PI), a composite of:
  - the sensitivity of countries to changes in their aquatic provisioning services, and
  - their exposure to climate change in terms of temperature change
- The adaptive capacity of the country (AC), i.e. their capability to adapt to changing conditions

Sensitivity

We assume that sensitivity is represented by 'fisheries dependence'. We consider this to be the importance of fisheries to national economies and food security. Data for fisheries production (landings) were obtained from the UN FAO FishStat database and the Seas Around Us project (SAUP; http://www.seaaroundus.org/). Projections of future catch are not readily available, and hence the assumption had to be made that the relative geographic distribution and magnitude of catches by country remains constant into the future.

Landings were sub-divided geographically and sectorally which allowed geographical variation in exposure to be incorporated. The sub-divisions were:

1) freshwater catches (FAO data);
2) catches within the Exclusive Economic Zone (EEZ[4]) of a country (SAUP data), and
3) catches caught on the high seas (outside EEZs, SAUP data).

Exposure

We related exposure to the change in climate at the country (sector) level over set periods. Temperature data were estimated under the AVOID scenarios. We assumed that the relevant estimated land surface temperatures would directly affect freshwater fisheries. In contrast, marine fisheries would be affected by corresponding sea surface temperatures.

Average temperatures for the relevant time periods and AVOID scenarios were calculated based upon the borders of the country (freshwater catches), borders of the relevant EEZ area (EEZ catches) or the borders of the FAO high seas areas (high seas catches), through GIS. Where any of these did not encompass an entire temperature grid square (e.g. country-level temperatures for small island developing states), the temperature used was taken from the square whose centroid was closest to the centroid of the country.

The exposure was taken as the change in temperature from the baseline period 1961- 1990.

[4] The Exclusive Economic Zone (EEZ) is usually the area encompassed within 200 nautical miles from the coastline.

Potential impact

The potential impact of climate change (PI) was calculated as sensitivity *x* exposure. Potential impact was calculated based upon the marine component (EEZ and FAO high seas area) and total (freshwater, marine, high seas). It was calculated as a weighted average of the components included, scaled by the level of catch within each component. For example, the total PI for each country was calculated as:

$$PI_{total} = ((S_{freshwater}*E_{freshwater})+(S_{EEZ}*E_{EEZ})+(S_{highseas}*E_{highseas}))/\text{Total S}$$

In this way, the component of a country's fishery and its corresponding temperature change (E) would receive the highest weighting within the PI calculation.

As countries may fish in more EEZs than just their own, and more than one high seas area, these component were themselves weighted by the proportion of the total catch taken by a country in each EEZ/high seas area, and the corresponding temperature change.

Resulting PIs were then normalised through appropriate transformations and rescaled to a range from 0 and 1, with higher values representing higher potential impact.

Adaptive capacity

Adaptive capacity recognises the potential for a country to change its processes in order to adapt to a changing climate. As adaptive capacity will change into the future, we attempted to capture this by basing our primary adaptive capacity metric on the IMAGE 2-3 scenarios used to drive the Global Climate Models. Therefore, the underlying country-level IMAGE 2-3 data for per capita GDP under the A1 scenario (all AVOID scenarios relating to this 'reality'). This reflects the ability of particular nations to 'buy their way' out of trouble in face of the degree of potential impact expected. In a sense, it reflects the ability of countries to buy in protein from other sources, or subsidise fishers when changing fishing practices, for example. These GDP data are provided by decade.

Note for overseas dependent territories, it was assumed that the corresponding adaptive capacity was that of the 'mother' country.

Adaptive capacity by country was first normalised using an appropriate transformation, and scaled between 0 and 1, with values closer to 1 reflecting greater adaptive capacity.

Vulnerability

Based upon the above scenarios, we calculated the vulnerability of nations to fisheries impacts potentially resulting from climate change, as Vulnerability = PI-AC.

4.3.2 Results

Results are presented for the different AVOID policy scenarios for the periods 2020s, 2050s and 2080s. Initially, potential impact at the country level in both the marine sector and the total aquatic sector (freshwater, EEZ, high seas) are presented (Figures 1 and 2 respectively). The resulting country-or region-level vulnerability (PI-AC) for each sector is then presented (Figures 3 and 4).

The AVOID country/region arrangement means the outputs for individual countries are compared against world regions. This should be recognised when viewing the results. For example, while individual countries within AVOID regions may have more extreme impact values, the effect will be reduced by the averaging process during the calculation of potential impact and vulnerability for the region as a whole. Note also that the 'Rest of Central Asia' region does not have a marine catch (being landlocked). Other landlocked countries are included within regions that have coastal countries (e.g. West Africa). In this case, the marine potential impact value is based upon the temperature changes and catches from those coastal countries alone, since potential impact is scaled by country catch levels.

Potential impact

Marine potential impact due to future climate change appears relatively unaffected by assumptions underlying the alternative AVOID scenario runs. Changes between runs and time periods are generally very minor (see Appendix 1 and Figure 1), with very small increases in scaled PI over time.

The major marine sector potential impacts lie in the Middle East (in particular Saudi Arabia), China and Poland. This appears consistent over time and AVOID scenario. Notable impacts are also experienced in Italy, Mexico, Japan, South Korea and the North Africa and South America AVOID regions. It is notable that Brazil (one of the specific countries examined) shows a quite different level of impact to the rest of the region, reflecting either low marine catches, or an effect of the 'averaging' required for computation within the 'South America' region. Relatively minor impacts are experienced in Canada and the Southern and Eastern Africa region.

Greater differences are seen when looking at the total potential impact, which includes freshwater catches and hence is related to land surface temperatures. Values remain relatively consistent between scenarios, with the main differences occurring under the A1b-2030-2-high scenario when compared with the other runs. Potential impacts are higher in this scenario for many countries.

For the total potential impact, which includes freshwater catches, the greatest impact is consistently experienced in the 'Rest of Central Asia' region. This is due to not only the relatively high temperature change in this area, but also their sole reliance on freshwater catches (i.e. they are not 'buffered' against change by the opportunity of fishing in marine waters), which increases their vulnerability. Notable potential impacts are also experienced in China, Saudi Arabia, and increasingly South America, Brazil and Mexico, as well as North Africa and West Africa, dependent on the AVOID scenario.

Vulnerability

Both marine and total vulnerability are again relatively consistent between AVOID scenario runs. Over time, generally increasing adaptive capacity means that country level vulnerability values decrease.

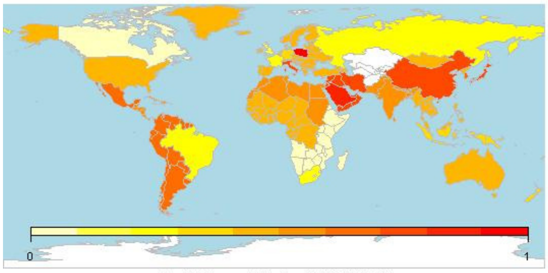
The marine sector vulnerabilities by country reflect more clearly the limited adaptive capacities of some African and Asian nations. Greatest vulnerabilities are found in China, Poland, Mexico, Northern and Western Africa, with also India, the Middle East and Saudi Arabia, and to a lesser extend the Southern America region. Over time, however, the projected increasing economy of China leads to a decrease in the level of vulnerability relative to the African (particularly West African) nations. Canada, USA, Australia, UK, France and Germany appear the least vulnerable countries.

As for potential impact, the main difference for total vulnerability occurs under the A1b-2030-2-high scenario when compared to the other runs, with higher vulnerability values for many countries.

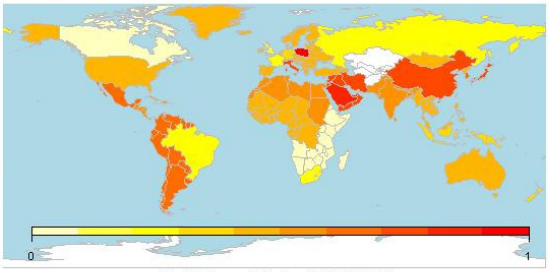
When considering total vulnerability, taking into account the freshwater potential impacts, the 'Rest of Central Asia' region appears consistently the most vulnerable over time. China is initially vulnerable, but as noted above shows increasing adaptive capacity with time, reducing its vulnerability to similar levels as Southern American and South and East Africa. West and Northern Africa remain vulnerable, along with India and the Middle East region to a lesser extent, dependent upon the AVOID scenario. Canada, USA, Australia, UK, France and Germany appear the least vulnerable countries, with the 'Europe' region and the Rest of East Asia improving over time.

2020s

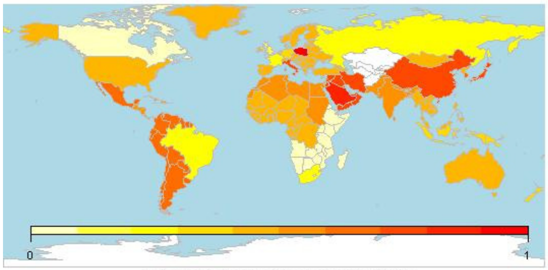
potential impact Marine 2020s ref



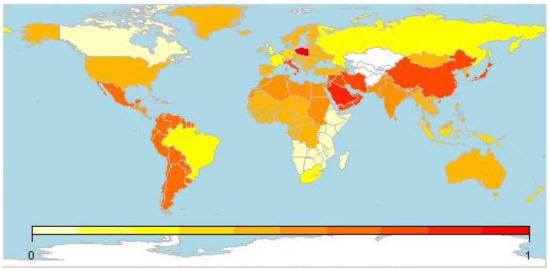
potential impact Marine 2020s 2016_2high



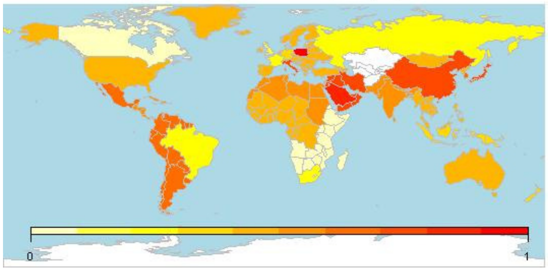
potential impact Marine 2020s 2016_4low



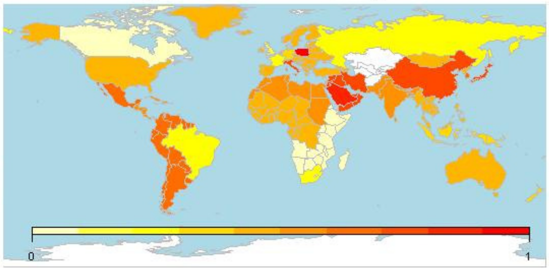
potential impact Marine 2020s 2016_5low



potential impact Marine 2020s 2030_2high

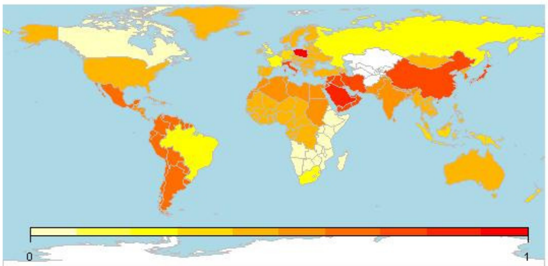


potential impact Marine 2020s 2030_5low

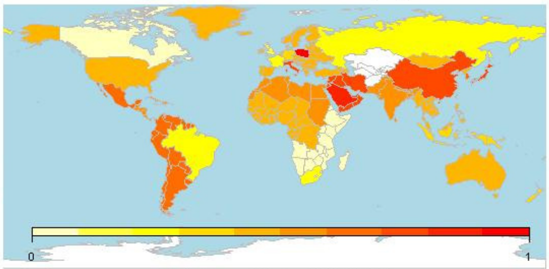


2050s

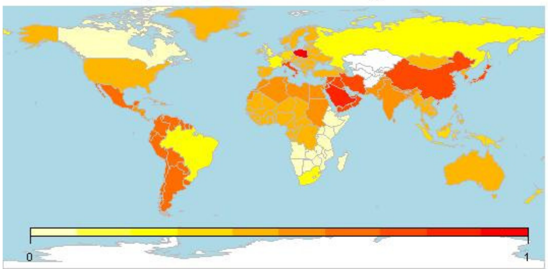
potential impact Marine 2050s ref



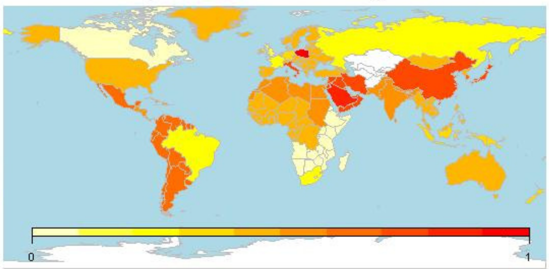
potential impact Marine 2050s 2016_2high



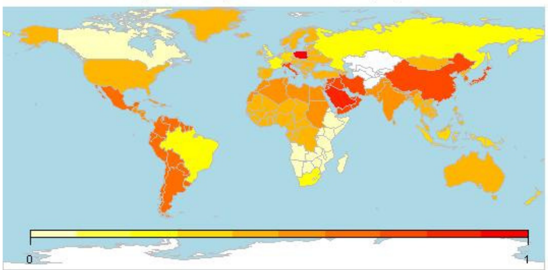
potential impact Marine 2050s 2016_4low



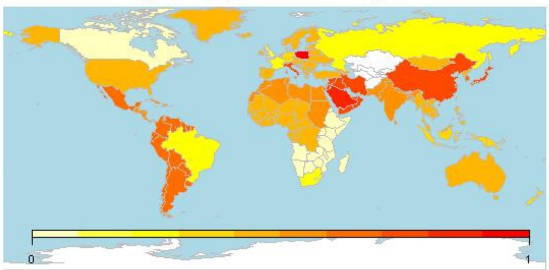
potential impact Marine 2050s 2016_5low



potential impact Marine 2050s 2030_2high



potential impact Marine 2050s 2030_5low



2080s

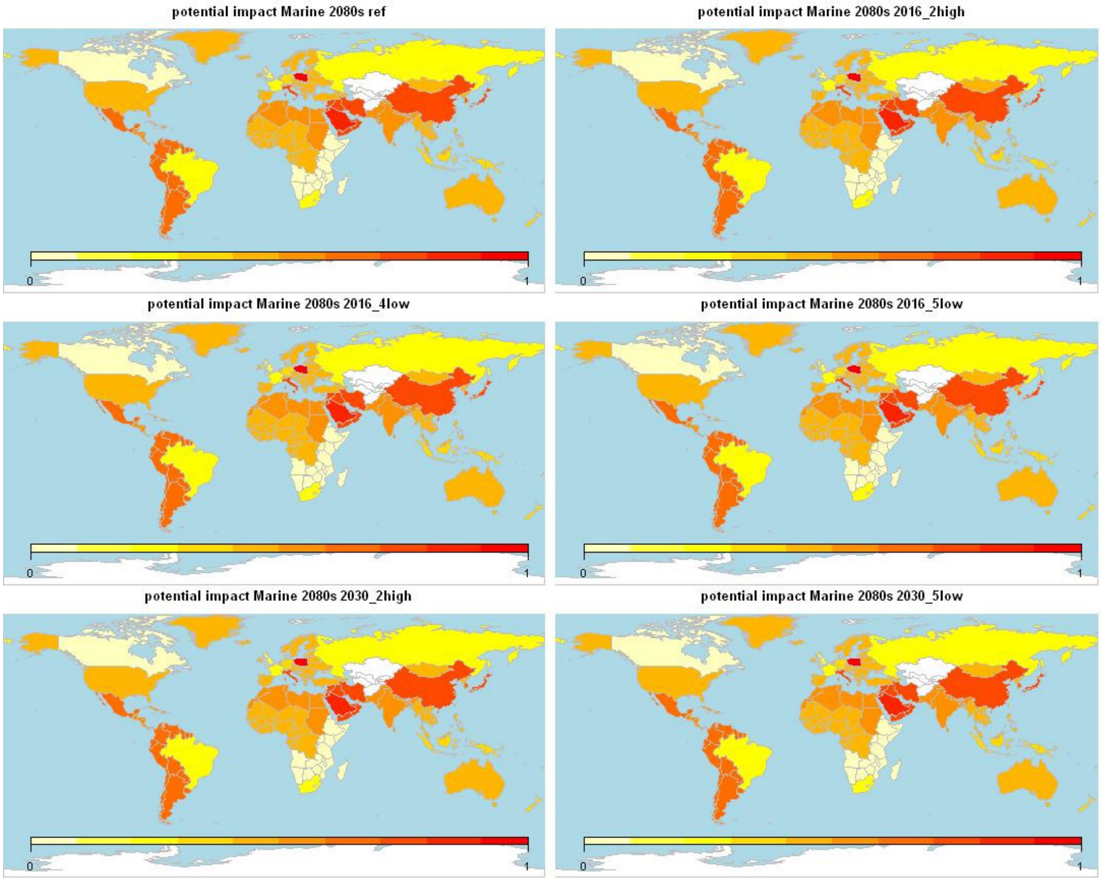
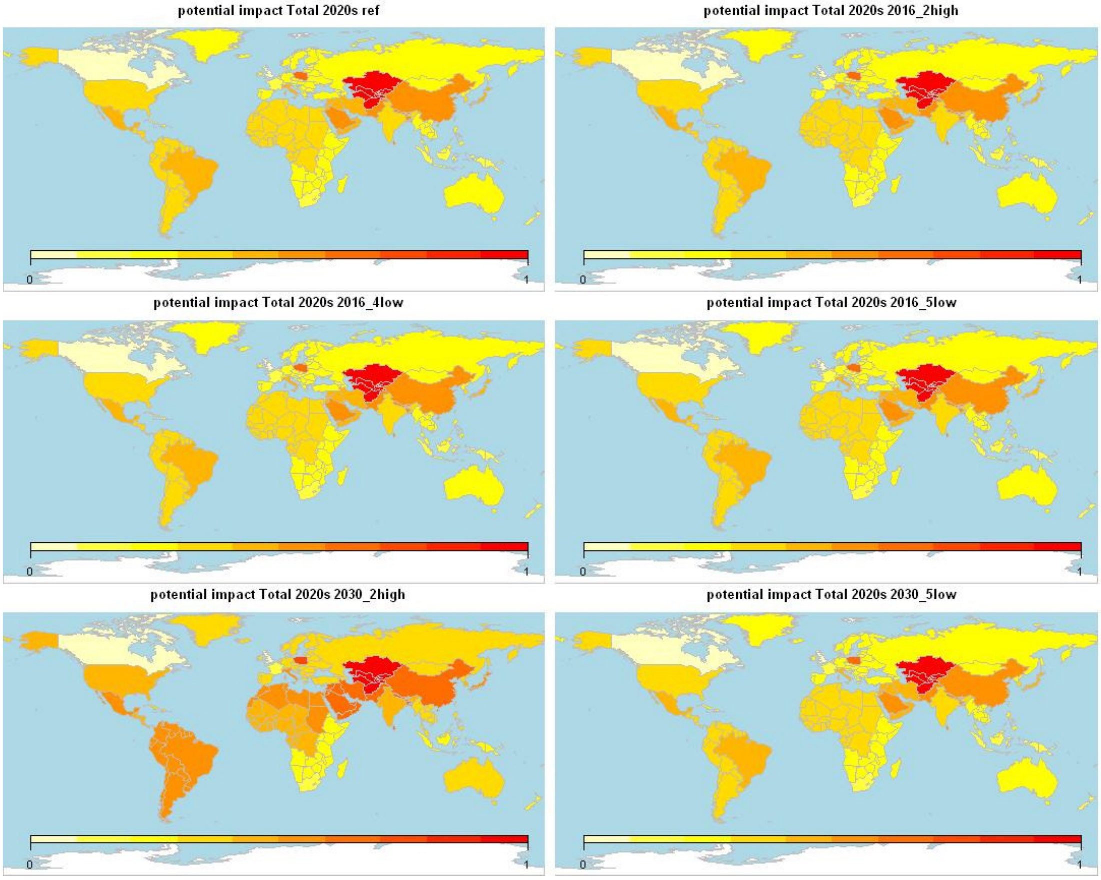
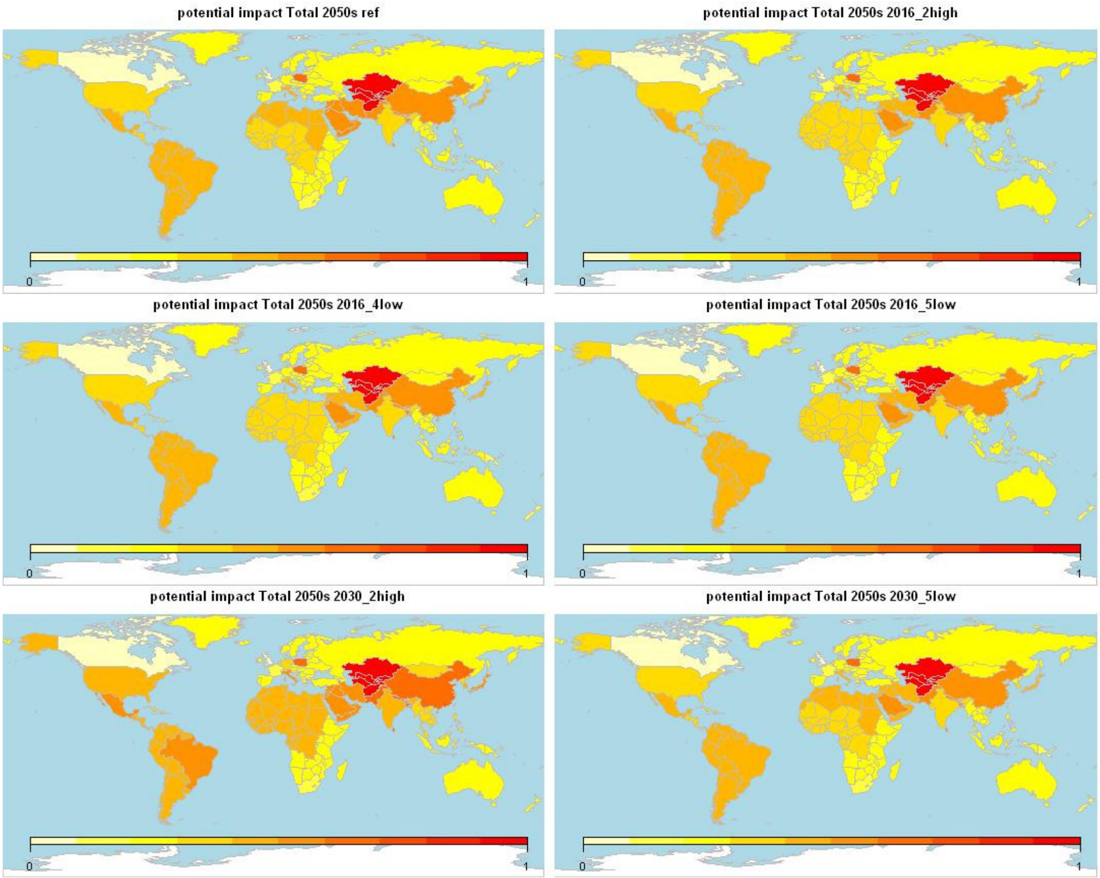


Figure 1. Maps of scaled AVOID region scale Potential Impacts in the marine sector.

2020s



2050s



2080s

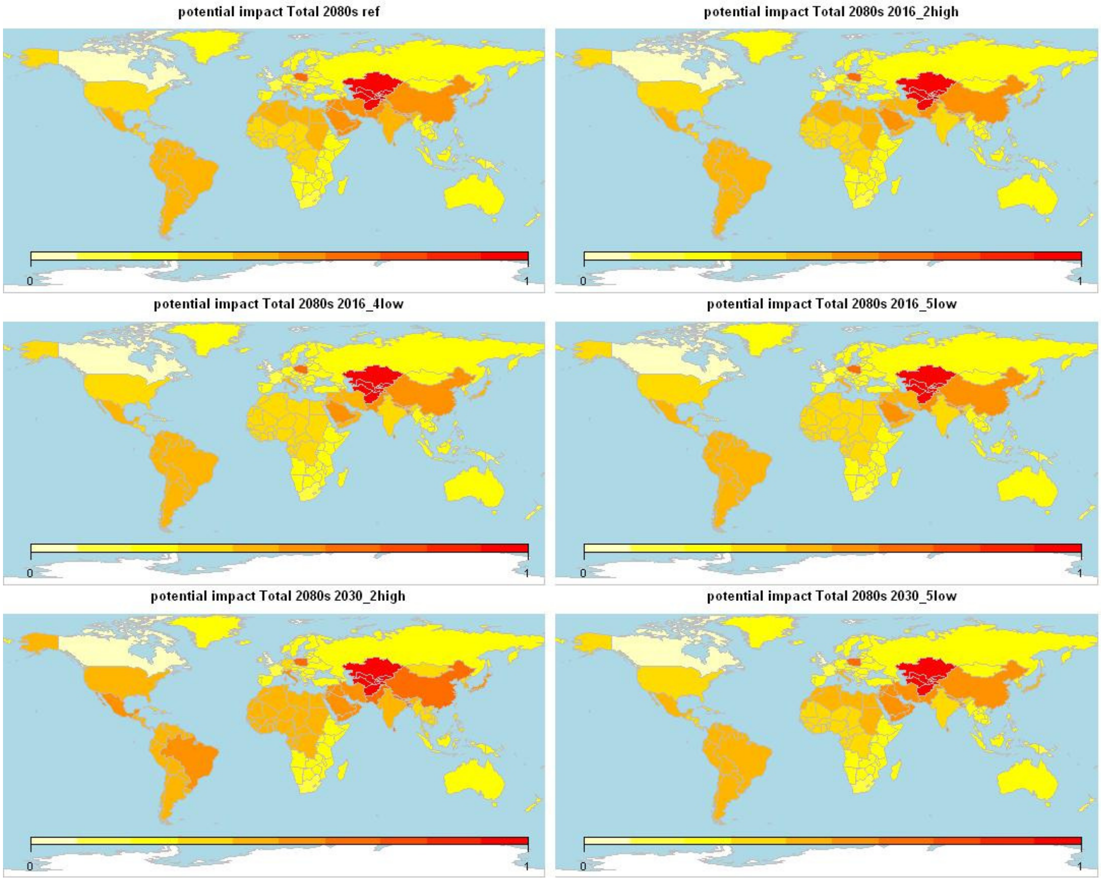
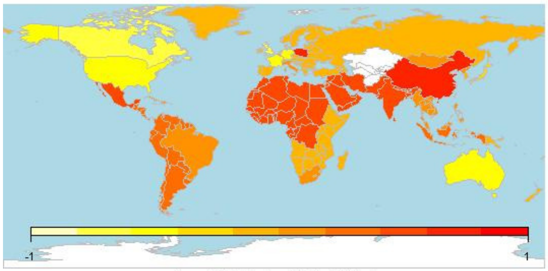


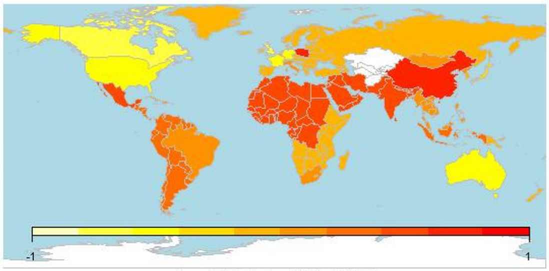
Figure 2. Maps of scaled AVOID region scale Potential Impacts in the marine and freshwater sectors combined (Total).

2020s

vulnerability Marine 2020s ref



vulnerability Marine 2020s 2016_2high



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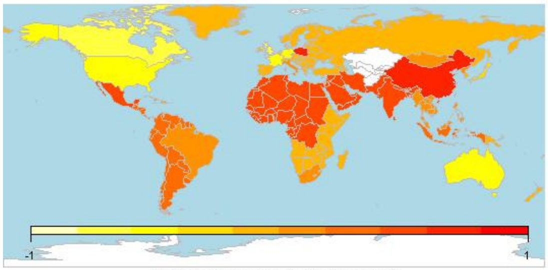
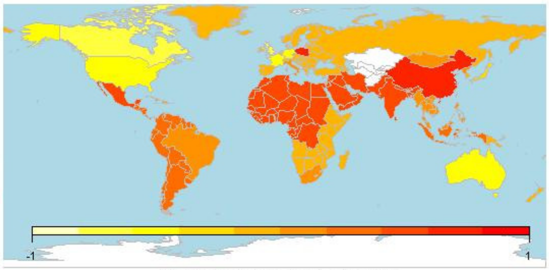
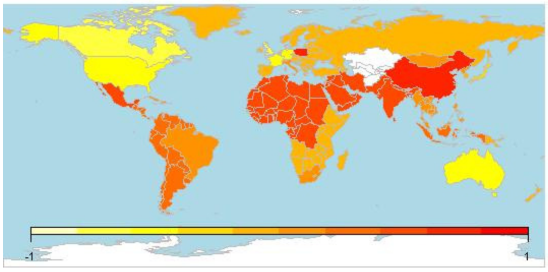


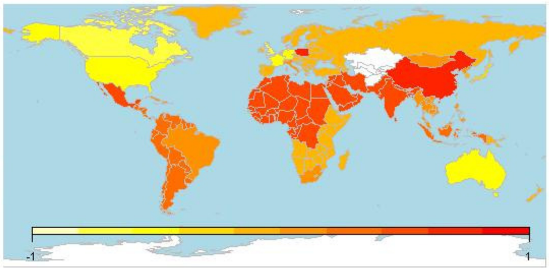
vulnerability Marine 2020s 2016_5low



vulnerability Marine 2020s 2030_2high

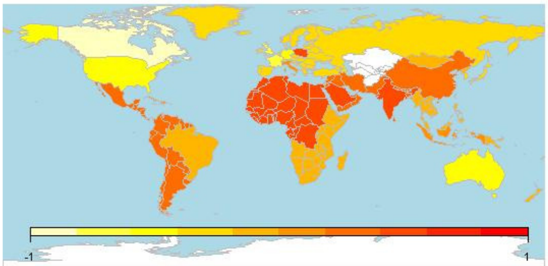


vulnerability Marine 2020s 2030_5low

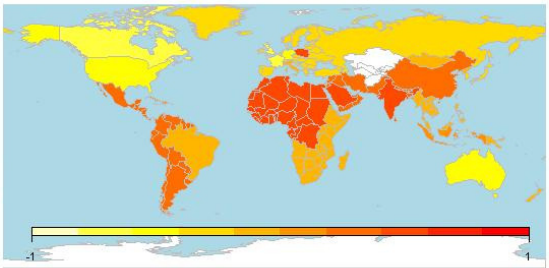


2050s

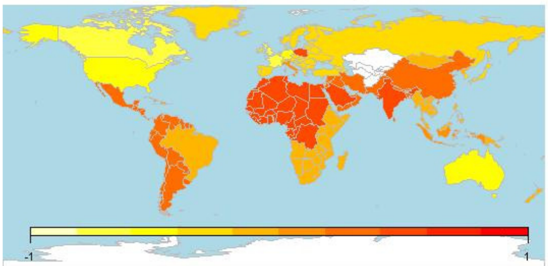
vulnerability Marine 2050s ref



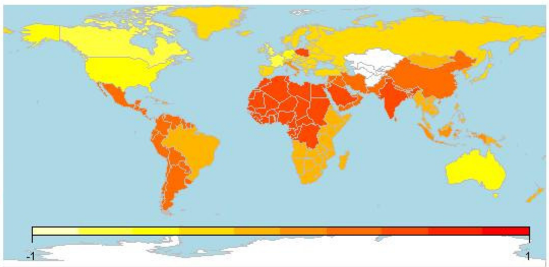
vulnerability Marine 2050s 2016_2high



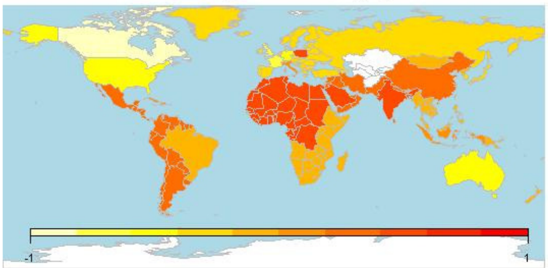
vulnerability Marine 2050s 2016_4low



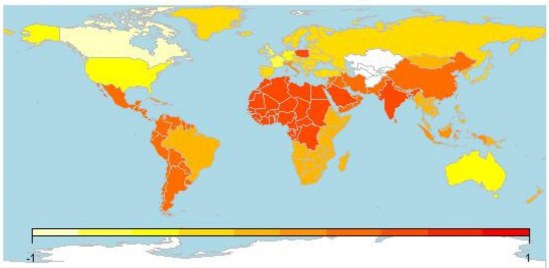
vulnerability Marine 2050s 2016_5low



vulnerability Marine 2050s 2030_2high



vulnerability Marine 2050s 2030_5low



2080s

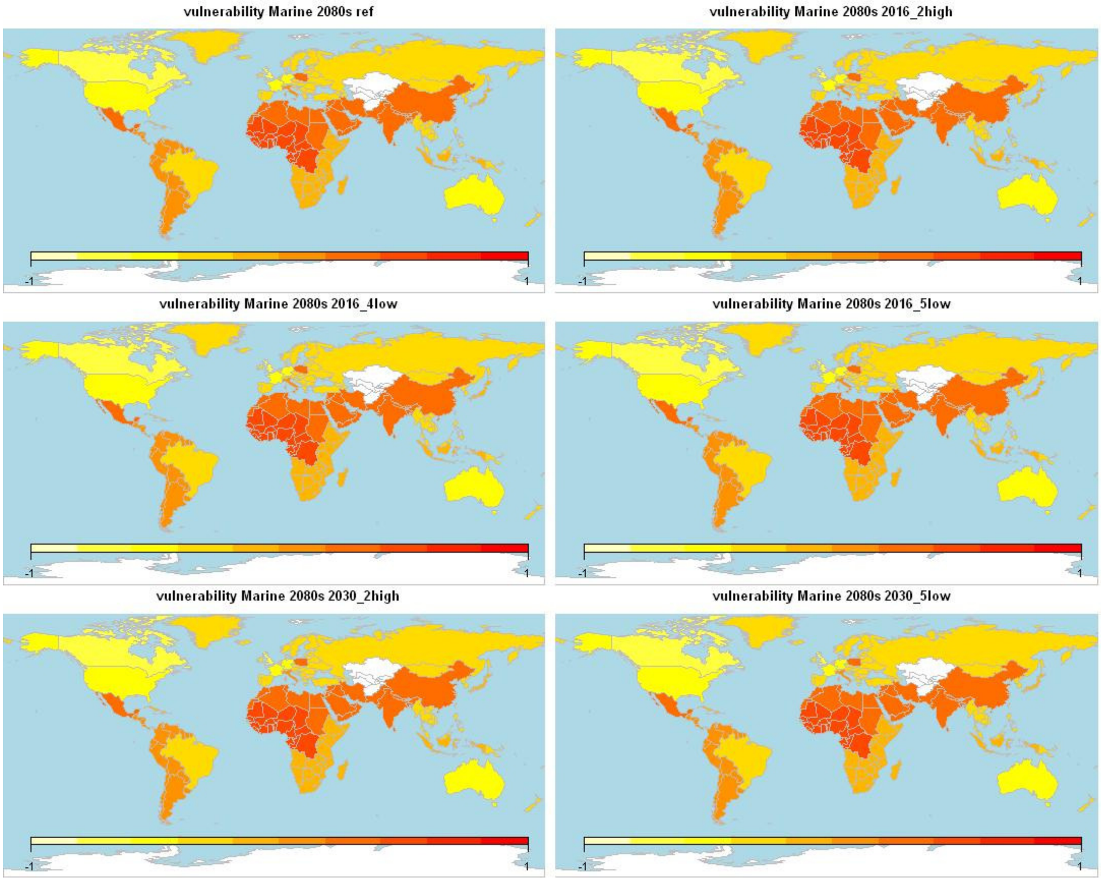
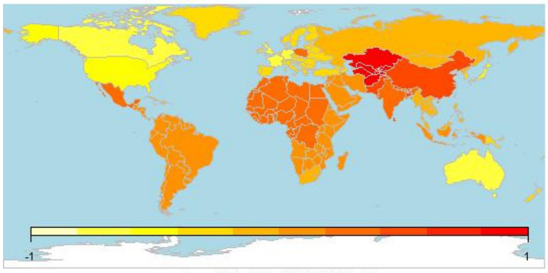


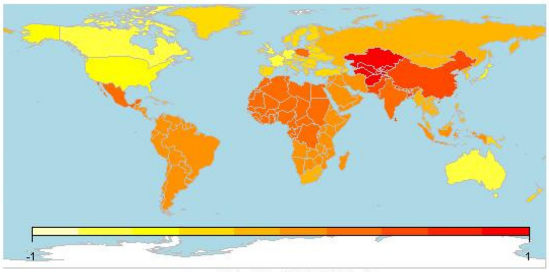
Figure 3. Maps of scaled AVOID region scale Vulnerabilities (PI-AC) in the marine sector.

2020s

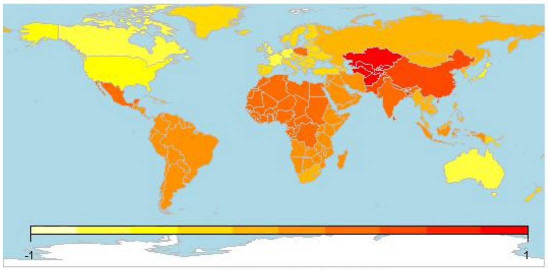
vulnerability Total 2020s ref



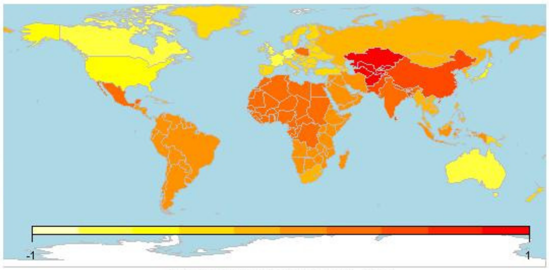
vulnerability Total 2020s 2016_2high



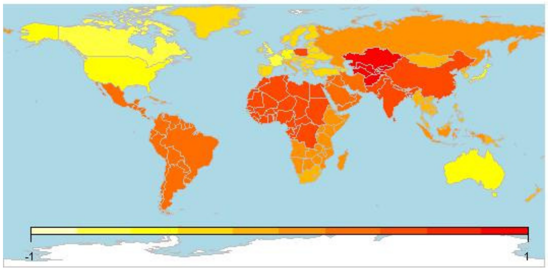
vulnerability Total 2020s 2016_4low



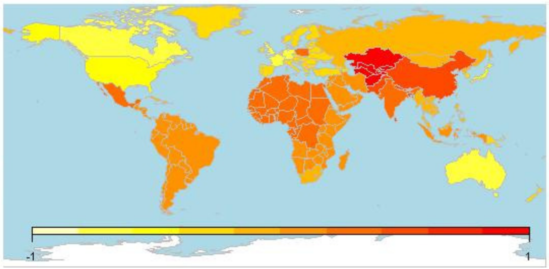
vulnerability Total 2020s 2016_5low



vulnerability Total 2020s 2030_2high

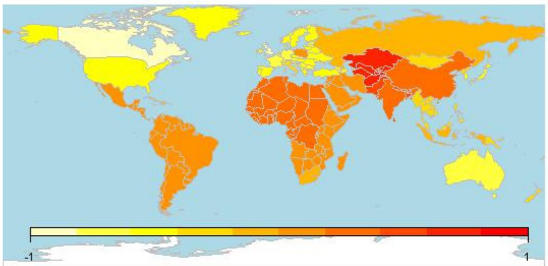


vulnerability Total 2020s 2030_5low

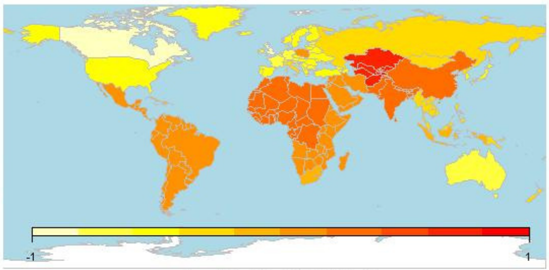


2050s

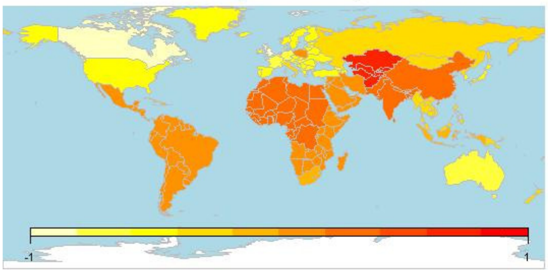
vulnerability Total 2050s ref



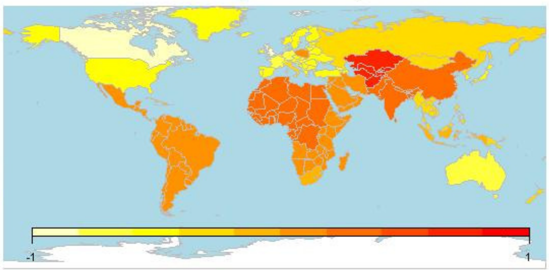
vulnerability Total 2050s 2016_2high



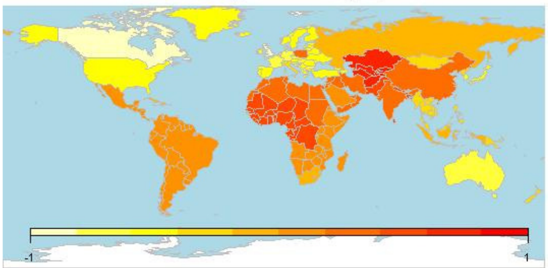
vulnerability Total 2050s 2016_4low



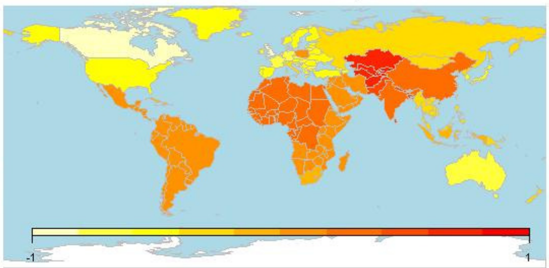
vulnerability Total 2050s 2016_5low



vulnerability Total 2050s 2030_2high



vulnerability Total 2050s 2030_5low



2080s

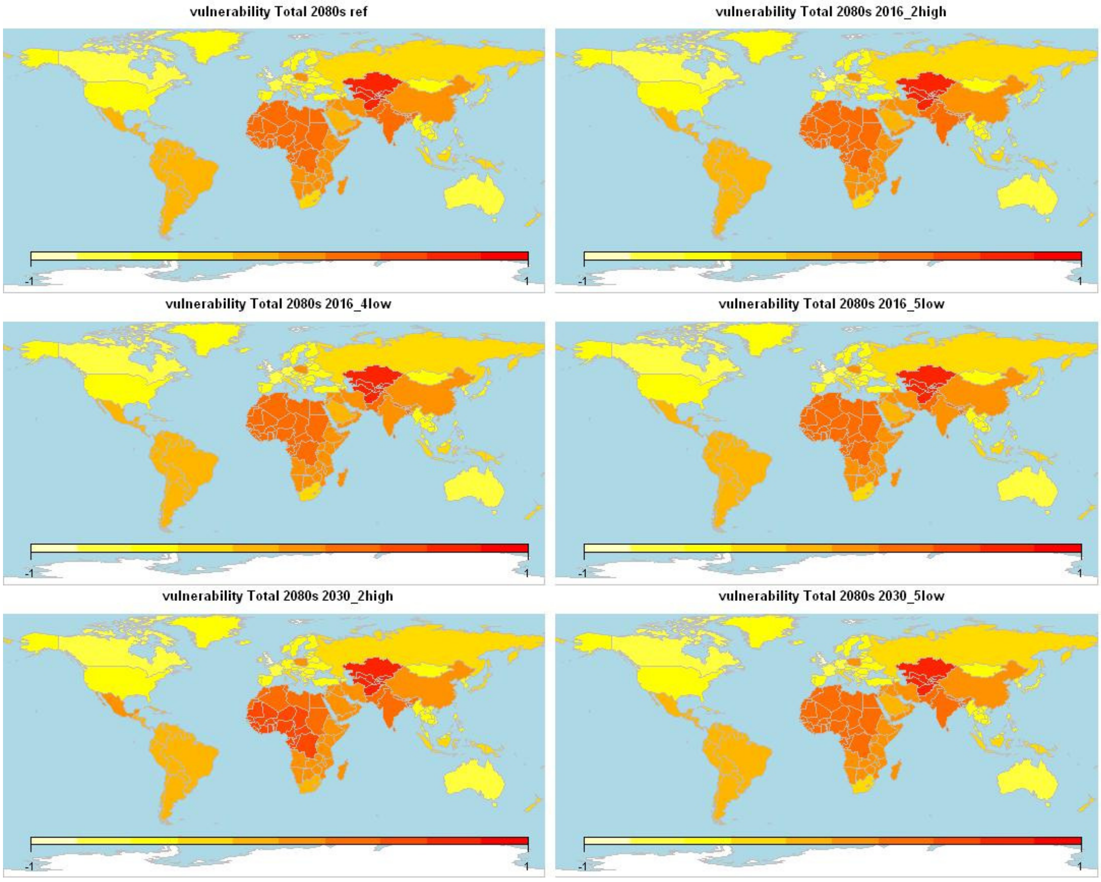


Figure 4. Maps of scaled AVOID region scale Vulnerabilities (PI-AC) in the marine and freshwater sectors combined (total).

4.3.3 References

Adger, W.N. (2000) Social and ecological resilience: Are they related? Progress in Human Geography 24, 347–364.

Allison, E.H., Perry, A.L., Badjeck, M-C, Adger, N., Brown, K., Conway, D., Halls, A.S., Pilling, G.M., Reynolds, J.D., Andrew, N.L. and Dulvy, N.K. (2009). Vulnerability of national economies to the impacts of climate change on fisheries. Fish and Fisheries 10, 173–196.

IPCC (2001) Climate Change 2001: Impacts, Adaptation & Vulnerability, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Vol. Cambridge University Press, Cambridge.

Appendix 1 – Scaled potential impact values

Marine scaled potential impact values by AVOID region

	A1b reference			A1b 2016-5-low			A1b 2016-2-high			A1b 2016-4-low			A1b 2030-2-high			A1b 2030-5-low		
Country	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
China	0.76	0.77	0.78	0.77	0.77	0.77	0.77	0.77	0.77	0.76	0.77	0.77	0.76	0.77	0.77	0.76	0.77	0.77
US	0.46	0.45	0.46	0.46	0.45	0.45	0.46	0.45	0.45	0.46	0.45	0.45	0.46	0.45	0.45	0.46	0.45	0.45
Russia	0.24	0.21	0.21	0.24	0.22	0.22	0.24	0.22	0.21	0.24	0.22	0.22	0.24	0.22	0.21	0.24	0.22	0.21
Japan	0.74	0.75	0.75	0.74	0.75	0.75	0.74	0.75	0.75	0.74	0.75	0.75	0.74	0.75	0.75	0.74	0.75	0.75
South.Africa	0.27	0.27	0.28	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
India	0.54	0.54	0.55	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Brazil	0.27	0.28	0.29	0.27	0.28	0.28	0.27	0.28	0.28	0.27	0.28	0.28	0.27	0.28	0.28	0.27	0.28	0.28
Mexico	0.69	0.69	0.70	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69
Canada	0.06	0.00	0.00	0.06	0.02	0.01	0.06	0.02	0.01	0.06	0.02	0.01	0.06	0.01	0.00	0.06	0.01	0.00
Australia	0.42	0.42	0.43	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Indonesia	0.37	0.37	0.38	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
South.Korea	0.67	0.68	0.68	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.68	0.67	0.67	0.68
UK	0.14	0.14	0.15	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
France	0.28	0.28	0.29	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Italy	0.77	0.78	0.78	0.77	0.78	0.78	0.77	0.78	0.78	0.77	0.78	0.78	0.77	0.78	0.78	0.77	0.78	0.78
Germany	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Poland	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Saudi.Arabia	0.85	0.86	0.86	0.85	0.86	0.86	0.85	0.85	0.86	0.85	0.86	0.86	0.85	0.86	0.86	0.85	0.86	0.86
Rest.of.South.Asia	0.54	0.54	0.55	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.55	0.54	0.54	0.54
Rest.of.East.Asia	0.49	0.49	0.50	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49
Rest.of.Central.Asia	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
North.Africa	0.52	0.53	0.53	0.52	0.52	0.53	0.52	0.52	0.53	0.52	0.52	0.52	0.52	0.53	0.53	0.52	0.52	0.53
West.Africa	0.44	0.45	0.46	0.45	0.45	0.45	0.44	0.45	0.45	0.44	0.45	0.45	0.44	0.45	0.45	0.44	0.45	0.45
Southern.and.East.Africa	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Europe	0.41	0.41	0.42	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
South.America	0.61	0.62	0.62	0.61	0.62	0.62	0.61	0.62	0.62	0.61	0.62	0.62	0.61	0.62	0.62	0.61	0.62	0.62
Central.America	0.54	0.55	0.56	0.55	0.55	0.55	0.55	0.55	0.55	0.54	0.55	0.55	0.54	0.55	0.55	0.54	0.55	0.55
Caribbean	0.50	0.51	0.51	0.50	0.51	0.51	0.50	0.51	0.51	0.50	0.51	0.51	0.50	0.51	0.51	0.50	0.51	0.51
Rest.of.Australasia	0.33	0.34	0.34	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.34	0.33	0.33	0.33
Middle.East	0.73	0.74	0.75	0.74	0.74	0.74	0.74	0.74	0.74	0.73	0.74	0.74	0.73	0.74	0.74	0.73	0.74	0.74

Total scaled potential impact values by AVOID region

	A1b reference			A1b 2016-5-low			A1b 2016-2-high			A1b 2016-4-low			A1b 2030-2-high			A1b 2030-5-low		
Country	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
China	0.58	0.58	0.59	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.69	0.64	0.64	0.58	0.58	0.58
US	0.37	0.38	0.38	0.37	0.37	0.38	0.37	0.37	0.38	0.37	0.37	0.38	0.49	0.44	0.43	0.37	0.38	0.38
Russia	0.24	0.24	0.24	0.24	0.23	0.23	0.24	0.23	0.24	0.24	0.23	0.24	0.33	0.28	0.28	0.24	0.24	0.24
Japan	0.47	0.48	0.49	0.47	0.48	0.48	0.47	0.48	0.48	0.47	0.48	0.48	0.59	0.55	0.54	0.47	0.48	0.48
South.Africa	0.12	0.15	0.16	0.12	0.14	0.14	0.12	0.14	0.14	0.12	0.14	0.14	0.18	0.17	0.18	0.13	0.14	0.15
India	0.38	0.39	0.40	0.38	0.39	0.39	0.38	0.39	0.39	0.38	0.39	0.39	0.49	0.45	0.45	0.38	0.39	0.39
Brazil	0.45	0.47	0.47	0.45	0.46	0.46	0.45	0.46	0.46	0.45	0.46	0.46	0.57	0.53	0.53	0.45	0.46	0.47
Mexico	0.44	0.45	0.46	0.44	0.44	0.45	0.44	0.44	0.45	0.44	0.44	0.45	0.56	0.51	0.51	0.44	0.45	0.45
Canada	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.00
Australia	0.23	0.25	0.25	0.23	0.24	0.24	0.23	0.24	0.24	0.23	0.24	0.24	0.32	0.29	0.29	0.23	0.24	0.25
Indonesia	0.20	0.22	0.23	0.20	0.21	0.21	0.20	0.21	0.22	0.20	0.21	0.21	0.28	0.26	0.26	0.20	0.21	0.22
South.Korea	0.38	0.39	0.40	0.38	0.39	0.39	0.38	0.39	0.39	0.38	0.39	0.39	0.50	0.45	0.45	0.38	0.39	0.39
UK	0.00	0.03	0.04	0.00	0.01	0.02	0.00	0.02	0.02	0.00	0.01	0.02	0.00	0.03	0.04	0.00	0.02	0.03
France	0.12	0.14	0.15	0.12	0.13	0.13	0.12	0.13	0.14	0.12	0.13	0.13	0.17	0.16	0.17	0.12	0.13	0.14
Italy	0.46	0.47	0.48	0.46	0.47	0.47	0.46	0.47	0.47	0.46	0.47	0.47	0.58	0.53	0.53	0.46	0.47	0.47
Germany	0.24	0.26	0.26	0.24	0.25	0.25	0.24	0.25	0.25	0.24	0.25	0.25	0.33	0.30	0.30	0.24	0.25	0.26
Poland	0.63	0.63	0.63	0.63	0.62	0.63	0.63	0.63	0.63	0.63	0.62	0.63	0.73	0.69	0.68	0.63	0.63	0.63
Saudi.Arabia	0.51	0.51	0.52	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.63	0.58	0.57	0.51	0.51	0.51
Rest.of.South.Asia	0.54	0.56	0.56	0.54	0.55	0.55	0.54	0.55	0.55	0.54	0.55	0.55	0.65	0.62	0.61	0.54	0.55	0.56
Rest.of.East.Asia	0.26	0.28	0.28	0.26	0.27	0.27	0.26	0.27	0.27	0.26	0.27	0.27	0.35	0.32	0.32	0.26	0.27	0.28
Rest.of.Central.Asia	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
North.Africa	0.39	0.41	0.41	0.39	0.40	0.40	0.39	0.40	0.40	0.39	0.40	0.40	0.50	0.46	0.46	0.39	0.40	0.40
West.Africa	0.37	0.39	0.40	0.37	0.38	0.38	0.37	0.38	0.39	0.37	0.38	0.38	0.48	0.45	0.44	0.37	0.38	0.39
Southern.and.East.Africa	0.21	0.24	0.25	0.21	0.23	0.23	0.21	0.23	0.24	0.21	0.23	0.23	0.29	0.28	0.28	0.21	0.24	0.24
Europe	0.23	0.24	0.25	0.23	0.23	0.24	0.23	0.24	0.24	0.23	0.23	0.24	0.32	0.29	0.28	0.23	0.24	0.24
South.America	0.40	0.41	0.42	0.40	0.40	0.41	0.40	0.40	0.41	0.40	0.40	0.41	0.52	0.47	0.47	0.40	0.41	0.41
Central.America	0.34	0.36	0.36	0.34	0.35	0.35	0.34	0.35	0.35	0.34	0.35	0.35	0.45	0.41	0.41	0.34	0.35	0.36
Caribbean	0.29	0.30	0.31	0.29	0.30	0.30	0.29	0.30	0.30	0.29	0.30	0.30	0.39	0.35	0.35	0.29	0.30	0.30
Rest.of.Australasia	0.16	0.18	0.19	0.16	0.17	0.18	0.16	0.17	0.18	0.16	0.17	0.18	0.23	0.21	0.22	0.16	0.18	0.18
Middle.East	0.49	0.50	0.51	0.49	0.50	0.50	0.49	0.50	0.50	0.49	0.50	0.50	0.61	0.56	0.56	0.49	0.50	0.50

Appendix 2 – Vulnerability values

Marine vulnerability values by AVOID region

	A1b reference			A1b 2016-5-low			A1b 2016-2-high			A1b 2016-4-low			A1b 2030-2-high			A1b 2030-5-low		
Country	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
China	0.63	0.40	0.25	0.63	0.40	0.24	0.63	0.40	0.24	0.63	0.40	0.24	0.63	0.40	0.24	0.63	0.40	0.24
US	-0.43	-0.48	-0.43	-0.43	-0.48	-0.43	-0.43	-0.48	-0.43	-0.43	-0.48	-0.43	-0.43	-0.48	-0.43	-0.43	-0.48	-0.43
Russia	-0.03	-0.23	-0.36	-0.03	-0.22	-0.35	-0.03	-0.22	-0.36	-0.03	-0.22	-0.35	-0.03	-0.22	-0.36	-0.03	-0.22	-0.36
Japan	-0.26	-0.25	-0.17	-0.26	-0.25	-0.18	-0.26	-0.25	-0.18	-0.26	-0.25	-0.18	-0.26	-0.25	-0.18	-0.26	-0.25	-0.18
South.Africa	0.04	-0.03	-0.09	0.04	-0.03	-0.10	0.04	-0.03	-0.10	0.04	-0.03	-0.10	0.04	-0.03	-0.09	0.04	-0.03	-0.10
India	0.52	0.45	0.36	0.52	0.45	0.35	0.52	0.44	0.35	0.52	0.45	0.35	0.52	0.45	0.35	0.52	0.45	0.35
Brazil	0.00	-0.15	-0.25	0.01	-0.15	-0.25	0.01	-0.15	-0.25	0.00	-0.15	-0.26	0.00	-0.15	-0.25	0.00	-0.15	-0.25
Mexico	0.46	0.32	0.21	0.46	0.32	0.20	0.46	0.32	0.20	0.46	0.32	0.20	0.46	0.32	0.20	0.46	0.32	0.20
Canada	-0.73	-0.81	-0.78	-0.73	-0.79	-0.77	-0.73	-0.79	-0.77	-0.73	-0.79	-0.77	-0.73	-0.80	-0.78	-0.73	-0.80	-0.78
Australia	-0.41	-0.48	-0.48	-0.41	-0.48	-0.49	-0.41	-0.48	-0.49	-0.41	-0.48	-0.49	-0.41	-0.48	-0.49	-0.41	-0.48	-0.49
Indonesia	0.24	0.06	-0.08	0.24	0.06	-0.09	0.24	0.06	-0.09	0.24	0.06	-0.09	0.24	0.06	-0.09	0.24	0.06	-0.09
South.Korea	-0.04	-0.25	-0.32	-0.03	-0.25	-0.33	-0.04	-0.25	-0.33	-0.04	-0.25	-0.33	-0.04	-0.25	-0.32	-0.04	-0.25	-0.32
UK	-0.61	-0.71	-0.70	-0.61	-0.71	-0.71	-0.61	-0.71	-0.71	-0.61	-0.71	-0.71	-0.61	-0.71	-0.71	-0.61	-0.71	-0.71
France	-0.57	-0.63	-0.59	-0.57	-0.63	-0.59	-0.57	-0.63	-0.59	-0.57	-0.63	-0.59	-0.57	-0.63	-0.59	-0.57	-0.63	-0.59
Italy	0.07	0.00	0.02	0.07	0.00	0.01	0.07	0.00	0.01	0.07	0.00	0.01	0.07	0.00	0.02	0.07	0.00	0.01
Germany	-0.51	-0.55	-0.50	-0.51	-0.55	-0.51	-0.51	-0.55	-0.51	-0.51	-0.55	-0.51	-0.51	-0.55	-0.51	-0.51	-0.55	-0.51
Poland	0.72	0.52	0.38	0.72	0.52	0.38	0.72	0.52	0.38	0.72	0.52	0.38	0.72	0.52	0.38	0.72	0.52	0.38
Saudi.Arabia	0.51	0.42	0.30	0.51	0.42	0.30	0.51	0.42	0.30	0.51	0.42	0.30	0.51	0.42	0.30	0.51	0.42	0.30
Rest.of.South.Asia	0.47	0.39	0.30	0.48	0.39	0.29	0.48	0.39	0.29	0.48	0.39	0.29	0.47	0.39	0.29	0.47	0.39	0.29
Rest.of.East.Asia	0.04	-0.13	-0.23	0.05	-0.13	-0.24	0.04	-0.14	-0.24	0.04	-0.13	-0.24	0.04	-0.13	-0.24	0.04	-0.13	-0.24
Rest.of.Central.Asia	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
North.Africa	0.43	0.40	0.34	0.43	0.40	0.34	0.43	0.40	0.34	0.43	0.40	0.34	0.43	0.40	0.34	0.43	0.40	0.34
West.Africa	0.44	0.45	0.46	0.45	0.45	0.45	0.44	0.45	0.45	0.44	0.45	0.45	0.44	0.45	0.45	0.44	0.45	0.45
Southern.and.East.Africa	-0.15	-0.16	-0.15	-0.15	-0.16	-0.16	-0.15	-0.16	-0.16	-0.15	-0.16	-0.16	-0.15	-0.16	-0.16	-0.15	-0.16	-0.16
Europe	-0.19	-0.27	-0.29	-0.19	-0.27	-0.30	-0.19	-0.27	-0.30	-0.19	-0.27	-0.30	-0.19	-0.27	-0.30	-0.19	-0.27	-0.30
South.America	0.39	0.24	0.13	0.39	0.24	0.13	0.39	0.24	0.13	0.39	0.24	0.13	0.39	0.24	0.13	0.39	0.24	0.13
Central.America	0.40	0.26	0.12	0.40	0.25	0.11	0.40	0.25	0.11	0.40	0.25	0.11	0.40	0.25	0.11	0.40	0.25	0.11
Caribbean	0.15	0.05	-0.03	0.15	0.04	-0.04	0.15	0.04	-0.04	0.15	0.05	-0.04	0.15	0.05	-0.04	0.15	0.05	-0.04
Rest.of.Australasia	-0.06	-0.15	-0.23	-0.06	-0.15	-0.23	-0.06	-0.15	-0.23	-0.06	-0.15	-0.23	-0.06	-0.15	-0.23	-0.06	-0.15	-0.23
Middle.East	0.42	0.38	0.31	0.43	0.38	0.30	0.42	0.38	0.30	0.42	0.38	0.30	0.42	0.38	0.30	0.42	0.38	0.30

Total vulnerability values by AVOID region

	A1b reference			A1b 2016-5-low			A1b 2016-2-high			A1b 2016-4-low			A1b 2030-2-high			A1b 2030-5-low		
Country	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s	2020s	2050s	2080s
China	0.44	0.21	0.06	0.44	0.21	0.05	0.44	0.21	0.05	0.44	0.21	0.05	0.55	0.27	0.11	0.44	0.21	0.05
US	-0.52	-0.55	-0.50	-0.52	-0.56	-0.51	-0.52	-0.56	-0.51	-0.52	-0.56	-0.51	-0.40	-0.50	-0.45	-0.52	-0.56	-0.51
Russia	-0.03	-0.20	-0.33	-0.03	-0.20	-0.33	-0.03	-0.20	-0.33	-0.03	-0.20	-0.33	0.06	-0.16	-0.29	-0.03	-0.20	-0.33
Japan	-0.53	-0.52	-0.44	-0.53	-0.52	-0.45	-0.53	-0.52	-0.45	-0.53	-0.52	-0.45	-0.41	-0.45	-0.39	-0.53	-0.52	-0.44
South.Africa	-0.11	-0.15	-0.21	-0.11	-0.16	-0.23	-0.11	-0.16	-0.23	-0.11	-0.16	-0.23	-0.05	-0.13	-0.19	-0.11	-0.16	-0.22
India	0.35	0.30	0.21	0.35	0.29	0.20	0.35	0.29	0.20	0.35	0.29	0.20	0.47	0.35	0.26	0.35	0.29	0.20
Brazil	0.18	0.05	-0.06	0.18	0.04	-0.07	0.18	0.04	-0.07	0.18	0.04	-0.07	0.30	0.11	-0.01	0.18	0.04	-0.06
Mexico	0.21	0.08	-0.03	0.21	0.07	-0.04	0.21	0.07	-0.04	0.21	0.07	-0.04	0.33	0.14	0.02	0.21	0.07	-0.04
Canada	-0.78	-0.81	-0.78	-0.78	-0.81	-0.78	-0.77	-0.81	-0.78	-0.78	-0.81	-0.78	-0.77	-0.81	-0.78	-0.77	-0.81	-0.78
Australia	-0.61	-0.65	-0.66	-0.61	-0.66	-0.67	-0.61	-0.66	-0.67	-0.61	-0.66	-0.67	-0.51	-0.61	-0.62	-0.61	-0.66	-0.67
Indonesia	0.07	-0.08	-0.23	0.07	-0.10	-0.25	0.07	-0.10	-0.24	0.07	-0.10	-0.25	0.15	-0.05	-0.20	0.07	-0.09	-0.24
South.Korea	-0.32	-0.53	-0.60	-0.32	-0.54	-0.61	-0.32	-0.54	-0.61	-0.32	-0.54	-0.61	-0.21	-0.47	-0.55	-0.32	-0.54	-0.61
UK	-0.74	-0.82	-0.81	-0.74	-0.84	-0.83	-0.74	-0.83	-0.82	-0.74	-0.84	-0.82	-0.74	-0.82	-0.81	-0.74	-0.83	-0.82
France	-0.74	-0.77	-0.73	-0.74	-0.78	-0.74	-0.74	-0.78	-0.74	-0.74	-0.78	-0.74	-0.68	-0.75	-0.71	-0.74	-0.78	-0.74
Italy	-0.24	-0.30	-0.29	-0.24	-0.31	-0.30	-0.24	-0.31	-0.29	-0.24	-0.31	-0.30	-0.12	-0.24	-0.24	-0.24	-0.31	-0.29
Germany	-0.64	-0.66	-0.61	-0.64	-0.67	-0.62	-0.64	-0.67	-0.62	-0.64	-0.67	-0.62	-0.54	-0.62	-0.57	-0.64	-0.67	-0.62
Poland	0.34	0.15	0.01	0.34	0.15	0.01	0.34	0.15	0.01	0.34	0.15	0.01	0.45	0.21	0.06	0.34	0.15	0.01
Saudi.Arabia	0.17	0.08	-0.04	0.17	0.07	-0.05	0.17	0.07	-0.05	0.17	0.07	-0.05	0.29	0.14	0.01	0.17	0.07	-0.05
Rest.of.South.Asia	0.47	0.40	0.31	0.47	0.40	0.30	0.47	0.40	0.30	0.47	0.40	0.30	0.59	0.46	0.36	0.47	0.40	0.30
Rest.of.East.Asia	-0.19	-0.35	-0.45	-0.19	-0.36	-0.46	-0.19	-0.36	-0.46	-0.19	-0.36	-0.46	-0.09	-0.30	-0.41	-0.19	-0.35	-0.45
Rest.of.Central.Asia	0.94	0.79	0.64	0.94	0.79	0.64	0.94	0.79	0.64	0.94	0.79	0.64	0.94	0.79	0.64	0.94	0.79	0.64
North.Africa	0.29	0.28	0.22	0.29	0.28	0.21	0.29	0.28	0.21	0.29	0.28	0.21	0.41	0.34	0.27	0.29	0.28	0.22
West.Africa	0.37	0.39	0.40	0.37	0.38	0.38	0.37	0.38	0.39	0.37	0.38	0.38	0.48	0.45	0.44	0.37	0.38	0.39
Southern.and.East.Africa	0.06	0.08	0.09	0.06	0.07	0.07	0.06	0.07	0.07	0.06	0.07	0.07	0.14	0.12	0.12	0.06	0.07	0.08
Europe	-0.38	-0.44	-0.46	-0.38	-0.45	-0.47	-0.37	-0.45	-0.47	-0.38	-0.45	-0.47	-0.28	-0.40	-0.43	-0.37	-0.45	-0.47
South.America	0.17	0.04	-0.07	0.17	0.03	-0.08	0.17	0.03	-0.08	0.17	0.03	-0.08	0.29	0.10	-0.02	0.17	0.03	-0.08
Central.America	0.19	0.06	-0.07	0.19	0.05	-0.08	0.19	0.05	-0.08	0.19	0.05	-0.08	0.31	0.12	-0.03	0.19	0.06	-0.08
Caribbean	-0.06	-0.16	-0.23	-0.06	-0.17	-0.25	-0.06	-0.16	-0.24	-0.06	-0.17	-0.25	0.04	-0.11	-0.19	-0.06	-0.16	-0.24
Rest.of.Australasia	-0.23	-0.30	-0.38	-0.23	-0.31	-0.39	-0.23	-0.31	-0.39	-0.23	-0.31	-0.39	-0.16	-0.27	-0.35	-0.23	-0.31	-0.39
Middle.East	0.18	0.14	0.07	0.18	0.14	0.06	0.18	0.14	0.06	0.18	0.13	0.06	0.30	0.20	0.12	0.18	0.14	0.06

5. HUMAN HEALTH

AVOIDed heat-related deaths attributable to climate change

How the health models works

Heat-related mortality attributable to climate change is estimated using six city-specific heat-related mortality models, for Boston, Budapest, Dallas, Lisbon, London and Sydney. Each model quantifies the non-linear relationship between daily heat-related mortality and surface temperature. The models were constructed from observed relationships in each city between heat-related mortality and temperature. The models have been validated and shown to give an accurate representation of observed heat-related mortality for each city, meaning they can be used reliably for climate change impacts assessment. A more detailed description of the model construction and validation process is described in Gosling et al. (2007) and the models have previously been used to assess the impacts of climate change on heat-related mortality in Gosling et al. (2009a and 2009b). The models output the annual heat-related mortality *rate* (i.e. the number of deaths per 100,000 of the population per year) *attributable* to climate change (i.e. the heat-related mortality death rate that is only due to climate change and which occurs above the 'normal' expected rate in the absence of climate change). Six temperature time series were calculated for each city respectively by perturbing the observed daily temperature time series of each city by the projected mean global temperature increase for each policy scenario (2016.R5.L, 2016.R2.H, 2016.R4.L, 2030.R2.H, and 2030.R5.L) and the reference scenario (A1B) respectively. These temperature time series were then applied to the city-specific heat-related mortality models to yield heat-related mortality rates attributable to climate change for each city.

Caveats of the health models

In this application of the heat-related mortality models it is assumed that there is no change in demographic structure in the future. This is unrealistic but at the same time advantageous because it allows for an explicit representation of the sole impacts of climate change on heat-related mortality, which are not effected by changes in population. Therefore the impacts presented here should be interpreted as an indicator of how heat-related mortality might change with climate change.

The heat-related mortality models do not account for the possibility that populations may acclimatise to warmer temperatures in a warmer future climate. The degree to which populations will acclimatise, if at all, is highly contested within the climate change-health academic community. This is due to lack of evidence, e.g. records of daily temperature and heat-related mortality are generally not expansive enough to observe evidence of historical acclimatisation occurring. However, it has been postulated that in the same way that populations living in hot countries are acclimatised to high temperatures, so populations may acclimatise to warmer temperatures with climate change. However, the rate at which populations may acclimatise is unknown. If some acclimatisation to warmer future temperatures is assumed to happen, then the impact estimates presented here may be considered as being slightly over-estimated.

What the main results are and what they mean

Table 1 shows the number of heat-related deaths attributable to climate change using the 50% (median) climate change outcome. The avoided impacts associated with each policy scenario for each city are displayed in Figure 1. Four main conclusions can be drawn from Table 1 and Figure 1:

1. **Climate change has an effect on the number of heat-related deaths regardless of policy scenario**

   Note that the heat-related mortality death rates presented in the 'Climate Change Impacts' columns of Table 1 represent deaths *attributable* to climate change. This means the deaths occur on top of the heat-related mortality rate that would be expected in the absence of climate change (see the column labelled 'Obs' in Table 1). For instance, with Budapest and the 2035-2064 time horizon, the heat-related mortality rate attributable to climate change with the A1B scenario is 5.5/100,000. The observed rate for 1961-1990 is 5.4/100,000. The rate of 5.5 attributable to climate change would occur on top of the 'normal' expected rate of 5.4, meaning the total heat-related mortality rate would be 10.9 (5.4 + 5.5). This represents a doubling of the present-day death rate. The attributable mortality rates in Table 1 are all greater than zero, meaning that climate change is associated with an increase in heat-related mortality rates for all scenarios of climate change. Whilst the policy scenarios serve to reduce the number of heat-related deaths attributable to climate change, they do not eradicate the effects of climate change on heat-related mortality.

2. **The magnitude of avoided impacts are minor in the early 21st century**

   The numbers of heat-related deaths attributable to climate change that are avoided by the policy scenarios are minor in the early 21st century. For instance, the maximum number of deaths avoided for the 2015-2044 time horizon across all six cities and policy scenarios is 0.2/100,000 (Lisbon). Generally, there are no avoided impacts with the policy scenarios for the 2015-2044 time horizon, and Boston and Budapest actually present minor negative avoided impacts. This means that more heat-related deaths occur under a policy scenario than they would under the baseline A1B scenario. This is because the mean global temperature change for 2015-2034 relative to present is marginally greater for the 2016.R5.L and 2016.R4.L policy scenarios (1.04°C) than it is for the A1B baseline scenario (1.02°C). However, the increase in death rates is negligible at 0.1/100,000.

3. **The magnitude of avoided impacts increase with time in to the future**

   Figure 1 demonstrates that the numbers of heat-related deaths attributable to climate change that are avoided with policy scenarios increase with time in to the future. For example, with

London the number of avoided deaths for the 2070-2099 time horizon is around twice as large as the number of avoided deaths for the 2015-2044 period. During the early to mid-21st century the relationship between magnitude of avoided impacts and time appears non-linear but thereafter the relationship appears broadly linear.

4. **The magnitude of avoided impacts is more sensitive to the year at which emissions are reduced than to the rate at which emissions are reduced**

   This conclusion can be drawn from Figure 1. By the end of the 21st century there is a clear divergence in avoided impacts between the three policy scenarios that reduce emissions from a peak in 2016 and the two policy scenarios that reduce emissions from a 2030 peak.

Table 1. The number of heat-related deaths attributable to climate change using the 50% (median) climate change outcome. Deaths are given as annual crude mortality rates, i.e. deaths per 100,000 of the population per year. 'Obs' displays the observed heat-related mortality rate for 1961-1990 (i.e. in the absence of a climate change effect).

			Climate Change Impacts						Avoided Impacts				
Time Horizon	Region	Obs	A1B	2016.R5.L	2016.R2.H	2016.R4.L	2030.R2.H	2030.R5.L	A1B-2016.R5.L	A1B-2016.R2.H	A1B-2016.R4.L	A1B-2030.R2.H	A1B-2030.R5.L
2015-2044	Boston	3.1	2.5	2.5	2.5	2.5	2.4	2.4	-0.1	0.0	-0.1	0.1	0.1
	Budapest	5.4	2.6	2.7	2.6	2.7	2.5	2.5	-0.1	0.0	-0.1	0.1	0.1
	Dallas	1.4	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0
	Lisbon	4.6	2.5	2.5	2.5	2.5	2.3	2.3	0.0	0.0	0.0	0.2	0.2
	London	1.8	1.0	1.0	1.0	1.0	0.9	0.9	0.0	0.0	0.0	0.0	0.0
	Sydney	1.6	0.6	0.7	0.6	0.7	0.6	0.6	0.0	0.0	0.0	0.0	0.0
2035-2064	Boston	3.1	5.8	3.8	3.8	3.7	4.6	4.7	2.0	2.0	2.1	1.2	1.1
	Budapest	5.4	5.5	3.8	3.8	3.7	4.5	4.6	1.7	1.6	1.7	0.9	0.8
	Dallas	1.4	2.3	1.5	1.5	1.5	1.8	1.9	0.8	0.7	0.8	0.5	0.4
	Lisbon	4.6	5.9	3.8	3.9	3.7	4.7	4.8	2.1	2.0	2.2	1.2	1.1
	London	1.8	2.1	1.4	1.4	1.4	1.7	1.7	0.7	0.7	0.7	0.4	0.3
	Sydney	1.6	1.3	0.9	0.9	0.9	1.1	1.1	0.4	0.4	0.4	0.2	0.2
2070-2099	Boston	3.1	13.6	4.6	5.1	4.6	7.1	6.4	9.0	8.5	8.9	6.5	7.2
	Budapest	5.4	10.6	4.5	4.9	4.5	6.4	5.9	6.1	5.7	6.0	4.2	4.7
	Dallas	1.4	5.0	1.8	2.0	1.8	2.7	2.5	3.2	3.0	3.2	2.3	2.5
	Lisbon	4.6	14.3	4.7	5.2	4.7	7.3	6.4	9.6	9.1	9.6	7.0	7.9
	London	1.8	4.3	1.7	1.9	1.7	2.5	2.3	2.6	2.5	2.6	1.8	2.1
	Sydney	1.6	2.4	1.1	1.2	1.1	1.5	1.4	1.3	1.2	1.3	0.9	1.0

Figure 1. The number of avoided heat-related deaths attributable to climate change using the 50% (median) climate change outcome, from the year 2030 onwards. Deaths are given as annual crude mortality rates, i.e. deaths per 100,000 of the population per year.

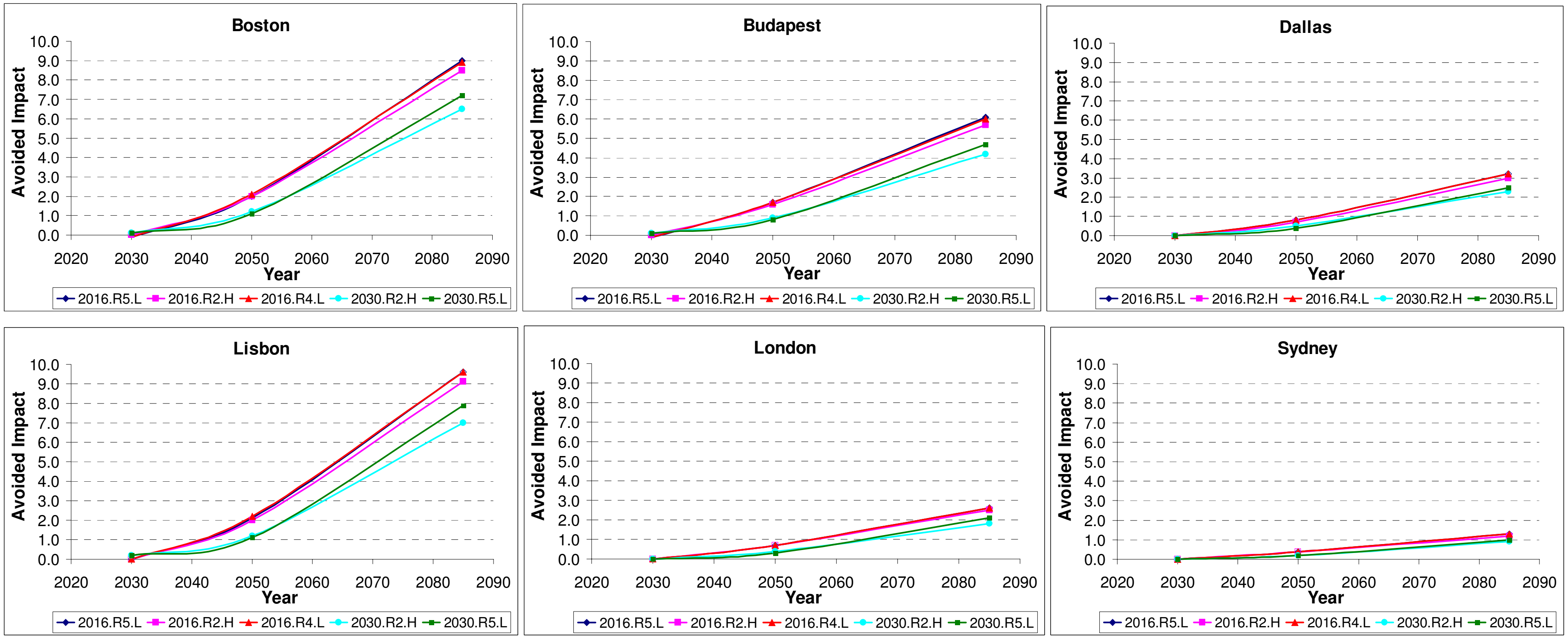
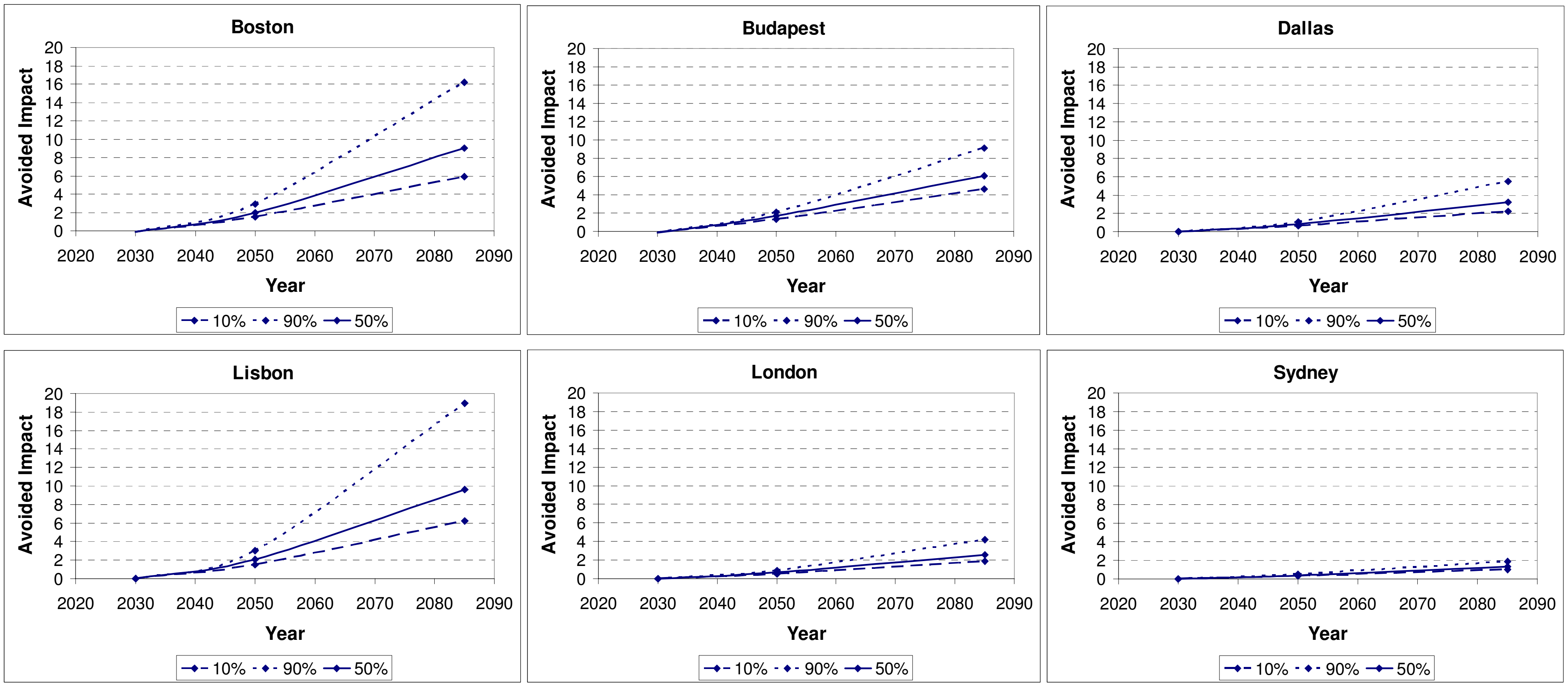


Table 2 shows the number of heat-related deaths attributable to climate change using the 10% and 90% climate change outcomes respectively. The avoided impacts using the 10%, median (50%), and 90% climate change outcomes respectively, with the 2016.R5.L policy scenario only are displayed in Figure 2. Figure 2 can be compared with Figure 1. An important conclusion is that the range in avoided impacts across the climate change outcomes for one policy scenario (2016.R5.L; Figure 2) is greater than the range across the 5 policy scenarios with the median (50%) climate change outcome (Figure 1).

Table 2. The number of heat-related deaths attributable to climate change using the 10% and 90% climate change outcomes respectively. Deaths are given as annual crude mortality rates, i.e. deaths per 100,000 of the population per year.

		10% Outcome of Climate Change Scenario			90% Outcome of Climate Change Scenario		
		Climate Change Impacts		Avoided Impacts	Climate Change Impacts		Avoided Impacts
Time Horizon	Region	A1B	2016.R5.L	A1B-2016.R5.L	A1B	2016.R5.L	A1B-2016.R5.L
2015-2044	Boston	2.0	2.0	-0.1	3.3	3.4	-0.1
	Budapest	2.1	2.2	-0.1	3.3	3.4	-0.1
	Dallas	0.8	0.8	0.0	1.3	1.3	0.0
	Lisbon	2.0	2.0	0.0	3.3	3.3	-0.1
	London	0.8	0.8	0.0	1.2	1.3	0.0
	Sydney	0.5	0.5	0.0	0.8	0.8	0.0
2035-2064	Boston	4.2	2.8	1.5	8.4	5.5	2.9
	Budapest	4.2	2.9	1.3	7.3	5.2	2.1
	Dallas	1.7	1.1	0.6	3.2	2.1	1.1
	Lisbon	4.3	2.8	1.5	8.6	5.6	3.0
	London	1.6	1.1	0.5	2.9	2.0	0.9
	Sydney	1.0	0.7	0.3	1.7	1.2	0.5
2070-2099	Boston	9.0	3.1	5.9	23.9	7.7	16.2
	Budapest	7.8	3.2	4.6	16.0	6.9	9.1
	Dallas	3.4	1.3	2.2	8.5	2.9	5.5
	Lisbon	9.3	3.1	6.2	26.8	7.9	18.9
	London	3.1	1.2	1.9	6.8	2.7	4.2
	Sydney	1.8	0.8	1.0	3.5	1.6	1.9

Figure 2. The number of avoided heat-related deaths attributable to climate change using the 10%, median (50%), and 90% climate change outcomes respectively, with the 2016.R5.L policy scenario. Deaths are given as annual crude mortality rates, i.e. deaths per 100,000 of the population per year.



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6. ECOSYSTEMS AND BIODIVERSITY

6.1 Species modeling

6.1.1 How the Neural Ensembles model works

Neural Ensembles (O'Hanley, 2009) is an integrated modelling and assessment tool for projecting areas of species bioclimatic suitability based on presence/absence data and uses an artificial neural network (ANN). It uses ensembles of ANN model runs to significantly improve model accuracy and precision (thus serving to reduce spatial variance of model outputs). Primary model inputs include climatology data (temperature, rainfall, solar radiation and wind speed) and soils data (AWC) which are pre-processed using a number of integrated algorithms to derive relevant bioclimatic variables for subsequent input into the NeuralEnsembles. The five main bioclimate inputs are: (1) absolute minimum temperature expected over a 20-year period, (2) annual maximum temperature, (3) growing degree days ≥ 5°C, (4) accumulated annual soil water deficit and (5) accumulated annual soil water surplus. To improve performance, these variables, which can vary by several orders of magnitude, are first normalised onto an approximate 0 to 1 range using baseline minimum and maximum values for the given study area. The ANNs are trained and tested using empirical data on species distributions. Given the difficulty of obtaining global distributions of species at a sufficient accuracy and resolution for the modelling, the models were run for all 194 mammals in the Atlas of European Mammals published by the Societas Europaea Mammalogica and for 500 plants randomly selected from the Atlas Flora Europaea database of more than 4000 European plants (Jalas and Suominen, 1972- 1991). The performance of each network was statistically evaluated using the Area Under the Receiver Operating Characteristic Curve (AUC) and impacts were only analysed for those species with 20 or more presence records and an AUC of 0.8 or greater. This resulted in a subset of 121 mammals and 221 plants which were used in the report for computing impacts.

The objective of the calculations is to simulate the number of species which become critically endangered due to climate change alone (i.e., the number of additional species which become critically endangered due to climate change). It is assumed that under current climates no European species are critically endangered due to climate change. Model runs were projected using a 95% sensitivity threshold, meaning that the cutoff for presence/absence should cover at least 95% of the observed presence points. This should make the future projections somewhat conservative in terms of projected areal losses relative to present day suitable climate space. The percentage loss of projected suitable climate space was calculated as an indication of the potential threat to species. This was divided into the following categories, based loosely on those of the IUCN (2001):

Critically Endangered: ≥ 80% loss of current suitable climate space
Endangered: ≥ 50% loss of current suitable climate space
Vulnerable: ≥ 30% current suitable climate space
Near Threatened: ≥ 20% current suitable climate space
Least Concern: none of the above

There are a number of important limitation and assumptions with this approach which are dealt with in (iii), but it gives an indication of possible impacts on species. These simulations were carried out and analysed by Jesse O’Hanley (University of Kent) and Pam Berry (University of Oxford).

6.1.2 What the main results are and what they mean

Five main conclusions can be drawn from the results:

1. ***The climate change impacts increase with time***
   Under the A1B scenario, the number of European mammal and plant species in our sample which are in the critically endangered category steadily increases with time, whilst the number in the least concern category decreases. Specifically, between the 2030s and the 2050s the number critically endangered rises from zero to 1 mammal and 5 plants, and further to 9 mammals and 9 plants by the 2080s. Meanwhile, the number in the least concerned category falls from 98, 193 mammals and plants respectively in the 2030s to 82, 168 by the 2050s (decreases of 16% and 13%), and further to 75, 162 by the 2080s (i.e. further decreases of 9% and 4%). The number of species in more threatened categories also shows an increase with time (See Tables 6.1-6.3). Thus the trends in all the categories demonstrate the increased impacts of climate change upon species with time.

2. ***The rate of emissions' reduction have negligible effects for the 2030s***
   The avoided impacts achieved by the different emissions reduction scenarios are negligible in the 2030s. In particular, there is no change in the number of mammals in the two extreme categories (least concern and critically endangered), although two or three species do move to less threatened categories. A similar pattern is seen for plants, except that there is a small increase in the number of plants in the least concerned category (Tables 6.1-6.3).

3. ***The avoided impacts increase with time***
   Policy scenarios reduce the number of species in the more threatened categories compared to the reference scenario. These avoided climate change impacts increase in magnitude in the future for any given policy scenario. For example, with the 2016.R5.L scenario, by the 2080s, 9 fewer mammals and 7 fewer plants become critically endangered due to climate change than in the baseline scenario. By the 2050s, the corresponding numbers are smaller (1 and 5) and by the 2030s, there is no discernible effect in this category. Similar trends are discernible in the other categories of endangerment and in the other policy scenarios (Tables 6.1-6.3, Figure 6.1).

4. ***Avoided impacts are greater with the 2016-R policy scenarios than they are with the 2030-R policy scenarios***
   The scenarios in which global emissions peak in 2016 are generally more effective in avoiding climate change impacts than those which peak in 2030. For example, when comparing the scenario 2030-R2-H with scenarios 2016-R2-H and 2030-R5-L, greater benefits result in the 2080s from moving the peak year forward to 2016 than from increasing the emission reduction rate from 2% to 5%. The tables also show that the 2016-R scenarios often have quite similar values of species in categories (e.g. for plants, close to 175 for least concern in the 2080s) whilst the 2030-R scenarios also have similar values (e.g. close to 166 for least concern) in the 2080s). Thus the year at which emissions reduction begin, in general, has a greater effect on avoided impacts than the annual rate of emissions reduction (Tables 6.1-6.3).

5. ***Avoided impacts vary with GCM***
   In the baseline scenario, A1B, in the 2030s the number of species in the least concern category is slightly more when using ECHAM5 to project climate change compared with HadCM3 i.e. (103, 200) species of mammals, plants in the least concern category with ECHAM5, compared with (98, 193) with HadCM3 (Tables 9.1-9.3, 9.6, Figure 9.4). However by the 2080s the numbers are

smaller (71,158) with ECHAM5, compared with (75,162) with HadCM3. The numbers in this category in the 2080s for the policy scenario 2016.R5.L, however, are slightly larger with ECHAM5 (94, 189) than with HadCM3 (84, 177). The net effect is that avoided impacts can sometimes be smaller with the ECHAM5 GCM than with HadCM3 by the 2080s. However, trends in either direction are possible, for example in the 2080s, 6 mammals and 8 plants are removed from the critically endangered category by this policy using ECHAM5, compared with 9 mammals and 7 plants for HadCM3. This inter-GCM difference is less significant than the effect of using the 10% and 90% percentiles of climate change outcome (Figures 6.2-6.4, Tables 6.4-6.6). The differences between the effects of using the different emission reduction policies are also smaller than the effects of using different percentiles of climate change outcome, but in all cases the numbers are relatively small (fewer than 10 species).

6.1.3 Caveats

While Neural Ensembles captures some of the modelling uncertainty through an ensemble approach, there are other potential sources of uncertainty, including the use of a single type of model, choice of model parameters and their calculation. One of the main assumptions of climate envelope models like Neural Ensembles is based on the assumptions that species are currently in equilibrium with climate and that climate is the dominant factor affecting the species' distributions. While climate is generally thought to be the key parameter affecting species' distributions at the continental scale, other important factors such as habitat availability and species dispersal to realise new climate space have not included. Due to a lack of reliable and available global species' distributions, the analysis was restricted to Europe for mammals and a random selection of plants. Europe is less exposed to climate change than some other areas of the world, although parts of Europe, such as the Mediterranean region are projected to experience high impacts. Also the species used will not represent the full range of global sensitivity of biodiversity and thus the results need to be treated as indicative.

Although researchers have linked bioclimate envelope models to extinction rates, using approaches loosely based on the IUCN Red List Criteria (IUCN, 2001), as has been used here (e.g., Thomas et al., 2004; Thuiller et al, 2005), there are a number of inherent problems. These involve quantitative estimates of extinction risk, temporal and spatial scales, spatial resolution, and assumptions about species–area relationships leading to population reductions and are discussed fully in Akçakaya et al. (2006). This study is not free of these problems and has only examined changes in climate space, which are not necessarily the same of change in range size or abundance, thus the results presented here are likely to be conservative.

IMPACTS USING 50% (MEDIAN) CLIMATE CHANGE OUTCOME AND ClimGen TUNED to HadCM3: AT RISK EUROPEAN MAMMALS AND PLANTS – 2015-2044

	Climate Change Impacts						Avoided Impacts				
Category	**A1B**	**2016.R2.H**	**2016.R4.L**	**2016.R5.L**	**2030.R2.H**	**2030.R5.L**	**A1B-2016.R2.H**	**A1B-2016.R4.L**	**A1B-2016.R5.L**	**A1B-2030.R2.H**	**A1B-2030.R5.L**
European Mammals											
Least Concern	98	98	98	98	98	98	0	0	0	0	0
Near Threatened	12	15	15	14	15	15	3	3	2	3	3
Vulnerable	10	8	8	9	8	8	-2	-2	-1	-2	-2
Endangered	1	0	0	0	0	0	-1	-1	-1	-1	-1
Critically Endangered	0	0	0	0	0	0	0	0	0	0	0
European Plants											
Least Concern	193	196	194	194	194	194	3	1	1	1	1
Near Threatened	17	16	18	17	18	18	-1	1	0	1	1
Vulnerable	7	6	5	6	6	5	-1	-2	-1	-1	-2
Endangered	4	3	4	4	3	4	-1	0	0	-1	0
Critically Endangered	0	0	0	0	0	0	0	0	0	0	0

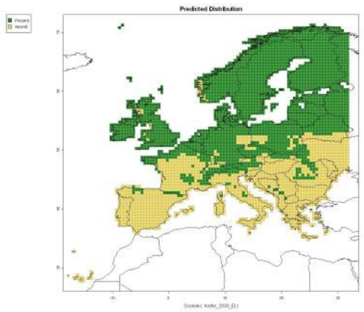
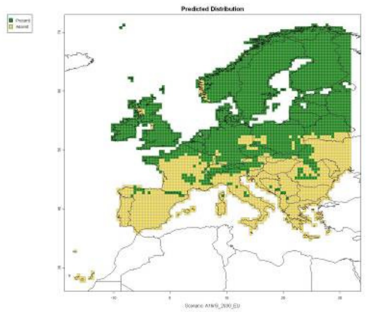
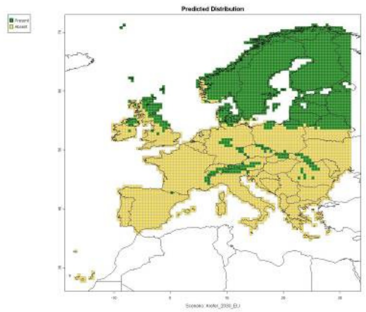
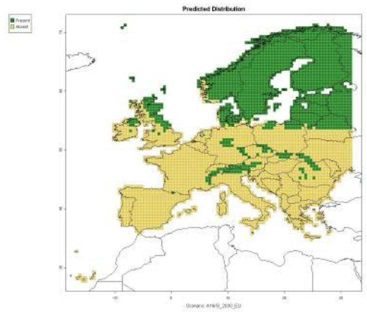
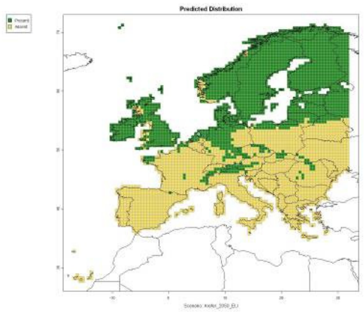
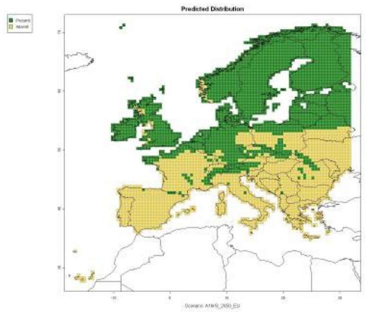
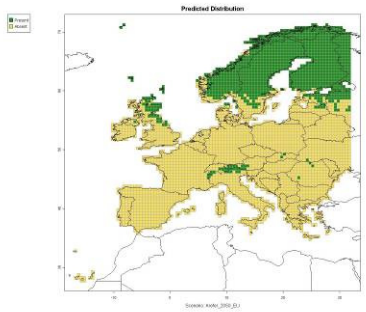
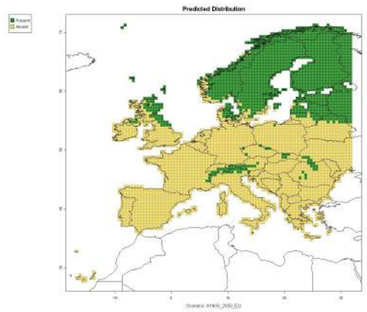
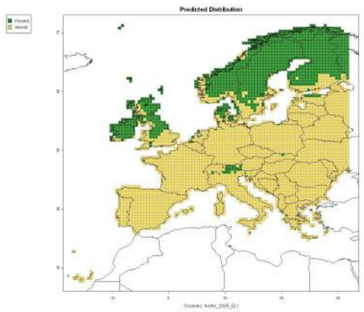
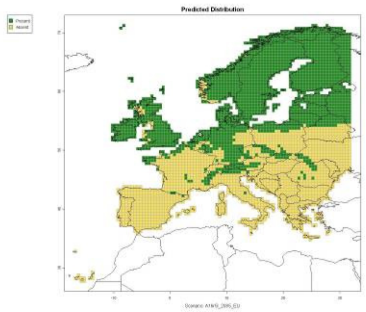
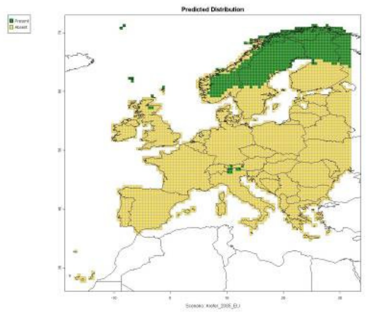
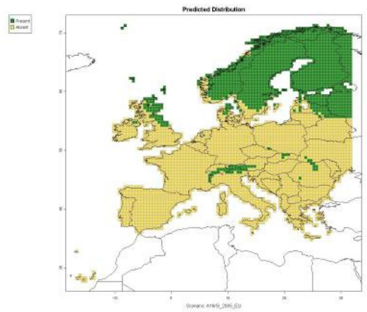
IMPACTS USING 50% (MEDIAN) CLIMATE CHANGE OUTCOME AND ClimGen TUNED to HadCM3: AT RISK EUROPEAN MAMMALS AND PLANTS – 2035-2064

	Climate Change Impacts						Avoided Impacts				
Category	**A1B**	**2016.R2.H**	**2016.R4.L**	**2016.R5.L**	**2030.R2.H**	**2030.R5.L**	**A1B-2016.R2.H**	**A1B-2016.R4.L**	**A1B-2016.R5.L**	**A1B-2030.R2.H**	**A1B-2030.R5.L**
European Mammals											
Least Concern	82	89	89	89	84	84	7	7	7	2	2
Near Threatened	10	10	10	10	15	12	0	0	0	5	2
Vulnerable	22	20	21	21	17	20	-2	-1	-1	-5	-2
Endangered	6	2	1	1	5	5	-4	-5	-5	-1	-1
Critically Endangered	1	0	0	0	0	0	-1	-1	-1	-1	-1
European Plants											
Least Concern	168	183	184	184	179	179	15	16	16	11	11
Near Threatened	23	16	15	15	17	17	-7	-8	-8	-6	-6
Vulnerable	21	17	17	17	20	20	-4	-4	-4	-1	-1
Endangered	4	5	5	5	3	3	1	1	1	-1	-1
Critically Endangered	5	0	0	0	2	2	-5	-5	-5	-3	-3

IMPACTS USING 50% (MEDIAN) CLIMATE CHANGE OUTCOME AND ClimGen TUNED to HadCM3:
AT RISK EUROPEAN MAMMALS AND PLANTS – 2070-2099

	Climate Change Impacts						Avoided Impacts				
Category	**A1B**	**2016.R2.H**	**2016.R4.L**	**2016.R5.L**	**2030.R2.H**	**2030.R5.L**	**A1B-2016.R2.H**	**A1B-2016.R4.L**	**A1B-2016.R5.L**	**A1B-2030.R2.H**	**A1B-2030.R5.L**
European Mammals											
Least Concern	75	82	84	84	79	80	7	9	9	4	5
Near Threatened	3	13	11	11	8	10	10	8	8	5	7
Vulnerable	9	19	20	20	18	21	10	11	11	9	12
Endangered	25	6	6	6	15	9	-19	-19	-19	-10	-16
Critically Endangered	9	1	0	0	1	1	-8	-9	-9	-8	-8
European Plants											
Least Concern	162	170	175	177	166	166	8	13	15	4	4
Near Threatened	2	22	20	18	18	20	20	18	16	16	18
Vulnerable	26	22	20	20	24	23	-4	-6	-6	-2	-3
Endangered	22	3	4	4	8	7	-19	-18	-18	-14	-15
Critically Endangered	9	4	2	2	5	5	-5	-7	-7	-4	-4

IMPACTS USING 50% (MEDIAN) CLIMATE CHANGE OUTCOME AND ClimGen TUNED to HadCM3:
PROJECTED POTENTIALLY SUITABLE CLIMATE SPACE FOR A EUROPEAN MAMMAL (*MUSTELA ERMINE*) AND A EUROPEAN PLANT (*RIBES SPICATUM*) Green = found, tan = not found

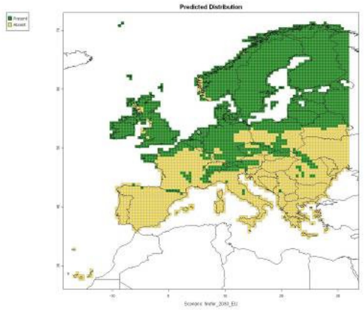
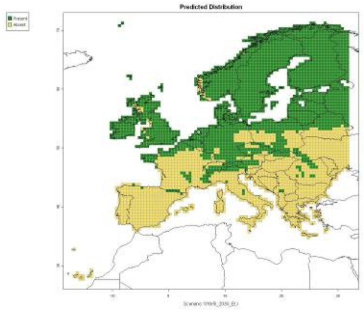
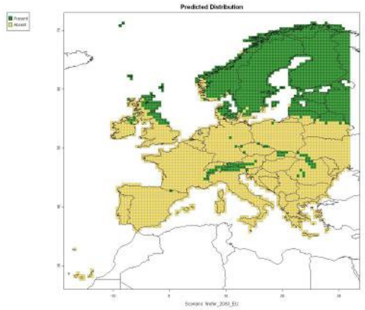
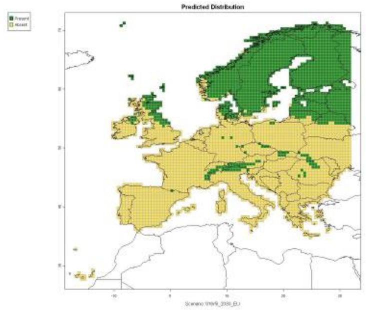
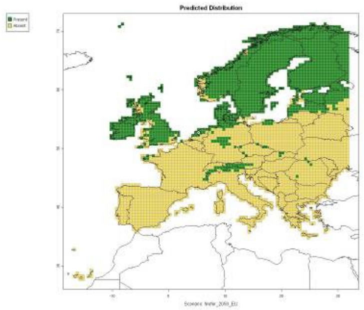
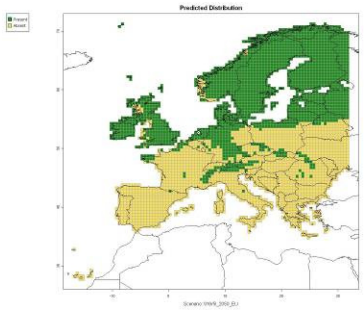
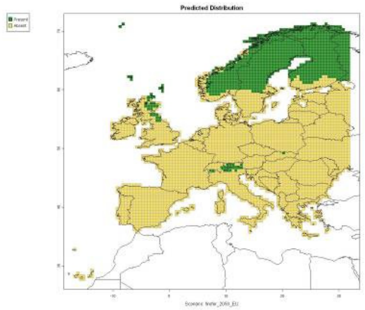
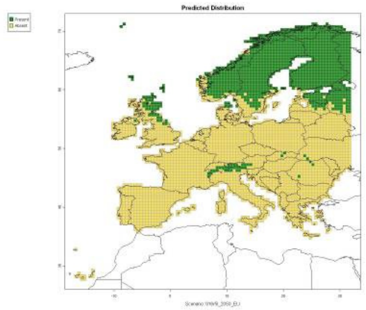
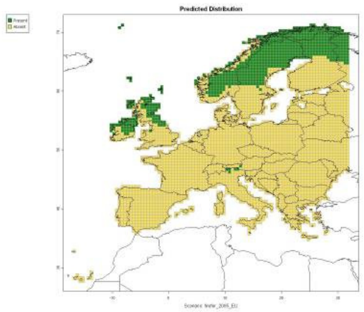
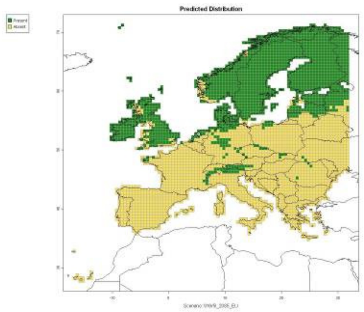
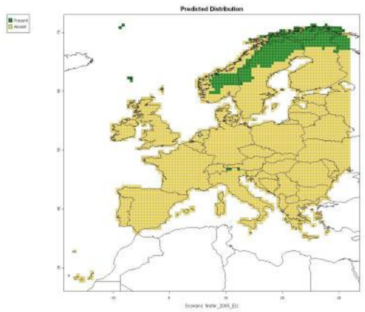
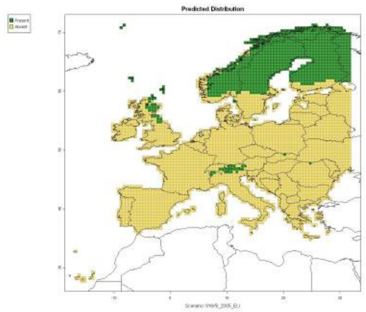
	Stoat (*Mustela ermine*)		**Red Currant (*Ribes spicatum*)**	
	A1B	2016.R5.L	A1B	2016.R5.L
2015-2044				
2035-2064				
2070-2099				

SENSITIVITY STUDY: 90% OUTCOME OF CLIMATE CHANGE SCENARIO 2016.R5.L AND ClimGen TUNED to HadCM3: AT RISK EUROPEAN MAMMALS AND PLANTS

	2015-2044			2035-2064			2070-2099		
Category	**A1B**	**2016.R5.L**	**A1B-2016.R5.L**	**A1B**	**2016.R5.L**	**A1B-2016.R5.L**	**A1B**	**2016.R5.L**	**A1B-2016.R5.L**
European Mammals									
Least Concern	90	95	5	78	82	4	70	78	8
Near Threatened	11	9	-2	7	12	5	5	8	3
Vulnerable	19	16	-3	18	20	2	7	17	10
Endangered	1	1	0	16	6	-10	23	17	-6
Critically Endangered	0	0	0	2	1	-1	16	1	-15
European Plants									
Least Concern	188	189	1	165	169	4	157	165	8
Near Threatened	14	13	-1	10	23	13	5	14	9
Vulnerable	14	14	0	26	20	-6	13	23	10
Endangered	5	5	0	15	5	-10	32	14	-18
Critically Endangered	0	0	0	5	4	-1	14	5	-9

IMPACTS USING 90% (MEDIAN) CLIMATE CHANGE OUTCOME AND ClimGen TUNED to HadCM3: PROJECTED POTENTIALLY SUITABLE CLIMATE SPACE FOR A EUROPEAN MAMMAL (*MUSTELA ERMINE*) AND A EUROPEAN PLANT (*RIBES SPICATUM*)

Green = found, tan = not found

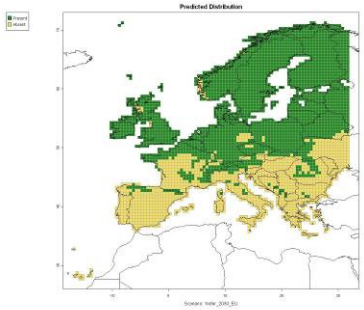
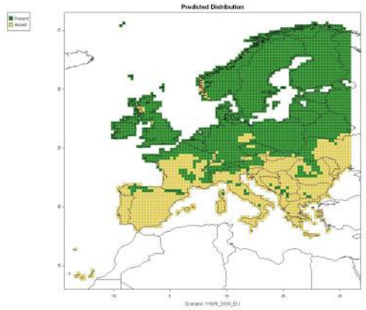
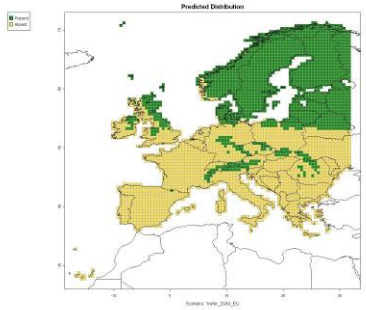
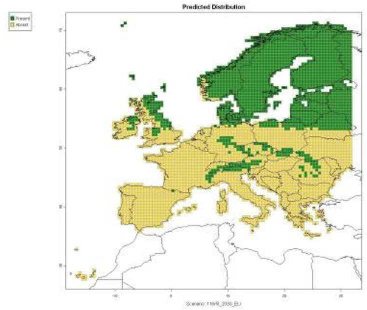
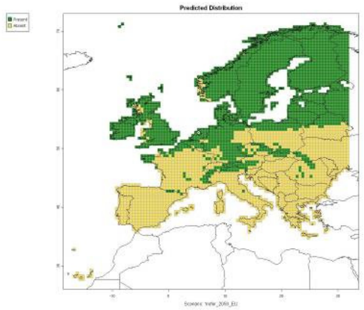
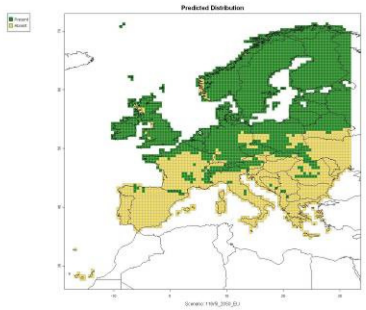
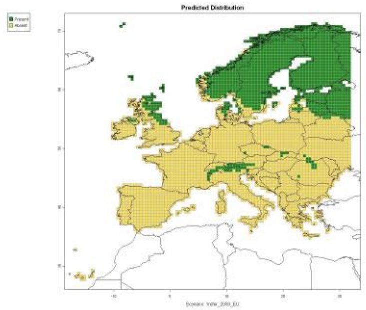
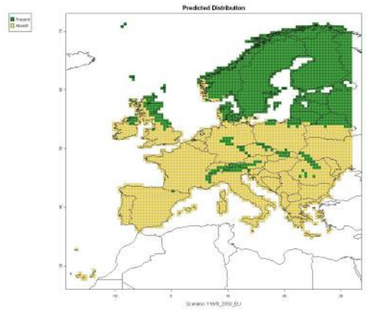
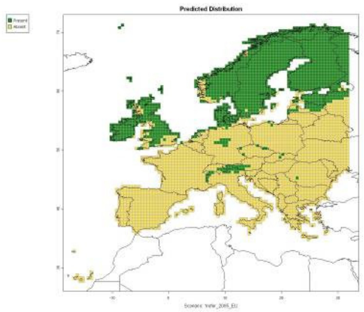
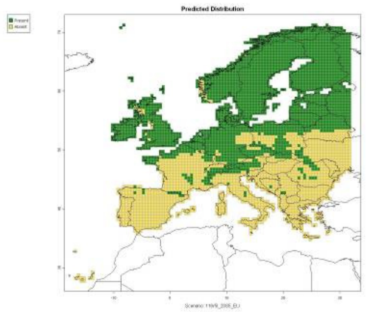
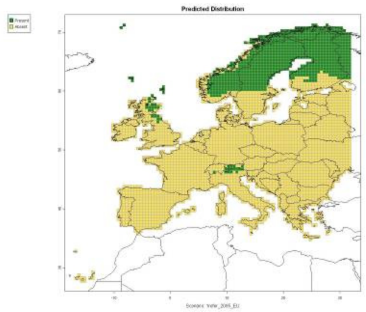
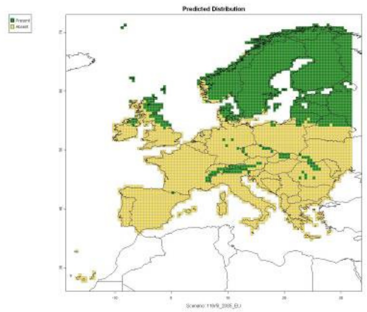
	Stoat (*Mustela ermine*)		Red Currant (*Ribes spicatum*)	
	A1B	2016.R5.L	A1B	2016.R5.L
2015-2044				
2035-2064				
2070-2099				

SENSITIVITY STUDY: 10% OUTCOME OF CLIMATE CHANGE SCENARIO 2016.R5.L AND ClimGen TUNED to HadCM3: AT RISK EUROPEAN MAMMALS AND PLANTS

	2015-2044			2035-2064			2070-2099		
Category	A1B	2016.R5.L	A1B-2016.R5.L	A1B	2016.R5.L	A1B-2016.R5.L	A1B	2016.R5.L	A1B-2016.R5.L
European Mammals									
Least Concern	100	104	4	87	97	10	77	95	18
Near Threatened	20	16	-4	12	12	0	6	10	4
Vulnerable	1	1	0	19	11	-8	13	15	2
Endangered	0	0	0	3	1	-2	19	1	-18
Critically Endangered	0	0	0	0	0	0	6	0	-6
European Plants									
Least Concern	202	203	1	181	190	9	163	189	26
Near Threatened	12	11	-1	15	17	2	6	16	10
Vulnerable	6	7	1	20	10	-10	32	11	-21
Endangered	1	0	-1	5	4	-1	13	5	-8
Critically Endangered	0	0	0	0	0	0	7	0	-7

IMPACTS USING 10% (MEDIAN) CLIMATE CHANGE OUTCOME AND ClimGen TUNED to HadCM3: PROJECTED POTENTIALLY SUITABLE CLIMATE SPACE FOR A EUROPEAN MAMMAL (*MUSTELA ERMINE*) AND A EUROPEAN PLANT (*RIBES SPICATUM*)

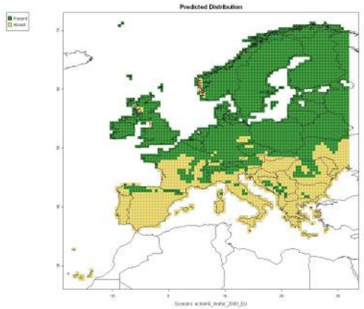
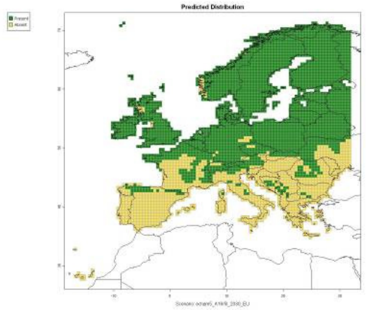
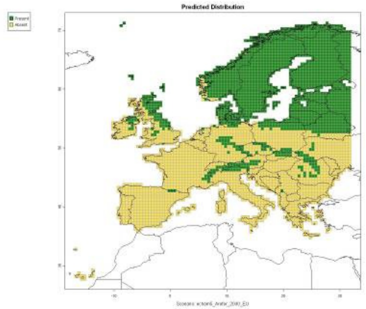
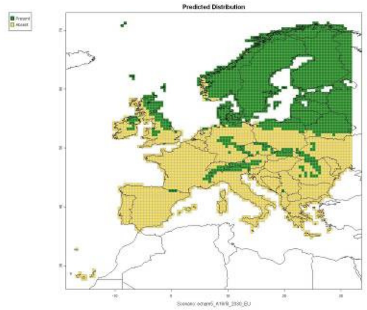
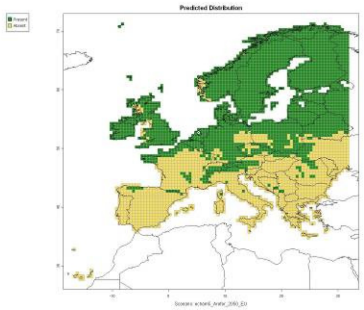
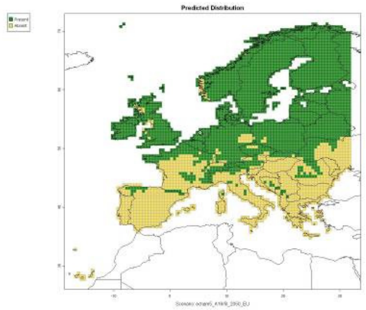
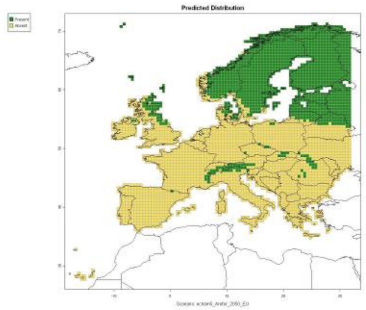
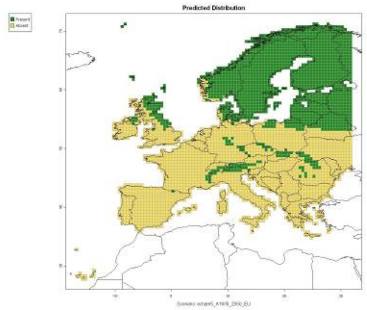
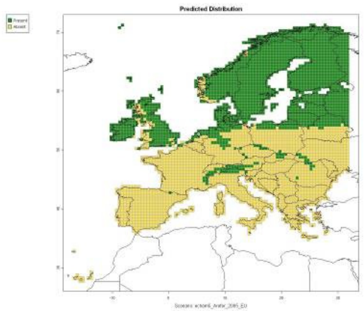
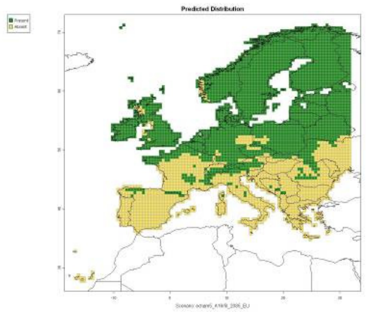
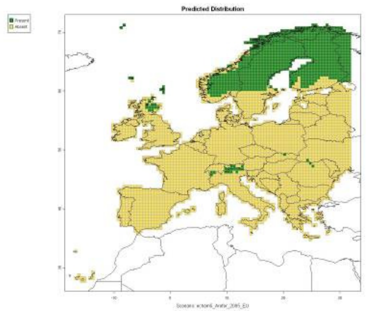
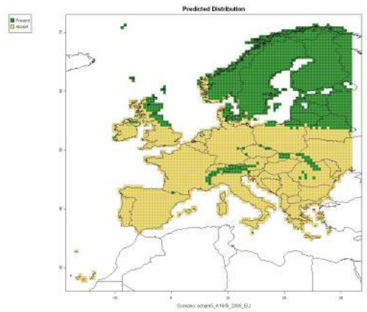
Green = found, tan = not found

	Stoat (*Mustela ermine*)		**Red Currant (*Ribes spicatum*)**	
	A1B	2016.R5.L	A1B	2016.R5.L
2015-2044				
2035-2064				
2070-2099				

SENSITIVITY STUDY: 50% OUTCOME OF CLIMATE CHANGE SCENARIO 2016.R5.L AND ClimGen TUNED to ECHAM5: AT RISK EUROPEAN MAMMALS AND PLANTS

	2015-2044			2035-2064			2070-2099		
Category	**A1B**	**2016.R5.L**	**A1B-2016.R5.L**	**A1B**	**2016.R5.L**	**A1B-2016.R5.L**	**A1B**	**2016.R5.L**	**A1B-2016.R5.L**
European Mammals									
Least Concern	103	104	1	90	96	6	71	94	23
Near Threatened	11	11	0	9	12	3	14	9	-5
Vulnerable	7	6	-1	15	12	-3	14	14	0
Endangered	0	0	0	7	1	-6	16	4	-12
Critically Endangered	0	0	0	0	0	0	6	0	-6
European Plants									
Least Concern	200	202	2	184	194	10	158	189	31
Near Threatened	17	15	-2	15	14	-1	25	11	-14
Vulnerable	4	4	0	15	9	-6	17	16	-1
Endangered	0	0	0	7	4	-3	13	5	-8
Critically Endangered	0	0	0	0	0	0	8	0	-8

IMPACTS USING 50% (MEDIAN) CLIMATE CHANGE OUTCOME AND ClimGen TUNED to ECHAM5:
PROJECTED POTENTIALLY SUITABLE CLIMATE SPACE FOR A EUROPEAN MAMMAL (*MUSTELA ERMINE*) AND A EUROPEAN PLANT (*RIBES SPICATUM*) Green = found, tan = not found

	Stoat (*Mustela ermine*)		**Red Currant (*Ribes spicatum*)**	
	A1B	2016.R5.L	A1B	2016.R5.L
2015-2044				
2035-2064				
2070-2099				

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6.2 Effects of climate policy on soil organic carbon (SOC) stocks and fluxes

6.2.1 Methodology and indicators

The assessment of the effects of different climate policies on soil carbon stocks and fluxes was undertaken using the RothC model run at a spatial resolution of 0.5x0.5o with climate scenarios constructed by rescaling climate model output to the global temperature changes associated with each climate policy. The analysis reported here uses climate change patterns derived from the HadCM3 climate model.

The RothC model

The RothC model (Coleman and Jenkinson 1996) is one of the most widely used SOC models (e.g. Post et al. (1982), Jenkinson et al. (1991), McGill (1996)) and has been evaluated in a wide variety of ecosystems including croplands, grasslands and forests
(e.g. Coleman & Jenkinson (1997), Smith et al. (1997), Falloon & Smith (2002))
and in various climate regions, including arid environments (Jenskinson et al. (1990), Skjemstad et al. (2004). It has been used to make regional and global scale predictions in a variety of studies (Post et al., (1982), Wand & Polglase (1995), Falloon et al. (1998), Tate et al. (2000), Falloon & Smith (2002), Smith et al. (2006), Smith et al. (2007).
The model has previously been adapted to run with large spatial data sets and to use potential evapotranspiration (PET) in place of open pan evaporation. Further details of the method of running the model was described in (Smith, Smith et al. 2005) .

The RothC model includes five pools of SOM: DPM (= decomposable plant material), RPM (= resistant plant material), BIO (= microbial biomass), HUM (= humified OM) and IOM (= inert OM). Each pool, apart from IOM, decomposes by first order kinetics and using a rate constant specific to the pool. Each pool decomposes into CO_2, BIO and HUM. The proportion of BIO to HUM is a fixed parameter whereas the proportion of CO_2 to BIO+HUM varies according to the clay content. Less clay leads to a relatively higher loss of CO_2. Decomposition is sensitive to the temperature, soil moisture and clay content of the soil, and so soil texture, monthly climate, land use and cultivation data are the inputs to the model (Coleman and Jenkinson 1996; Smith, Smith et al. 1997).

Soil data

Mean SOC stocks in t C ha-1 to 30 cm depth and the percentage of clay are derived from the ISRIC-WISE global data set of derived soil properties on a 0.5 by 0.5 degree grid (Version 3.0) (Batjes, 2005). Each grid cell is covered by up to ten dominant soil types. Each of these soil types are simulated consecutively in conjunction with the same input data within one scenario simulation.

Net primary production (NPP) & land use data

NPP and land use data are taken from the IMAGE 2.3 model. IMAGE land use classes were classified into the three land use types which are used in RothC. The classification is shown in

Landuse (IMAGE 2.3)	New landuse code according to ROTHC
Agricultural land	1 – arable
Extensive grassland	2 – grassland
C plantations (not used)	No cells
Regrowth forest (Abandoning)	3 – forest

Regrowth forest (Timber)	3 – forest
biofuel	1 – arable (for now)
Ice	-9999
Tundra	2 – grassland
Wooded tundra	2 – grassland
Boreal forest	3 – forest
Cool conifer	3 – forest
Temperate mixed forest	3 – forest
Temperate deciduous forest	3 – forest
Warm mixed forest	3 – forest
Grassland/steppe	2 – grassland
Hot desert	-9999
Scrubland	2 – grassland
Savanna	2 – grassland
Tropical woodland	3 – forest
Tropical forest	3 – forest

Table 1.

Landuse (IMAGE 2.3)	**New landuse code according to ROTHC**
Agricultural land	1 – arable
Extensive grassland	2 – grassland
C plantations (not used)	No cells
Regrowth forest (Abandoning)	3 – forest
Regrowth forest (Timber)	3 – forest
biofuel	1 – arable (for now)
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Boreal forest	3 – forest
Cool conifer	3 – forest
Temperate mixed forest	3 – forest
Temperate deciduous forest	3 – forest
Warm mixed forest	3 – forest
Grassland/steppe	2 – grassland
Hot desert	-9999
Scrubland	2 – grassland
Savanna	2 – grassland
Tropical woodland	3 – forest
Tropical forest	3 – forest

Table 1 Classification of IMAGE land use types into RothC land cover classes.

The indicators of climate impact used are the amount of carbon stored in soils, and changes in the flux of carbon between soil and atmosphere. SOC stores constitute the largest pool of the terrestrial C stores. CO_2 emissions from soils are estimated to be 7.9 Pg C per year, contributing 6-39% of the total emissions of CO2 to the atmosphere (IPCC 2007). SOC largely determines the natural productivity of ecosystems by influencing the soil structure, soil water regime and soil fertility. Due to its large size and long residence time, SOC stocks could also be a large sink of carbon taken up from the atmosphere (Post, Emanuel et al. 1982). However, human disturbance has caused a large loss of SOC, estimated to have contributed 11-35 ppm from 1850 to 2000 (IPCC 2007).

6.2.2 Results

Model results were first aggregated over the 10 dominant soil types and all land uses (arable, grassland, forest) to yearly total SOC / cell (half-degree grid). To visualise the impacts, the results of each policy scenario were compared to the reference scenario A1b. Assuming that SOC stocks are greater under the mitigating policy scenarios, the results of the reference scenario were subtracted from the scenario results. Hence, positive values represent the avoided loss of SOC under a policy scenario compared to A1b (Figures 1-3).

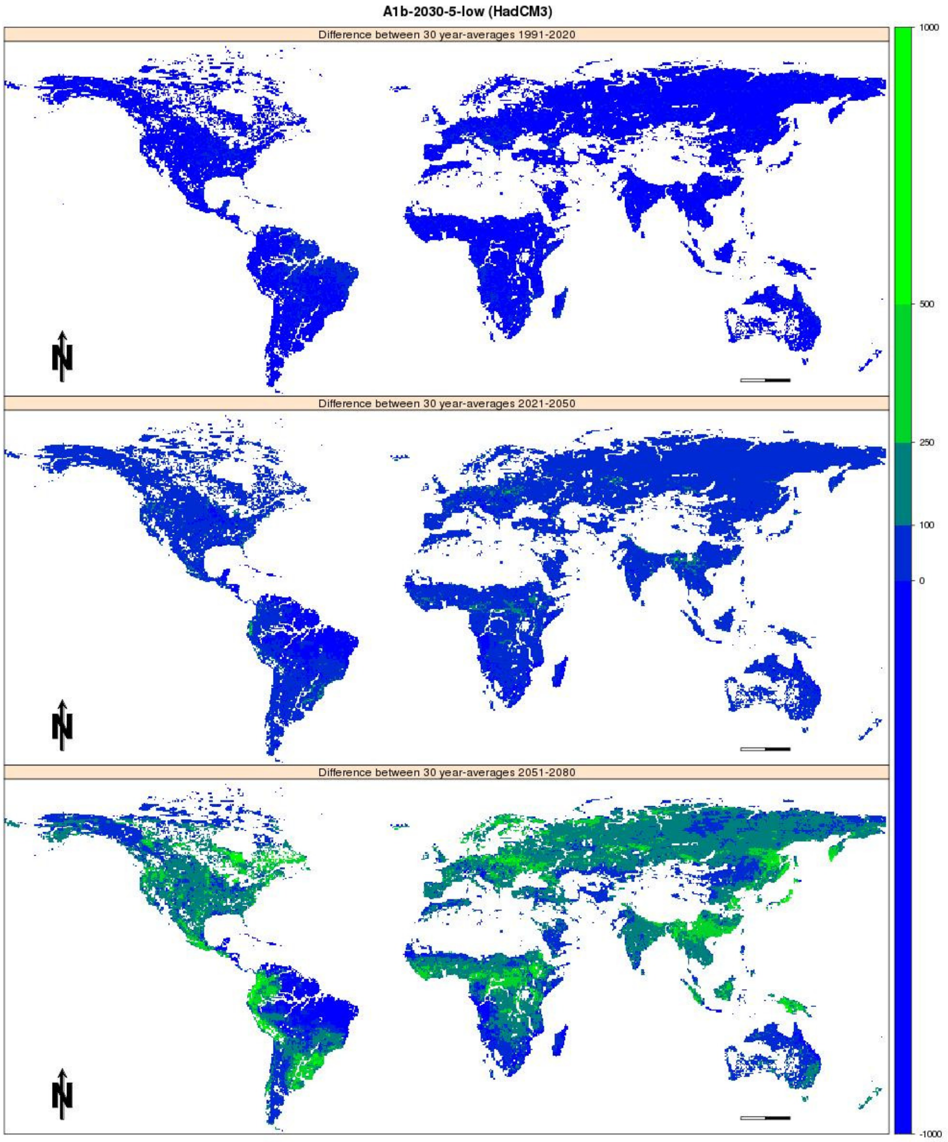

Figure 1

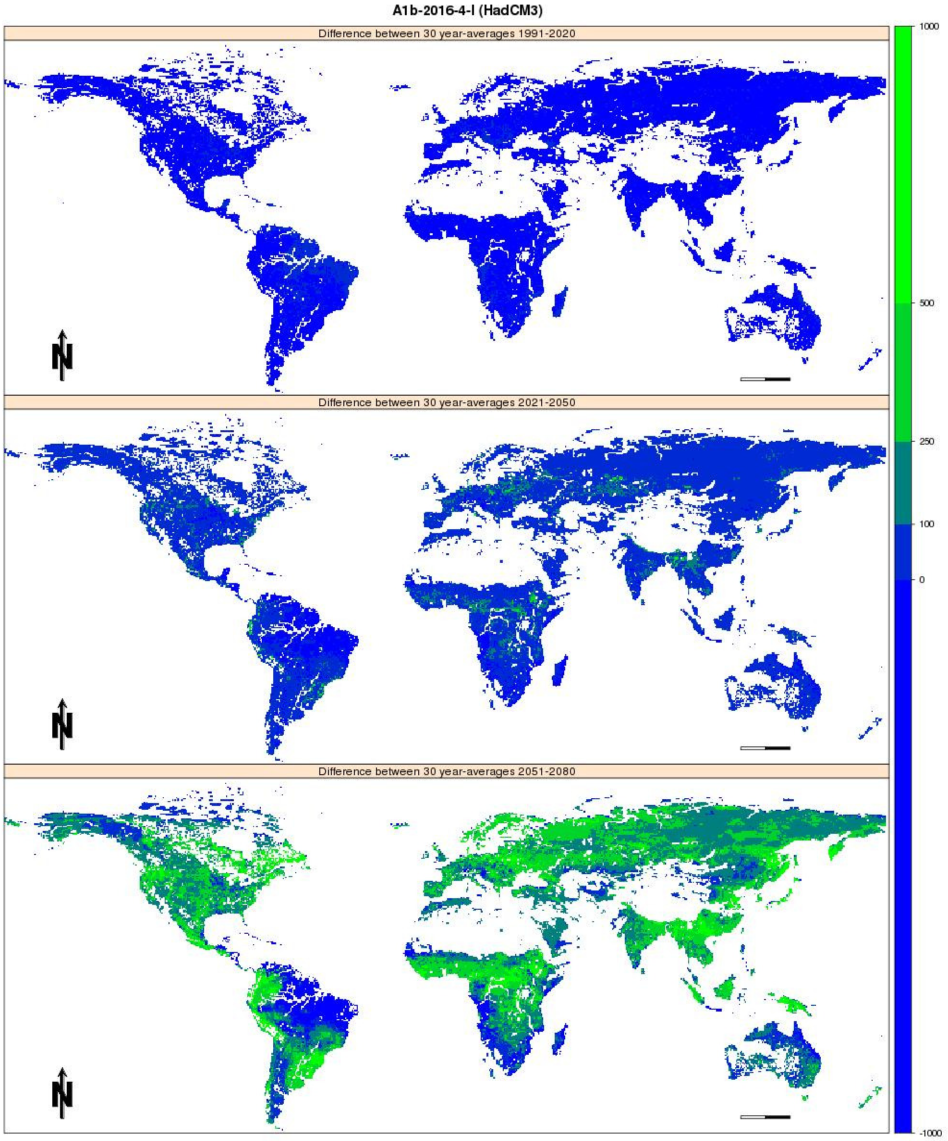
A1b-2016-4-I (HadCM3)
Difference between 30 year-averages 1991-2020
Difference between 30 year-averages 2021-2050
Difference between 30 year-averages 2051-2080
1000
500
250
100
0
-1000
N

Figure 2

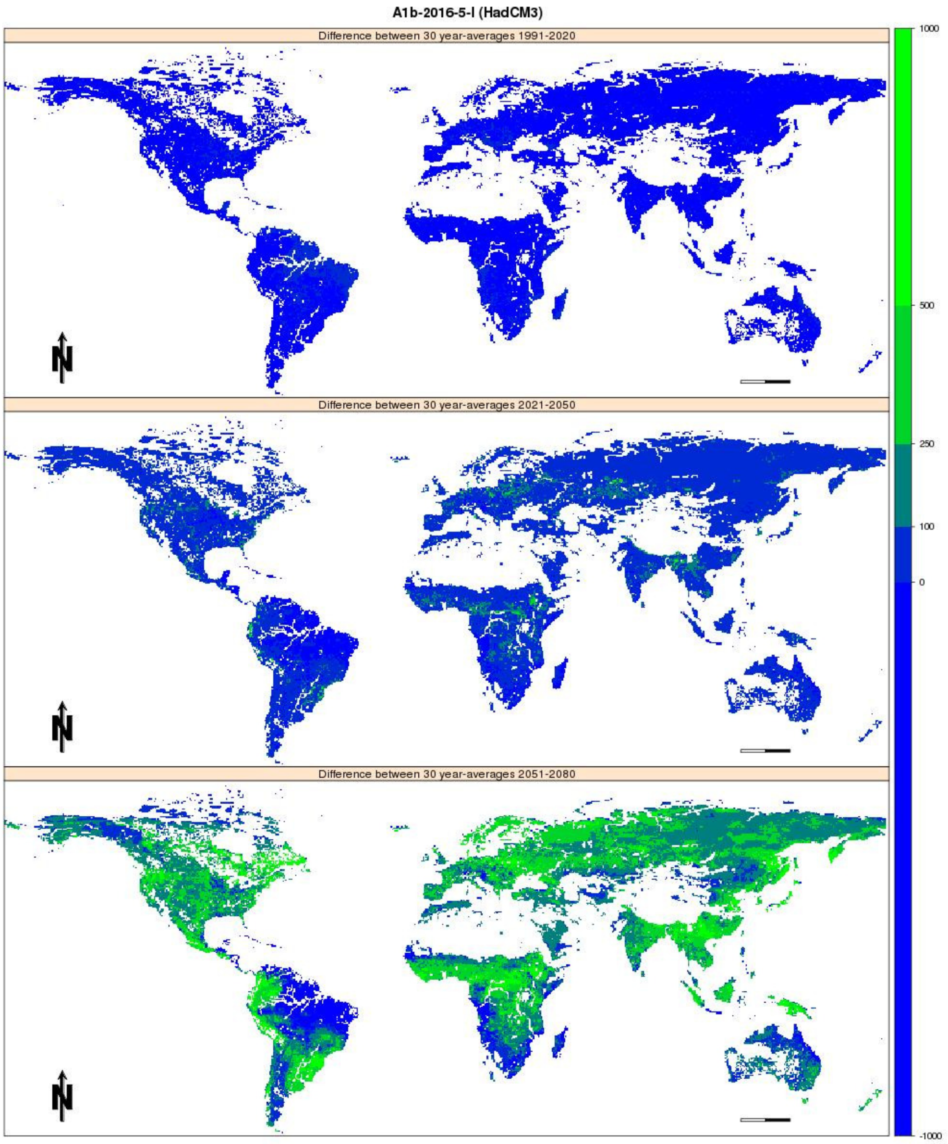

Figure 3

- **Mitigation slows down the rate at which stocks of carbon in soils are depleted**
- **There is strong regional variability in impact increasing with time**

6.2.3 Discussion

Current simulations did not take into account the impact of climate change on NPP which is also a driving variable of these simulations. The results shown here are based on one set of NPP values which does not vary between the simulations. Therefore, the differences in soil carbon stocks only reflect the differences in the climate variables of the scenarios and lower temperature under the policy scenarios lead to a slower turnover of SOC and hence to a slower rate of SOC stock depletion. However, lower temperature under policy scenarios would also decrease NPP values. This might balance or counteract the slower turnover of SOC and needs to be taken into account in further studies.

6.2.4 References

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7. COASTAL SYSTEMS

7.1 How the DIVA model works

This study uses the DIVA model to estimate the following impacts of sea-level rise assuming an A1B socio-economic scenario:

1. The coastal flood plain population (i.e. the exposed population);
2. People at risk of coastal flooding, with and without improving protection (i.e. those who might experience flooding, taking account of defences);
3. Sea dike costs (to protect people from floods);
4. Saltmarsh loss;
5. Mangrove loss.

The sea-level rise scenarios are global-mean estimates derived from thermal expansion from the MAGICC model and ice melt due to global temperature rise using methods based on the IPCC Fourth Assessment report (Meehl et al., 2007). In IPCC AR4 21st century sea level projections for business as usual simulations are dominated by thermal expansion, and this is likely to be even more dominant in aggressive mitigation scenarios. We have incorporated the uncertainty in this term using the 10th, 50th and 90th percentiles from the climate model. Hence note that different AOGCMs are not compared in this section. Note that for some parameters (e.g. dike costs), results are also reported for a no sea-level rise scenario, so the global warming effect can be isolated.

The DIVA model (DINAS-COAST Consortium, 2006) is an integrated model of coastal systems that assesses biophysical and socio-economic impacts of sea-level rise and socio-economic development. It is based on 12,148 segments which collectively described the world's coast, except Antarctica (McFadden et al., 2007; Vafeidis et al., 2008). One important innovation introduced by DIVA is the explicit incorporation of a flexible range of adaptation options; impacts do not only depend on the selected climatic and socio-economic scenarios but also on the selected adaptation strategy.

DIVA first downscales the sea-level rise scenarios due to global warming by combining them with estimates of vertical land movement in each coastal segment to determine relative sea-level rise. Then four types of bio-physical impacts are assessed for each segment: (1) dry land loss due to coastal erosion, (2) flooding, (3) salinity intrusion in deltas and estuaries, and (4) wetland loss and change. Only the aspects of DIVA relevant to this study are considered here.

The flooding of the coastal zone caused by sea-level rise and associated storm surges is assessed. Large parts of the coastal zone are already threatened by flooding due to extreme sea levels produced during storms. These extreme events produced by a combination of storm surges and astronomical tides will be raised by mean sea level: the return period of extreme sea levels is reduced by higher mean sea levels. The magnitude of this effect depends on the shape of the exceedance curve. Sea-level rise also raises water levels in the coastal parts of rivers (via the backwater effect), increasing the probability of extreme water levels. DIVA considers both these flooding mechanisms. Due to the difficulties of predicting changes in storm surge characteristics, the present storm surge characteristics are simply displaced upwards with the rising sea level following 20th Century observations (e.g., Zhang et al., 2000; Woodworth and Blackman, 2004). Taking into account the effects of dikes, flood areas for a range of return periods are computed. River flooding is evaluated along 200 major rivers, contained in the DIVA database. The population of the coastal flood plain (the number of people below the 1 in 1,000 year flood elevation) and the number of people experiencing flooded (the expected number of people subject to flooding per year taking into account population, relative elevation and the effect of defences) are used as indicators of flooding.

The adaptation option considered for flooding is dikes, building on the global analysis of Hoozemans et al (1993). Since there is no empirical data on actual dike heights available at a global level, dikes heights were estimated for the base year (1995) using a demand for safety function which is increases with per capita income and population density and decreases in the costs of dike building. (This demand function is posited as the solution to a cost-benefit analysis (Tol, 2006)). DIVA implements different adaptation options. The simplest strategy is no adaptation (as considered here), in which DIVA computes potential impacts in a traditional impact analysis manner. In this case dike heights are maintained at 1995 heights, but not raised, so flood risk rises with time as relative sea level rises. For the adaptation scenario, the demand function for safety is applied through time, subject to population density. Dikes are only built when population density exceeds 1 person/km^2, with an increasing proportion of the recommended height being built as population density rises – for example, 98% of the dike height is built at densities of 1000 persons/km^2. Based on these improving dikes, and the other factors, the number of people actually flooded can again be computed. The costs of dikes are calculated based on the length of the defence and the unit costs reported by Hoozemans et al. (1993).

The loss and change in coastal wetlands is assessed in terms of wetland area and composition of wetland vegetation types. Wetlands respond to sea-level rise by horizontal inland migration, vertical elevation change and transitions to other wetland types (Nicholls et al., 1999; McFadden et al., 2007). The response is a function of the relation of relative sea-level rise to tidal range, sediment supply and migration space. The latter is, in turn, negatively influenced through the building of sea dikes. Six different wetland types are considered in DIVA, including saltmarsh and mangroves. DIVA includes a global database on the current occurrence which is used to establish a starting baseline.

7.2 What the main results are and what they mean

Six main conclusions can be drawn from the results:

1. ***While six emission scenarios were considered, in terms of global sea-level rise and coastal impacts only three distinct sets of change are apparent.***
   Of the six emissions scenarios considered, in terms of the resulting global sea-level rise and its impacts, three *families* of scenarios are apparent relating to no emission reductions and the 2016.R and 2030.R policy scenarios, respectively. Within a family, sea-level rise (and hence impacts) is in practical terms indistinguishable even at 2100 within each policy family (Figures 7.1 and 7.2). Hence, it is only meaningful to analyze each policy family (Table 7.1) and the later figures only show three emissions scenarios: (1) SRES A1B, (2) 2016.R5.Low, and (3) 2030.R5.Low. The subtleties of the different mitigation actions within each family of policies will have no influence on coastal impacts during the 21st Century.

   Table 7.1. The sea-level rise scenarios considered and those selected for detailed analysis (in bold). For those selected, the 10th, 50th and 90th percentiles of sea-level rise prediction were considered.

Emissions Scenario	Family
SRES A1B (Unmitigated)	Family One (SRES A1B)
2016.R2.High	Family Two (2016.R policy scenarios)
2016.R4.Low	
2016.R5.Low	

2030.R2.High	Family Three (2030.R policy scenarios)
2030.R5.Low	

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2. ***Emission reductions will reduce the global losses of saltmarsh and mangrove by 2080s, but there are negligible benefits before the 2050s.***
   Impacts are almost identical to the 2050z and diverge thereafter. The net losses by the 2080s are shown in Figures 7.3 and 7.4. Under the 2016.R policy scenario, losses of saltmarsh are reduced by 6% to 7%, and mangrove losses by 4% to 5%. These translate into saved areas of about 3,900 to 4,500 square kilometres, and 8,800 to 10,500 square kilometres, respectively. The benefits under the 2030.R policy are lower.

3. ***The coastal flood plain population is insensitive to future sea-level rise.***
   The number of people in the coastal flood plain is about 200 million people in 2000 and changes are mainly determined by socio-economic change (and hence the coastal flood plain population follow the A1B population scenario in falling after 2050). Hence, mitigation has little effect on these numbers (Figure 7.5).

4. ***However, emission reductions will reduce the global number of people experiencing flooding by 2050, and the benefits are substantial by 2100, assuming no adaptation.***
   The number of people who experience flooding grows rapidly with sea-level rise (and also to a lesser degree the growing coastal population under the A1B socio-economic scenario). Presently, DIVA estimates that about 3 million people per year experienced coastal flooding in 2000. By 2050 this number grows 6.5 to 10 times without mitigation (Figure 7.6). The 2016.R scenarios can reduce the number of people being flooded by 2 to 5 million per year. By 2100, the effect of mitigation is much larger, and the reduction of people could be 36 to 69 million people per year under the 2016.R scenario. However, even with this policy scenario, the incidence of flooding will have increased 10 to 20 times on levels in 2000, and significant adaptation would also be necessary.

5. ***These reductions in flood impacts represent delayed rather than avoided damages***
   Earlier research by Nicholls and Lowe (2004) demonstrated that climate mitigation will only delay rather than avoid flood impacts due to the inertia in sea-level rise which will increase for centuries even if climate is stabilised. In other words, the impacts avoided during the 21st Century are still expected to occur in the 22nd Century. This further reinforces the importance of adaptation for coastal areas.

6. ***Assuming quazi-optimum adaptation greatly reduces any benefits of adaptation.***
   Figure 7.7 shows the absolute number of people experiencing flooding under the 9 emission scenarios assuming a quazi-optimum adaptation via protection using dikes. It is hard to distinguish the lines, even though there is a large difference in sea-level rise of up to about 35 cm, and the impacts diminish with time. In this analysis the main effect of sea-level rise is to increase the investment in protection (Figure 7.8). The main message is that effective adaptation can greatly reduce the benefits of mitigation and this raises the question about the appropriate mixture of the two policies raised in the IPCC AR4 assessment (Nicholls et al., 2007).

7.3 Caveats

There are several caveats that are important to not about the results and their interpretation:

- The benefits of saving coastal wetlands identified here require that the wetlands are conserved to be impacted by sea-level rise. Wetlands are declining rapidly due to non-climate stress (e.g., Hoozemans et al., 1993; Coleman et al., 2008). Based on these observed trends, Nicholls (2004) argues that climate is a secondary threat to these systems compared to direct and other indirect human stresses. Under business-as-usual conditions, 50% to 60% of existing saltmarsh and mangrove areas could be destroyed by direct and indirect human pressures, excluding climate change.
- Different socio-economic scenarios (population and gdp) would give different human impacts for the same sea-level rise scenarios. As well as the global assumptions, net coastward migration has been significant during the last few decades, and it could also be an important process in terms of increasing exposure and risks in the future (see Nicholls, 2004). This has not been considered in these results.
- Protection may not be implemented as effectively as the projections in DIVA suggest (e.g. see discussion in Nicholls and Tol, 2006). On the other hand, a scenario of no adaptation is definitely implausible. This work shows how important adaptation will to determine future impacts in coastal areas. In terms of uncertainty about coastal impacts, the success or failure of adaptation is our biggest uncertainty with wildly different viewpoints being apparent (Nicholls and Tol, 2006; Nicholls et al., 2007).

  The dike costs assume prefect foresight: a precautionary approach to adaptation would raise costs substantially (of order two times or more) (see for example the guidance on sea-level rise by DEFRA (2006) or the US Army Corps of Engineers (2009)). While in theory, there are substantial savings in dike costs due to mitigation (see Figure 7.8), due to the large uncertainties about future sea levels these are likely to difficult to realise during the 21st Century. Looking beyond the 21st Century timescale, real cost savings could be substantial.

Table 7.1 GLOBAL-MEAN SEA-LEVEL RISE SCENARIOS BY EMISIONS SCENARIO (IN METRES). THE RANGE OF UNCERTAINTY IS EXPRESSED BY THE PERCENTILE RANGE FOR EACH EMISSIONS SCENARIO. THE BASE PERIOD IS 1961 TO 1990.

Emissions Scenario	Percentile	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**	**2080**	**2090**	**2100**
SRES A1B	10th	0.05	0.07	0.08	0.11	0.14	0.17	0.21	0.25	0.29	0.33	0.37
	50th	0.06	0.08	0.10	0.13	0.17	0.21	0.26	0.31	0.36	0.42	0.47
	90th	0.07	0.09	0.12	0.15	0.20	0.25	0.31	0.37	0.44	0.51	0.58
A1B.2016.R2.high	10th	0.05	0.07	0.09	0.11	0.13	0.16	0.18	0.20	0.22	0.23	0.25
	50th	0.06	0.08	0.10	0.13	0.16	0.19	0.22	0.25	0.28	0.30	0.33
	90th	0.07	0.09	0.12	0.15	0.19	0.23	0.26	0.30	0.34	0.37	0.40
A1B.2016.R4.low	10th	0.05	0.07	0.09	0.11	0.13	0.15	0.17	0.19	0.21	0.22	0.23
	50th	0.06	0.08	0.10	0.13	0.16	0.19	0.22	0.24	0.27	0.29	0.31
	90th	0.07	0.09	0.12	0.15	0.19	0.23	0.26	0.30	0.33	0.36	0.39
A1B.2016.R5.low	10th	0.05	0.07	0.09	0.11	0.13	0.16	0.17	0.19	0.21	0.22	0.23
	50th	0.06	0.08	0.10	0.13	0.16	0.19	0.22	0.24	0.27	0.29	0.31
	90th	0.07	0.09	0.12	0.15	0.19	0.23	0.26	0.30	0.33	0.36	0.39
A1B.2030.R2.high	10th	0.05	0.07	0.09	0.11	0.13	0.16	0.19	0.22	0.24	0.27	0.28
	50th	0.06	0.08	0.10	0.13	0.16	0.20	0.24	0.27	0.31	0.34	0.37
	90th	0.07	0.09	0.12	0.15	0.19	0.24	0.28	0.33	0.37	0.42	0.46
A1B.2030.R5.low	10th	0.05	0.07	0.09	0.11	0.13	0.16	0.19	0.21	0.24	0.25	0.27
	50th	0.06	0.08	0.10	0.13	0.16	0.20	0.24	0.27	0.30	0.33	0.35
	90th	0.07	0.09	0.12	0.15	0.19	0.24	0.28	0.32	0.37	0.40	0.44

Table 7.2 GLOBAL RESULTS FOR MANGROVE AREA AND SALTMARSH AREA.

Emissions Scenario	Percentile	Mangroves (sq. km)			Saltmarsh (sq. km)		
		2025	2055	2085	2025	2055	2085
SRES A1B	10th	226361	213650	195601	63365	57363	49774
	50th	225632	210267	191249	62985	55816	47339
	90th	224862	208018	186581	62615	54606	45493
A1B.2016.R2.high	10th	226335	215190	203949	63339	58251	53381
	50th	225547	212999	199182	62968	57019	51374
	90th	224862	210584	195693	62542	56134	49701
A1B.2016.R4.low	10th	226309	215287	204392	63330	58312	53549
	50th	225552	213004	199488	62969	57134	51628
	90th	224862	210767	197035	62542	56172	49905
A1B.2016.R5.low	10th	226310	215279	204471	63330	58314	53647
	50th	225563	213014	199887	62969	57134	51690
	90th	224862	210816	197092	62542	56159	49948
A1B.2030.R2.high	10th	226346	214040	200442	63340	57800	52198
	50th	225583	212160	197458	62972	56750	50245
	90th	224862	208934	190722	62611	55201	47520
A1B.2030.R5.low	10th	226346	214040	201738	63340	57800	52586
	50th	225583	211972	197942	62972	56725	50486
	90th	224862	208924	191306	62611	55199	47872

Table 7.3 GLOBAL RESULTS FOR COASTAL FLOOD PLAIN POPULATION, PEOPLE FLOODED PER YEAR, AND SEA DIKE COSTS ASSUMING CONSTANT PROTECTION (I.E. NO UPGRADE).

Emissions Scenario	Percentile	Flood plain population (000s)			People flooded per year (000s)			Sea dike costs (millions US dollars/year, 1995 dollars)		
		2025	2055	2085	2025	2055	2085	2025	2055	2085
No sea-level rise	n/a	250354	267097	237270	4755	6799	8200	0	0	0
SRES A1B	10th	253173	275300	250591	8418	25160	56352	0	0	0
	50th	253755	277279	254196	9886	32072	81944	0	0	0
	90th	254335	279251	257762	11683	40680	112126	0	0	0
A1B.2016.R2.high	10th	253229	273892	246099	8440	21287	32830	0	0	0
	50th	253822	275730	248989	9906	26111	48327	0	0	0
	90th	254414	277552	251814	13552	33022	66350	0	0	0
A1B.2016.R4.low	10th	253229	273804	245680	8440	21028	31114	0	0	0
	50th	253822	275645	248535	9906	25684	46562	0	0	0
	90th	254414	277470	251328	13552	32917	59172	0	0	0
A1B.2016.R5.low	10th	253229	273808	245603	8440	21030	31011	0	0	0
	50th	253821	275653	248460	9906	25685	46300	0	0	0
	90th	254413	277481	251254	13551	32927	58766	0	0	0
A1B.2030.R2.high	10th	253208	274544	247677	8430	22786	40375	0	0	0
	50th	253795	276435	250794	9901	28169	57280	0	0	0
	90th	254382	278316	253890	13501	35968	80737	0	0	0
A1B.2030.R5.low	10th	253208	274571	247210	8430	22809	38391	0	0	0
	50th	253795	276469	250315	9901	28197	54912	0	0	0
	90th	254382	278357	253385	13501	36041	77379	0	0	0

Table 7.4 GLOBAL RESULTS FOR PEOPLE FLOODED PER YEAR, ASSUMING PROTECTION UPGRADE BASED ON A QUAZI-OPTIMUM ANALYSIS. TOTAL AND THE CLIMATE-INDUCED DIKE COSTS ARE DISTINGUISHED. COASTAL FLOOD PLAIN POPULATION ARE THE SAME VALUES AS IN TABLE 7.3.

Emissions Scenario	Percentile	People flooded per year (000s)			Total Sea dike costs (millions US dollars/year, 1995 dollars)			Climate-Induced Sea dike costs (millions US dollars/year, 1995 dollars)		
		2025	2055	2085	2025	2055	2085	2025	2055	2085
No sea-level rise	n/a	1845	469	169	7030	4857	3192	0	0	0
SRES A1B	10th	1954	524	193	9264	9382	8939	2234	4525	5747
	50th	1963	538	202	9840	10745	10626	2810	5888	7435
	90th	1989	555	216	10428	12080	12325	3398	7223	9134
A1B.2016.R2.high	10th	1956	502	179	9376	7511	5535	2346	2654	2344
	50th	1964	520	183	9970	8642	6626	2940	3785	3434
	90th	1990	532	189	10578	9790	7735	3548	4933	4543
A1B.2016.R4.low	10th	1956	502	178	9373	7303	5259	2343	2447	2067
	50th	1964	515	183	9965	8439	6246	2935	3582	3054
	90th	1990	532	185	10571	9598	7256	3541	4741	4064
A1B.2016.R5.low	10th	1956	502	178	9369	7284	5171	2339	2428	1979
	50th	1964	515	182	9962	8429	6137	2932	3572	2946
	90th	1990	532	185	10568	9596	7129	3538	4739	3937
A1B.2030.R2.high	10th	1956	513	182	9344	8411	6472	2313	3554	3281
	50th	1964	530	188	9929	9644	7788	2898	4787	4597
	90th	1990	542	196	10527	10869	9106	3497	6012	5914
A1B.2030.R5.low	10th	1956	513	180	9344	8484	5921	2313	3628	2729
	50th	1964	530	185	9929	9735	7128	2898	4879	3936
	90th	1990	547	194	10527	10978	8341	3497	6121	5150

Table 7.5 Regional results for people flooded per year (000s) for selected sea-level rise scenarios and no adaptation.

AVOID Regions		A1B									A1B.2016.R5.low									A1B.2030.R5.low								
		10th percentile			50th percentile			90th percentile			10th percentile			50th percentile			90th percentile			10th percentile			50th percentile			90th percentile		
		2025	**2055**	**2085**	**2025**	**2055**	**2085**	**2025**	**2055**	**2085**	**2025**	**2055**	**2085**	**2025**	**2055**	**2085**	**2025**	**2055**	**2085**	**2025**	**2055**	**2085**	**2025**	**2055**	**2085**	**2025**	**2055**	**2085**
1	China	625.8	2714.5	9290.9	673.3	3786.3	11642	676.4	4919.4	17858	625.93	1786.8	3560.5	673.5	2740.4	8398.3	678.2	3792.6	9561.7	625.86	2216.8	5973.9	673.4	3468.0	9233.4	678.1	3895.3	11375.3
2	US	21.8	45.5	206.8	22.3	56.5	404.2	23.4	66.8	1038.9	21.772	42.9	104.2	22.4	46.7	168.1	23.5	57.0	241.8	21.8	44.3	116.5	22.3	50.0	185.7	23.4	59.7	365.8
3	Russia	35.1	78.7	208.9	36.6	83.9	342.6	37.9	100.7	430.5	35.144	65.0	77.0	36.6	79.6	186.2	37.9	84.3	214.1	35.1	70.4	82.6	36.6	83.2	204.9	37.9	94.5	293.0
4	Japan	1.5	5.8	25.8	2.0	11.8	121.6	2.1	16.3	233.8	1.5235	2.8	10.9	2.0	5.8	19.2	2.2	13.2	27.0	1.5	3.1	13.9	2.0	6.3	23.8	2.2	15.2	103.9
5	South Africa	0.4	2.1	16.6	0.4	3.3	33.2	0.5	5.4	116.7	0.4293	2.0	2.7	0.4	2.3	5.0	0.6	3.3	18.1	0.4	2.1	3.4	0.4	2.9	13.1	0.6	5.0	21.3
6	India	1152.8	4392.3	8632.0	1484.3	5178.8	13569	1517.7	6083.9	19709	1156.3	3132.1	4714.9	1485.5	4448.3	6542.5	1521.1	5699.4	8893.6	1153.0	3214.5	5052.4	1485.0	5041.9	8510.5	1519.0	5923.8	13049.2
7	Brazil	110.9	266.7	1039.8	114.5	476.1	1585.1	122.3	654.3	2444.7	113.24	224.5	412.9	117.9	289.8	617.1	122.7	489.0	1108.3	113.2	245.9	456.4	117.9	303.9	1036.8	122.3	603.0	1490.6
8	Mexico	17.5	61.5	283.7	18.1	89.4	441.9	19.3	120.5	561.5	17.57	40.4	152.5	18.3	70.1	210.2	19.8	90.3	345.7	17.5	50.1	197.6	18.1	80.6	229.7	19.8	110.4	421.8
9	Canada	29.8	45.6	119.1	30.4	48.9	252.5	30.6	69.8	432.6	29.97	39.2	66.1	30.4	45.9	97.9	30.6	56.3	126.1	29.9	42.3	88.5	30.4	47.1	118.8	30.6	59.9	217.7
10	Australia	11.1	16.1	23.7	11.4	16.6	43.6	11.6	20.1	78.0	11.091	12.9	14.7	11.4	16.2	18.6	11.6	16.6	26.1	11.1	14.3	15.7	11.4	16.4	23.6	11.6	17.8	40.5
11	Indonesia	360.5	872.4	3612.5	373.7	1810.2	5127.3	394.4	2834.7	6995.2	361.5	653.2	1586.6	375.7	989.4	2653.6	400.6	2025.1	3922.4	361.5	782.1	2280.2	373.7	1290.3	3393.5	400.3	2410.3	4872.5
12	South Korea	2.2	8.5	19.0	2.6	12.8	46.5	2.6	19.0	85.9	2.2352	7.3	7.6	2.6	10.1	14.3	2.6	12.8	36.5	2.2	8.5	10.1	2.6	10.2	16.7	2.6	13.5	37.9
13	UK	4.8	6.6	20.1	5.5	8.4	44.8	5.5	11.3	126.4	4.7554	6.0	7.7	5.5	6.8	12.7	5.5	8.5	27.2	4.8	6.2	9.3	5.5	7.7	19.5	5.5	9.3	38.1
14	France	2.7	3.8	13.0	2.8	5.7	36.5	2.8	7.9	64.1	2.7105	3.1	6.1	2.8	4.1	9.1	2.8	5.7	19.2	2.7	3.7	7.5	2.8	4.9	12.8	2.8	7.2	28.8
15	Italy	1.6	2.2	7.0	1.6	2.3	12.6	1.9	4.3	49.5	1.5937	1.9	3.6	1.6	2.2	4.3	1.9	2.4	7.9	1.6	2.1	4.0	1.6	2.3	6.9	1.9	4.1	12.0
16	Germany	2.1	4.8	18.2	2.2	5.2	24.7	2.2	5.2	119.4	2.1315	3.7	5.0	2.2	4.8	17.2	2.2	5.2	18.5	2.1	4.8	16.8	2.2	5.2	18.1	2.2	5.2	21.8
17	Poland	2.1	6.2	41.9	2.1	7.1	48.1	2.2	18.8	115.6	2.1422	4.8	14.2	2.1	6.3	31.0	2.2	7.1	42.1	2.1	4.9	14.8	2.1	6.3	33.9	2.2	7.9	43.6
18	Saudi Arabia	0.9	3.1	15.8	1.0	7.1	46.6	1.1	11.0	59.2	0.871	1.9	6.5	1.0	3.4	13.5	1.1	7.1	22.4	0.9	2.0	11.6	1.0	5.5	15.5	1.1	10.9	38.6
19	Rest of South Asia	1602.3	6341.0	8953.4	2403.3	8308.7	15640	132.2	1018.6	1515.8	1602.4	5816.3	8118.6	2403.6	6354.2	8710.5	4653.7	8317.6	9055.9	1602.4	6246.9	8254.5	2403.5	6536.7	8832.0	4625.2	9545.8	14419.6
20	Rest of East Asia	3006.5	5033.5	10835	3076.7	5506.1	14271	4206.5	7325.0	21422	3014.4	4836.7	5701.9	3083.9	5049.9	8927.5	4233.9	5538.3	11412	3013.4	4941.6	8123.3	3082.7	5145.3	10636	4216.8	5914.3	12634.4
21	Rest of Central Asia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	North Africa	57.4	236.9	1503.2	59.4	408.2	2168.7	64.2	593.7	4278.8	57.415	204.7	787.6	59.4	286.8	1299.0	64.4	409.0	1583.6	57.4	223.7	1045.9	59.4	366.1	1468.7	64.3	424.8	2127.1
23	West Africa	104.2	690.2	2152.7	212.4	890.1	2349.7	218.0	1135.5	3536.6	105.12	488.7	778.4	212.8	693.2	1137.4	236.7	891.6	2170.1	105.1	541.2	979.4	212.8	800.3	1669.9	236.7	982.2	2335.6
24	Southern and East Africa	992.1	3337.5	6145.7	1041.9	3734.3	8566.6	1152.1	4906.2	8719.4	992.27	2835.9	3385.3	1043.4	3375.3	4876.4	1152.4	3736.0	6155.8	992.2	3211.0	3729.4	1043.3	3617.5	6135.4	1152.3	4001.9	8522.3
25	Europe	38.3	116.4	463.3	41.3	155.3	1202.4	42.1	226.8	2089.1	38.587	82.5	147.9	41.3	120.6	282.7	42.3	169.4	715.9	38.4	108.8	229.7	41.3	132.6	450.8	42.2	208.2	1102.8
26	South America	129.5	339.7	1125.1	146.8	636.5	1689.4	165.6	854.0	2300.6	129.49	273.8	646.6	146.8	479.5	825.3	165.6	644.3	1316.6	125.9	290.3	531.7	143.2	457.9	872.3	162.2	577.1	1289.1
27	Central America	4.0	17.4	101.2	7.3	29.7	175.5	8.3	68.0	207.4	4.0253	13.7	23.0	7.3	24.9	61.7	8.3	29.9	113.7	4.0	14.9	30.2	7.3	26.6	98.3	8.3	35.7	171.0
28	Caribbean	14.1	63.2	432.9	22.1	173.2	734.7	26.5	261.9	857.9	19.154	58.6	113.9	22.1	67.1	321.7	27.7	175.8	489.6	14.4	60.3	206.7	22.1	97.2	388.6	26.6	198.6	681.6
29	Rest of Australasia	43.7	118.5	438.9	48.0	242.7	515.2	54.3	311.7	558.7	44.11	74.5	144.0	50.9	130.9	284.3	54.3	261.0	463.7	43.7	96.1	262.9	49.5	177.4	435.7	54.3	297.7	511.4
30	Middle East	42.3	329.2	606.5	42.7	377.3	809.2	45.0	448.6	922.6	42.312	314.1	410.4	43.0	330.9	554.6	45.1	378.3	631.0	42.3	324.1	467.5	43.0	371.5	596.7	45.0	415.8	800.2
	Total	8418	25160	56353	9886	32072	81944	8969	32120	96927	8440	21030	31011	9907	25685	46300	13551	32927	58766	8427	22777	38217	9897	28162	54681	13498	35855	77067

Table 7.6 Regional results for sea dike costs for selected sea-level rise scenarios and no adaptation (in millions of US 1995 US dollars/year).

	AVOID Regions	A1B									A1B.2016.R5.low									A1B.2030.R5.low									No global sea-level rise		
		10th percentile			50th percentile			90th percentile			10th percentile			50th percentile			90th percentile			10th percentile			50th percentile			90th percentile					
		2025	**2055**	**2085**	**2025**	**2055**	**2085**	**2025**	**2055**	**2085**	**2025**	**2055**	**2085**	**2025**	**2055**	**2085**	**2025**	**2055**	**2085**	**2025**	**2055**	**2085**	**2025**	**2055**	**2085**	**2025**	**2055**	**2085**	**2025**	**2055**	**2085**
1	China	574.7	467.7	386.6	605.8	533.2	477.7	636.9	598.8	568.8	582.0	361.7	229.6	614.9	412.5	276.1	647.7	463.2	322.7	578.7	413.2	257.4	610.7	473.1	316.0	642.8	533.0	374.7	459.2	256.4	146.2
2	US	1286.0	1053.4	2209.4	1327.9	1144.8	2412.0	1370.7	1236.6	2610.5	1295.8	907.6	1883.2	1340.8	978.8	2003.4	1385.1	1049.9	2122.1	1291.4	978.5	1953.6	1335.3	1062.2	2096.2	1378.5	1146.1	2239.7	1117.1	737.3	1622.9
3	Russia	490.7	323.9	253.9	514.7	385.5	335.4	545.4	445.8	417.0	495.5	233.6	122.4	521.7	275.6	155.3	555.6	321.2	196.9	493.4	274.4	140.3	518.5	330.2	191.0	551.1	385.3	243.4	411.1	162.5	71.4
4	Japan	193.5	287.7	319.6	227.4	359.3	421.3	261.4	431.2	521.9	201.6	172.0	146.5	237.3	227.4	198.2	273.1	283.0	250.7	197.9	228.2	177.4	232.8	293.7	242.3	267.8	359.3	308.1	69.6	58.5	54.9
5	South Africa	104.5	116.4	91.3	112.6	133.3	115.3	120.6	150.2	139.2	106.4	89.0	49.9	114.9	102.1	62.1	123.4	115.2	74.7	105.6	102.3	57.2	113.8	117.8	72.9	122.1	133.2	88.4	77.6	64.7	30.7
6	India	417.8	350.3	289.0	437.9	392.7	348.0	458.0	435.2	407.1	422.6	281.8	187.2	443.8	314.6	217.4	465.0	347.5	247.7	420.4	315.1	205.3	441.1	353.9	243.3	461.8	392.6	281.4	350.4	220.8	140.6
7	Brazil	838.0	714.4	550.5	892.6	830.1	710.8	947.2	946.8	871.7	850.9	526.9	274.5	908.5	616.9	356.5	966.1	706.6	438.4	845.1	617.7	323.6	901.3	724.0	426.6	957.4	830.6	529.7	668.1	374.4	160.9
8	Mexico	368.5	357.9	302.8	395.9	414.7	382.0	422.7	471.5	461.4	374.9	266.2	166.2	403.7	310.2	206.4	431.9	354.1	247.4	372.0	310.8	190.3	400.1	362.7	241.6	427.7	414.6	292.6	262.0	167.0	86.5
9	Canada	403.0	485.4	566.1	447.2	580.5	701.9	491.4	677.1	837.2	413.4	335.1	336.7	460.0	407.1	404.3	506.6	480.0	472.4	408.7	408.1	377.1	454.2	494.2	462.6	499.6	580.6	549.3	249.8	196.2	228.7
10	Australia	252.0	200.1	188.3	274.5	244.9	244.0	297.1	289.7	300.1	257.0	127.7	92.6	280.6	162.3	120.8	304.3	197.0	149.3	254.7	162.8	109.3	277.9	203.8	145.2	301.0	244.8	181.1	177.6	64.1	51.4
11	Indonesia	383.4	368.1	319.9	412.6	429.8	405.7	441.8	492.3	491.7	390.4	268.5	171.6	421.1	316.2	215.8	451.9	363.9	259.7	387.3	316.9	197.8	417.3	373.2	253.4	447.3	430.3	308.7	286.2	180.0	104.0
12	South Korea	323.6	292.4	234.4	346.1	339.7	301.2	368.5	387.0	368.0	328.9	215.9	119.4	352.6	252.5	153.8	376.3	289.1	188.2	326.5	253.0	139.9	349.6	296.3	183.2	372.7	339.5	226.4	238.1	137.3	55.1
13	UK	215.5	269.8	291.9	241.8	324.8	368.4	268.0	379.9	447.8	221.8	180.7	159.8	249.4	223.4	198.9	277.0	266.0	238.1	219.0	224.0	183.2	245.9	274.3	232.5	272.9	324.7	281.9	123.7	97.3	95.0
14	France	49.3	59.8	63.6	54.3	70.5	78.5	59.4	81.2	93.4	50.5	42.6	37.8	55.8	50.8	45.6	61.2	59.1	53.2	49.9	51.0	42.5	55.2	60.7	52.1	60.4	70.5	61.7	27.9	22.8	21.5
15	Italy	49.4	64.1	67.8	55.3	76.8	86.1	61.3	89.6	104.3	50.8	43.7	37.0	57.1	53.5	46.2	63.4	63.3	55.4	50.1	53.6	42.5	56.3	65.2	54.1	62.4	76.8	65.9	24.2	19.6	16.9
16	Germany	51.1	60.1	63.0	55.8	70.0	77.1	60.5	79.9	91.0	52.2	44.1	39.0	57.2	51.8	46.1	62.1	59.4	53.4	51.7	51.9	43.2	56.6	60.9	52.3	61.4	70.0	61.4	32.5	26.9	24.4
17	Poland	25.9	22.6	20.3	27.6	26.1	25.2	29.2	29.6	30.1	26.3	16.9	11.8	28.0	19.6	14.3	29.8	22.4	16.8	26.1	19.7	13.3	27.8	22.9	16.5	29.5	26.1	19.6	19.5	11.1	7.2
18	Saudi Arabia	54.9	55.2	42.3	58.6	63.0	53.1	62.3	70.8	65.1	55.8	42.6	23.6	59.7	48.6	29.1	63.6	54.7	34.7	55.4	48.7	26.9	59.2	55.8	33.9	63.0	63.0	40.8	40.1	29.0	12.6
19	Rest of South Asia	88.2	75.0	60.7	92.5	85.0	74.2	96.8	94.2	87.2	89.2	60.0	38.1	93.7	67.3	45.1	98.3	75.2	52.1	88.8	67.1	42.4	93.2	75.7	50.8	97.6	85.0	59.5	73.5	46.7	27.4
20	Rest of East Asia	749.5	707.7	606.2	798.5	810.8	749.8	847.6	914.1	893.4	761.2	540.9	358.7	812.8	620.8	432.1	864.5	700.7	505.5	755.9	622.0	402.6	806.3	716.3	495.0	856.7	810.6	587.6	584.5	391.8	244.2
21	Rest of Central Asia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	North Africa	309.9	191.2	152.5	322.9	221.0	189.0	335.9	246.9	225.4	312.7	150.6	90.3	326.3	173.5	108.8	339.9	193.5	127.3	311.5	170.3	101.3	324.8	197.3	124.6	338.1	221.0	148.2	255.2	104.8	51.5
23	West Africa	184.9	212.6	188.9	198.7	241.7	230.6	212.6	275.4	272.2	188.2	165.6	111.6	202.8	188.1	138.4	217.3	210.6	159.7	186.7	188.5	127.7	200.9	215.0	156.7	215.1	241.6	183.5	133.6	118.8	74.1
24	Southern and East Africa	454.4	445.4	356.4	480.3	504.0	439.4	506.1	562.2	521.7	460.5	351.4	217.1	487.8	396.4	258.4	515.0	441.9	299.7	457.8	397.1	241.8	484.4	450.7	293.8	511.0	503.8	347.3	362.9	263.3	148.2
25	Europe	828.3	953.6	1001.9	917.7	1186.7	1305.7	1017.9	1405.8	1613.0	847.5	636.2	508.3	943.4	789.3	637.5	1052.3	956.7	791.5	838.9	786.6	583.0	931.7	988.6	769.0	1036.3	1187.3	964.4	561.3	387.6	314.1
26	South America	707.3	587.2	455.1	748.6	674.4	579.3	789.9	764.8	704.6	716.9	449.0	245.2	760.4	515.2	306.6	804.0	582.8	372.4	712.6	516.2	281.9	764.0	609.3	373.7	797.6	674.2	441.9	553.6	313.5	137.0
27	Central America	132.0	133.8	112.7	143.0	157.9	145.9	154.0	180.2	178.4	134.6	96.4	57.2	146.2	114.3	73.6	157.8	132.2	90.1	133.4	114.6	67.0	144.7	135.7	87.7	156.0	156.9	109.2	81.1	53.6	26.5
28	Caribbean	138.3	147.3	125.8	149.1	173.8	163.6	161.4	199.1	207.8	140.5	107.0	66.4	151.9	128.4	83.6	164.8	148.3	102.6	139.7	125.7	76.7	150.9	151.0	99.7	163.5	174.6	125.1	93.5	64.2	30.4
29	Rest of Australasia	295.5	362.5	269.2	322.6	423.0	352.8	349.6	483.5	435.2	301.9	267.4	128.3	330.4	314.6	170.1	358.9	361.9	211.9	299.1	313.6	153.3	326.9	369.0	205.9	354.7	424.5	259.2	198.6	158.5	56.9
30	Middle East	103.3	115.0	86.8	111.7	132.7	111.2	120.0	150.4	135.6	105.3	86.6	44.7	114.1	100.4	57.2	122.9	114.1	69.7	104.4	100.4	52.2	113.0	116.6	67.9	121.6	132.8	83.6	73.2	58.5	23.0
	Total	10073	9480	9677	10774	11031	11885	11494	12570	14100	10235	7068	5954	10977	8232	7062	11740	9414	8204	10163	8232	6611	10894	9650	8040	11627	11033	9464	7606	4787	4064

Figure 7.1. Sea-level rise scenarios for Emissions Family Two (A1B.2016 family).

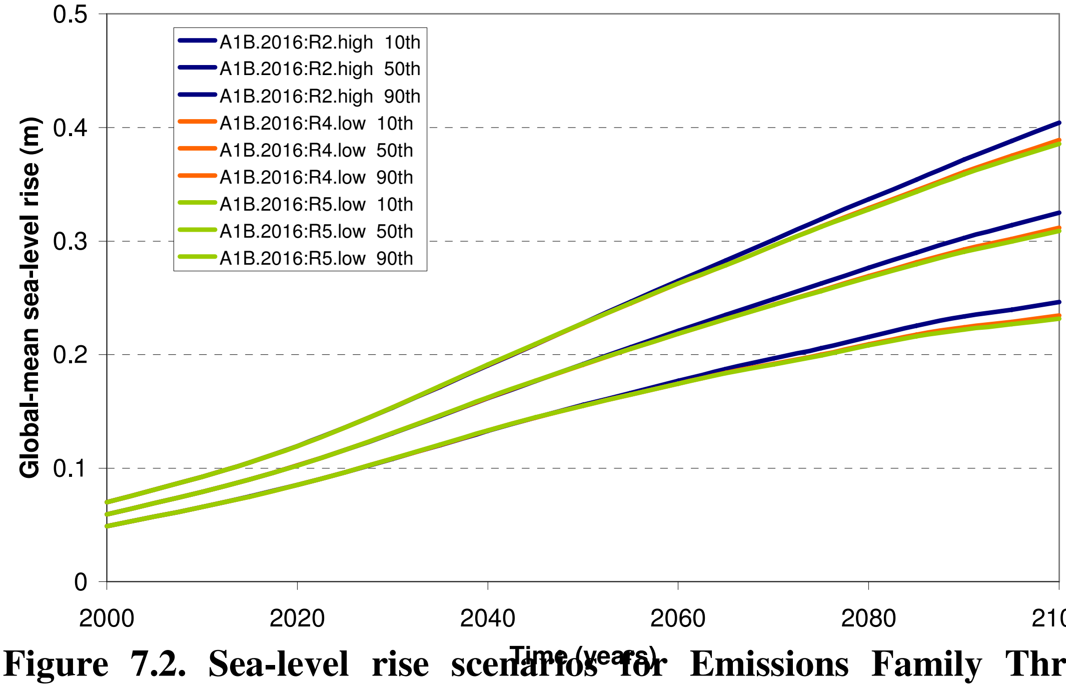


Figure 7.2. Sea-level rise scenarios for Emissions Family Three (A1B.2030 family).

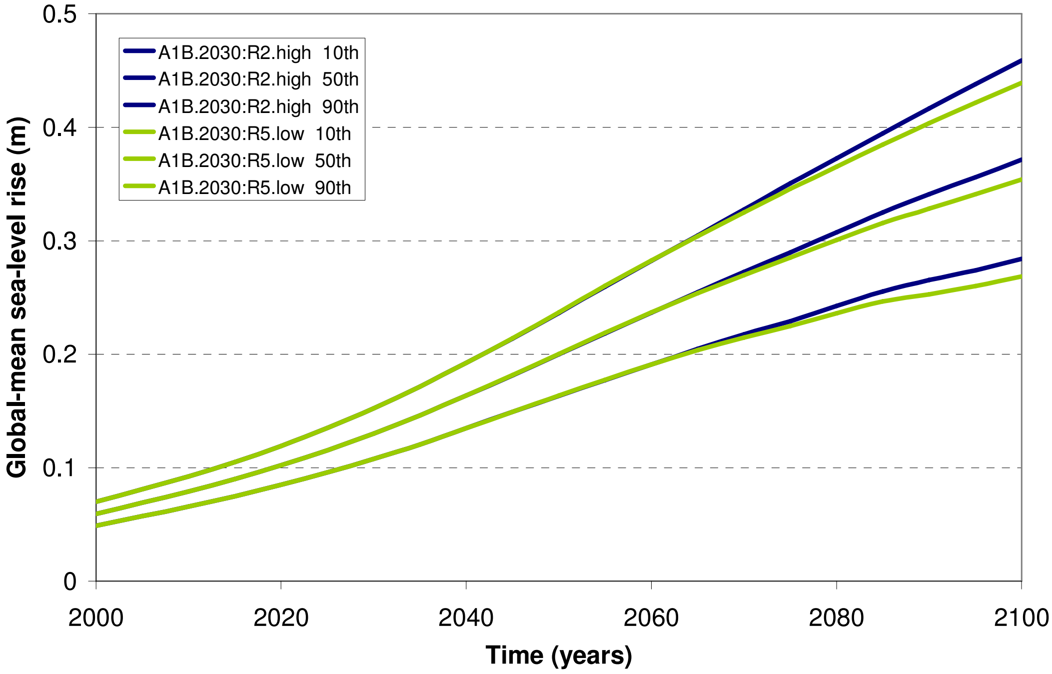


Figure 7.3. Net global losses of saltmarsh by the 2080s due to sea-level rise, including uncertainty.

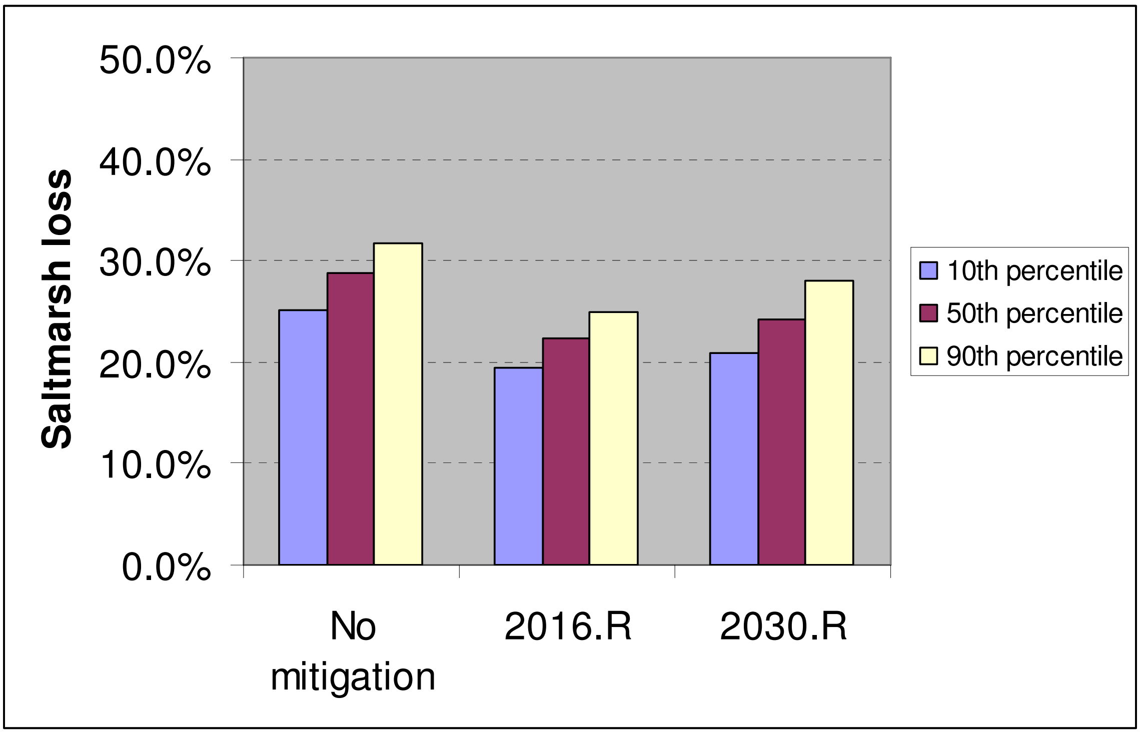


Figure 7.4. Net global losses of mangroves by the 2080s due to sea-level rise, including uncertainty.

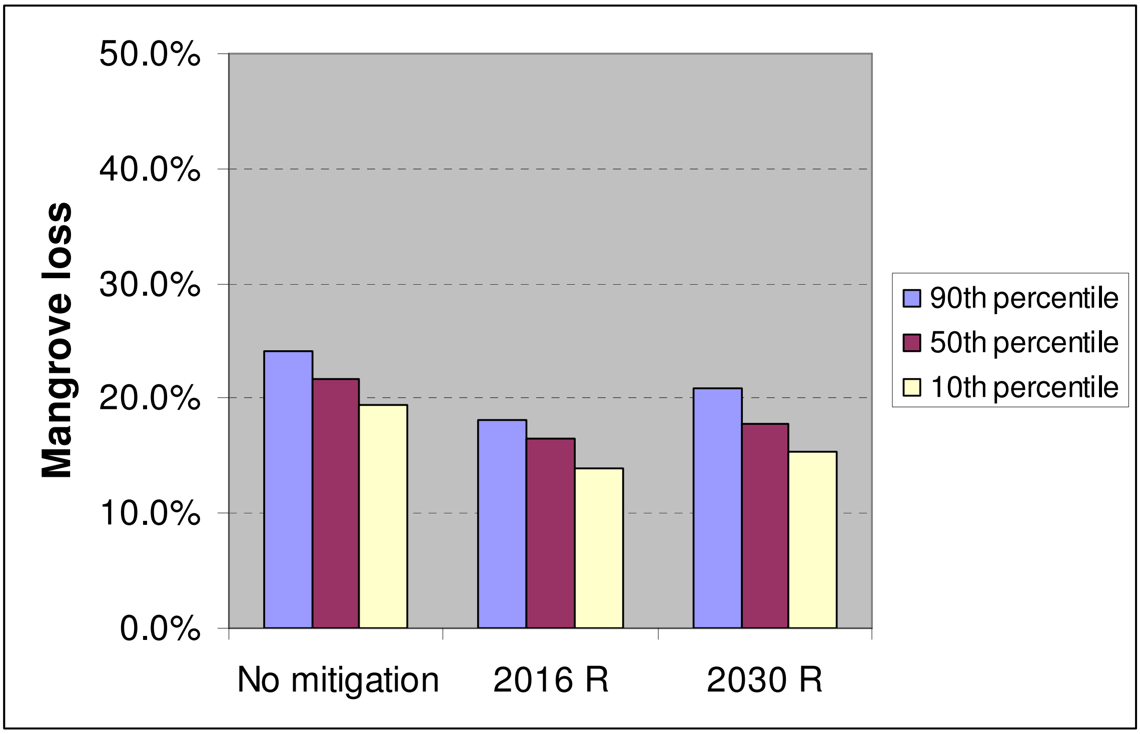


FIGURE 7.5. The global coastal flood plain population in the 2020s, 2050s and 2080s under the different sea-level rise scenarios.

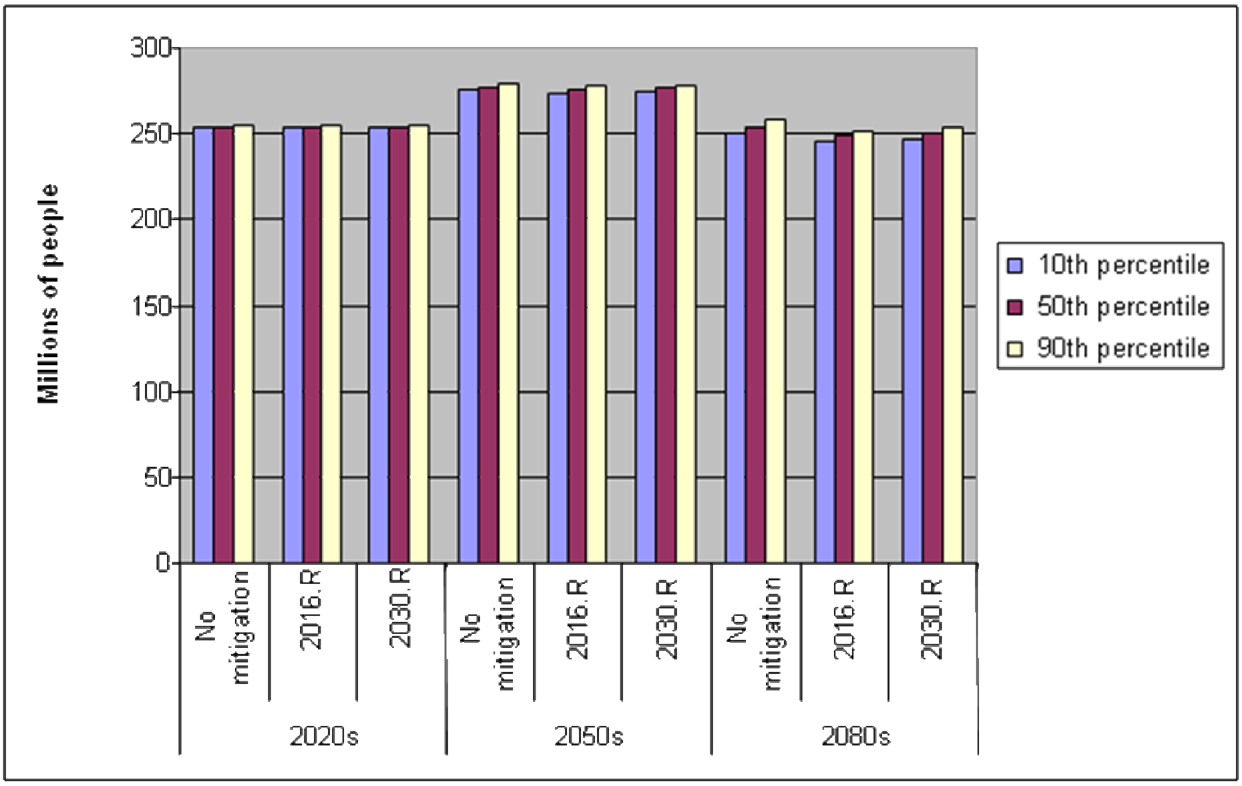


Figure 7.6. Relative increase in the global number of people being flooded per year due to sea-level rise, assuming no adaptation. Results are shown for 2050 and 2100.

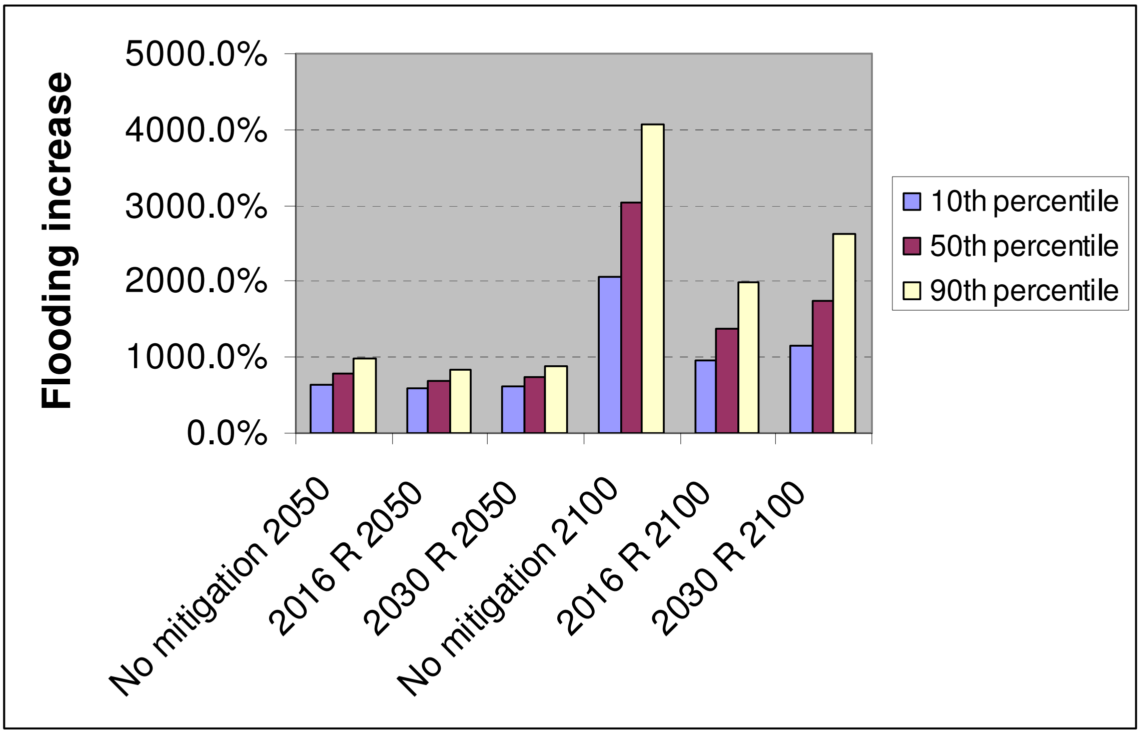


Figure 7.7. Global number of people being flooded per year through the 21st Century assuming an optimum adaptation response.

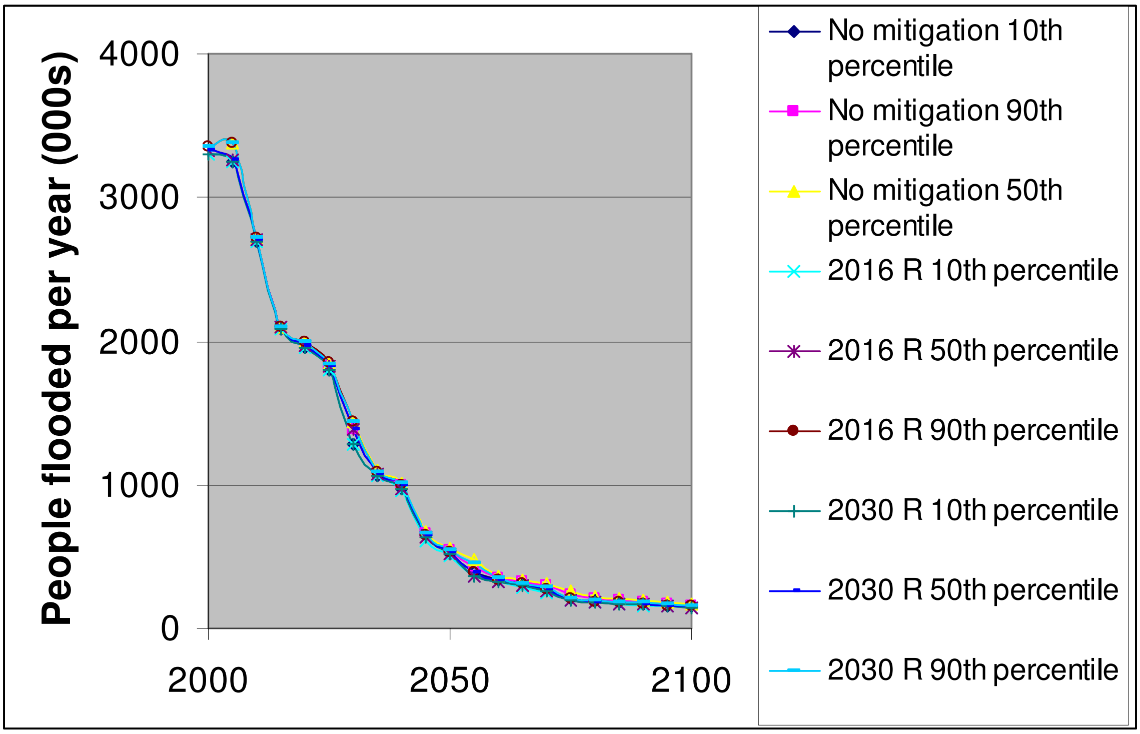
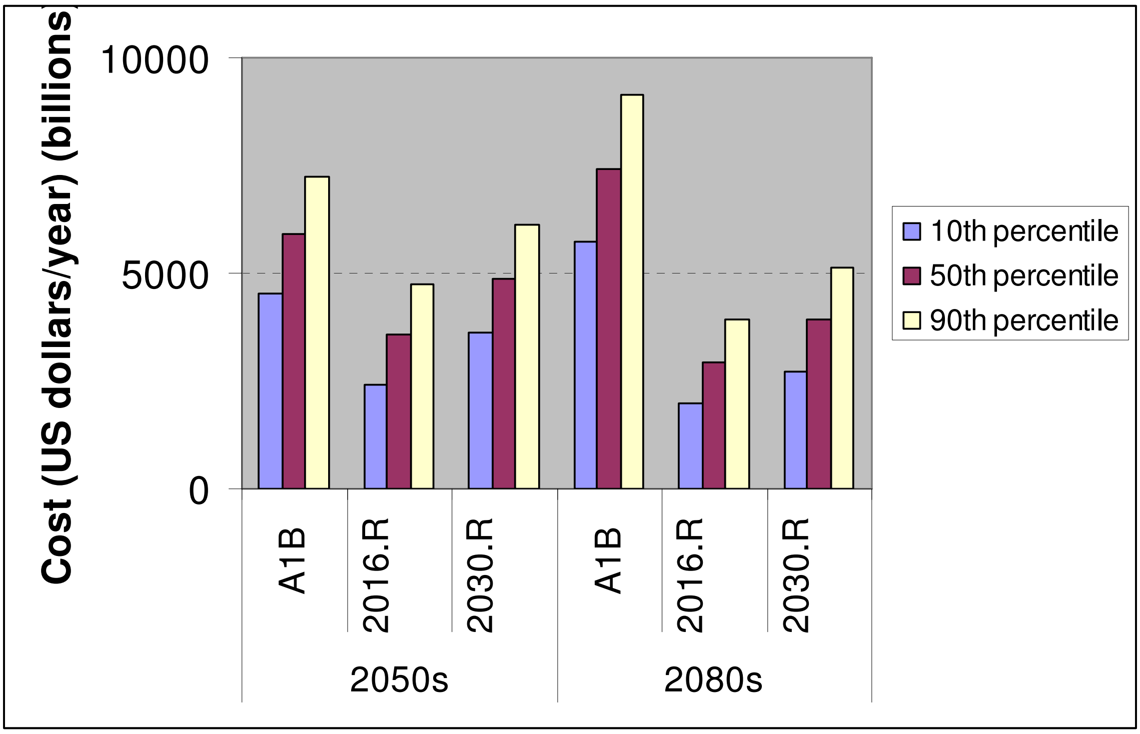


Figure 7.8. Global sea dike costs in response to sea-level rise in the 2050s and 2080s.



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8. HEATING AND COOLING

8.1 Methodology

Climate change has an impact on the requirement for energy for heating and cooling.
Energy requirements for heating or cooling are strongly related to cumulative temperature anomalies (Diaz and Quayle, 1980), as represented by heating degree days (HDD) and cooling degree days (CDD) respectively. Both HDD and CDD are calculated with reference to a base temperature, defined as the target "comfort" temperature, and are calculated from daily temperatures T_i.

$$HDD = \Sigma (B - T_i) \quad \text{where } T_i \text{ is less than B}$$

$$CDD = \Sigma (T_i - B) \quad \text{where } T_i \text{ is greater than B}$$

In North America and in most international-scale studies, the base temperature is taken to be 65^{o}F or 18^{o}C. An estimate of regional energy requirements can be determined by calculating regional population-weighted heating or cooling degree days, where the values for each point of calculation are weighted by the population in that area. Regional population-weighted heating degree days are used in the US and other countries for forecasting seasonal energy use.

In this assessment, HDD and CDD are calculated from monthly temperature data at a spatial resolution of 0.5x0.5^o, disaggregated to a daily resolution, using a temperature threshold of 18^{o}C. Regional population-weighted heating and cooling degree days are determined by weighting each cell value by grid cell population.

The indicator here shows percentage change in regional population-weighted HDD and CDD compared to the situation with no climate change. It is an indicator of exposure to impact, rather than a projection of actual impact because it assumes no change in the baes temperature threshold (arguably adaptation would lead to an increase in tolerated threshold temperatures). The indicator also does not necessarily directly reflect change in energy *demand*, as this is a function also of changes in energy efficiency of heating and cooling technologies. The same indicator was described in the Stern Review.

Key results

- **A climate policy with emissions peaking in 2016 leads to reductions in the changes in heating and cooling degree days by approximately a third in 2050, and approximately a half in 2080** (Figure 1); a policy with emissions peaking in 2030 has a smaller effect, particularly in 2050. Figure 1 shows the change in global heating and cooling degree days, assuming a HadCM3 climate model pattern of regional change in temperature.

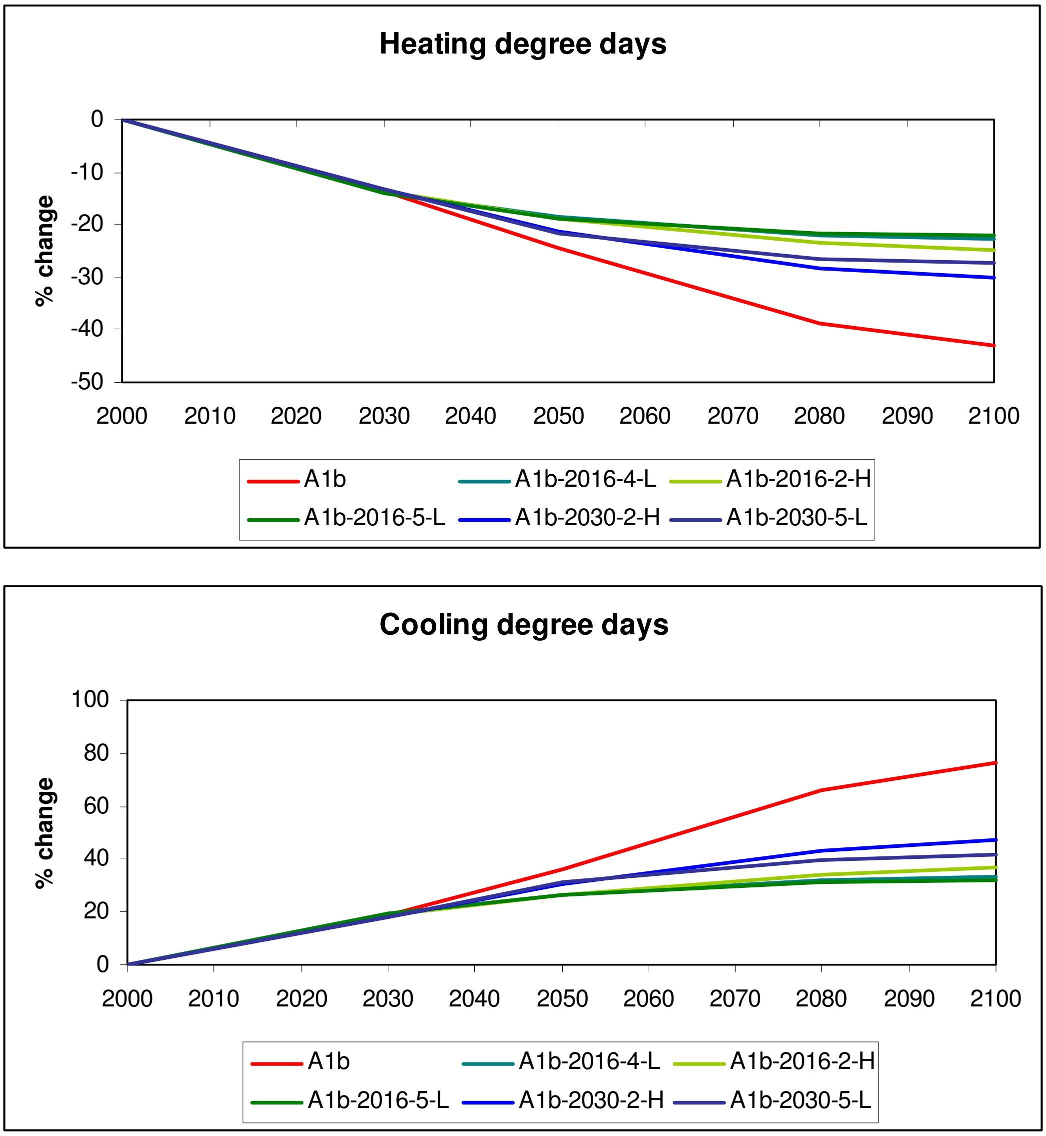


Figure 1: Change in global population-weighted heating and cooling degree days: HadCM3 climate model pattern and A1b population

- **There is relatively little difference in global-scale impact, and avoided impacts, between different climate models** (Figure 2). This is because variations in regional projections of temperature change between models are relatively small.

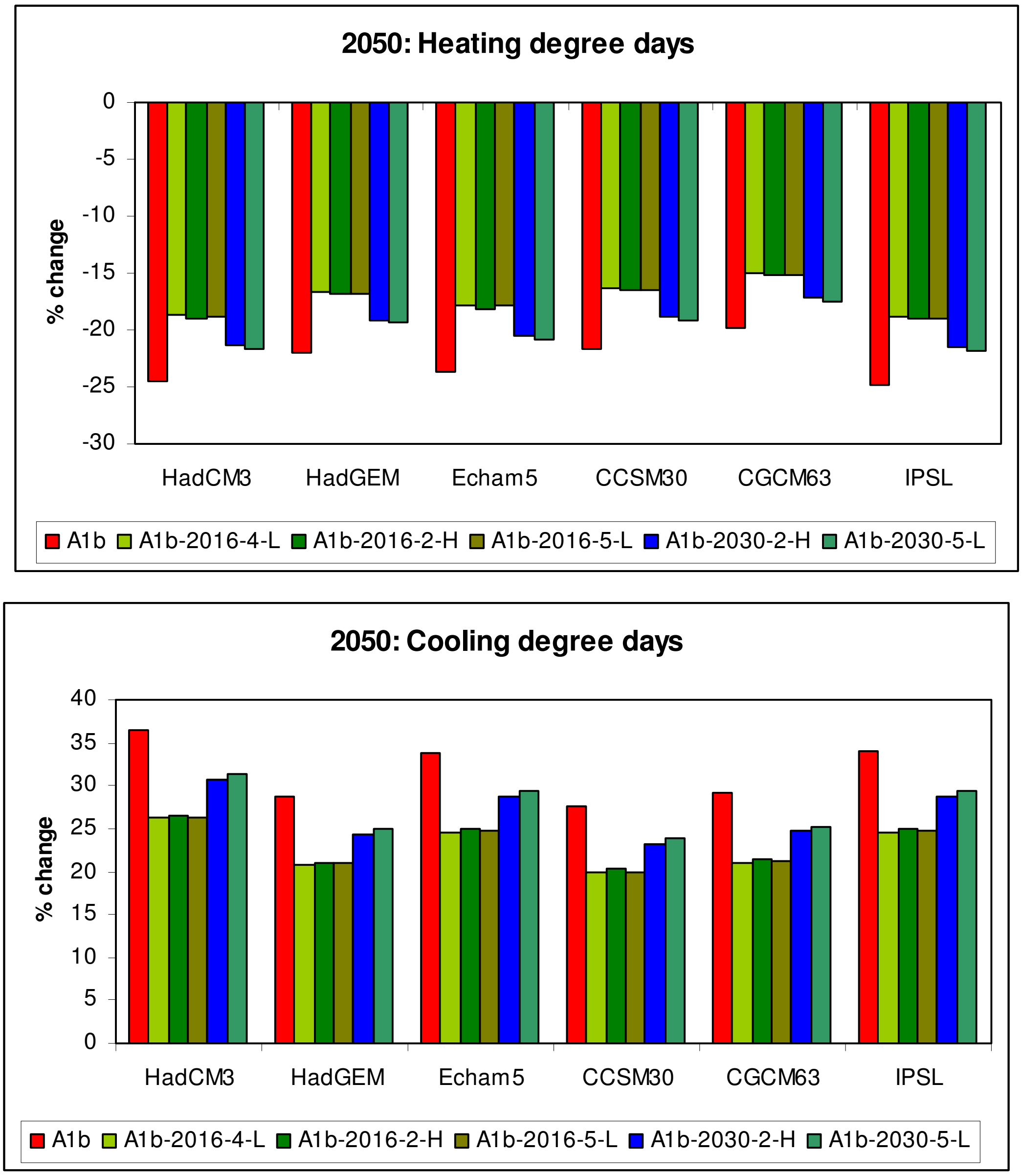


Figure 2: Change in global population-weighted heating and cooling degree days in 2050, assuming different climate model patterns

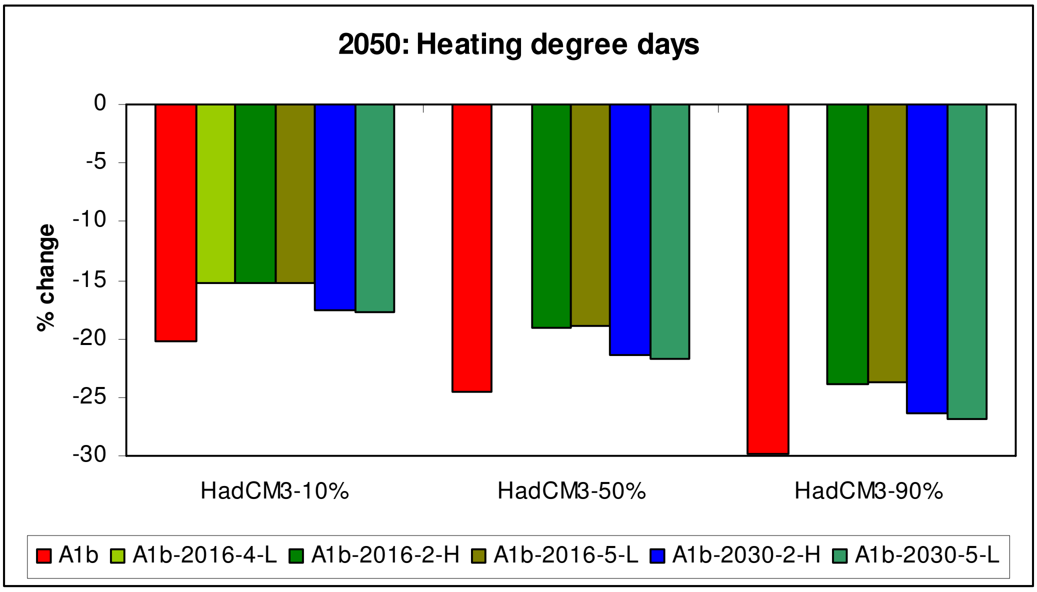
- **There is strong regional variability in the effect of climate change on heating and cooling requirements, and hence on the avoided impacts** (Table 1). The relative importance of heating and cooling requirements varies between regions, so the relative benefits of reducing extra cooling requirements and limiting reductions in heating requirements vary.

Table 1: Percentage change in regional population-weighted heating and cooling degree days: HadCM3 climate model pattern (note large percentage changes from small initial values in some regions) 2050 (upper table) and 2080 (lower table)

	Heating degree days						Cooling degree days					
	A1b	A1b-2016-4	A1b-2016-2	A1b-2016-5	A1b-2030-2	A1b-2030-5	A1b	A1b-2016-4	A1b-2016-2	A1b-2016-5	A1b-2030-2	A1b-2030-5
China	-22	-16	-17	-16	-19	-19	54	38	39	38	45	46
US	-23	-17	-18	-18	-20	-20	74	52	54	53	62	64
Russia	-17	-13	-13	-13	-15	-15	290	207	209	207	241	255
Japan	-26	-19	-20	-20	-22	-23	75	54	54	54	63	64
South Afric	-53	-41	-42	-42	-47	-47	95	67	68	67	79	81
India	-53	-44	-44	-44	-48	-49	26	19	19	19	22	23
Brazil	-85	-75	-76	-75	-80	-81	47	34	35	34	40	41
Mexico	-58	-46	-46	-46	-52	-53	61	43	44	44	51	52
Canada	-18	-13	-14	-14	-15	-16	198	131	134	130	177	163
Australia	-34	-26	-26	-26	-29	-30	75	54	55	54	63	65
Indonesia	-100	-100	-100	-100	-100	-100	19	14	14	14	17	17
South Kore	-24	-18	-18	-18	-20	-21	75	54	54	54	63	64
UK	-19	-15	-15	-15	-17	-17	3060	980	1090	1050	1810	1940
France	-22	-17	-17	-17	-19	-19	439	301	306	303	361	369
Italy	-23	-17	-18	-18	-20	-20	131	93	94	94	111	112
Germany	-21	-16	-16	-16	-18	-19	1080	638	657	649	836	855
Poland	-21	-16	-16	-16	-17	-18	1518	1018	978	973	1487	1503
Saudi Arab	-66	-53	-54	-54	-60	-60	34	25	25	25	29	30
Rest of So	-45	-34	-35	-35	-39	-40	28	20	21	21	24	24
Rest of Ea	-23	-18	-18	-18	-21	-21	27	20	20	20	23	24
Rest of Ce	-21	-16	-16	-16	-18	-19	61	43	43	43	52	52
North Afric	-42	-32	-32	-32	-37	-37	41	29	30	30	35	35
West Afric	-90	-78	-78	-78	-83	-85	28	21	21	21	24	25
Southern a	-76	-64	-65	-64	-70	-71	58	42	42	42	49	50
Europe	-21	-16	-16	-16	-18	-19	145	102	103	102	122	124
South Ame	-36	-27	-28	-28	-31	-32	52	37	38	38	44	45
Central Am	-86	-76	-77	-77	-81	-82	53	38	39	39	45	46
Caribbean	-100	-94	-94	-94	-100	-100	32	23	23	23	27	27
Rest of Au	-23	-17	-17	-17	-19	-20	27	20	20	20	23	24
Middle Eas	-27	-21	-21	-21	-24	-24	44	32	32	32	37	38
Global	-25	-19	-19	-19	-21	-22	36	26	27	26	31	31

	Heating degree days						Cooling degree days					
	A1b	A1b-2016-4	A1b-2016-2	A1b-2016-5	A1b-2030-2	A1b-2030-5	A1b	A1b-2016-4	A1b-2016-2	A1b-2016-5	A1b-2030-2	A1b-2030-5
China	-35	-19	-20	-19	-25	-23	99	46	50	46	63	58
US	-37	-20	-21	-20	-26	-25	138	64	70	63	89	81
Russia	-27	-15	-15	-14	-18	-18	595	252	287	253	402	321
Japan	-42	-23	-24	-22	-30	-28	139	64	69	63	89	82
South Afric	-76	-48	-50	-47	-59	-56	181	81	88	80	113	104
India	-65	-48	-49	-47	-56	-53	47	23	25	22	31	29
Brazil	-98	-81	-83	-80	-90	-88	84	41	44	40	56	51
Mexico	-80	-53	-55	-52	-65	-62	117	53	57	52	73	67
Canada	-28	-16	-17	-15	-20	-19	436	165	177	158	245	222
Australia	-52	-30	-32	-29	-38	-36	141	65	70	64	90	82
Indonesia	-100	-100	-100	-100	-100	-100	34	17	18	17	23	21
South Kore	-39	-21	-22	-20	-27	-25	137	65	69	63	89	83
UK	-31	-17	-18	-17	-22	-21	13550	1980	2450	1840	4930	3910
France	-34	-19	-21	-19	-25	-23	868	373	404	364	531	483
Italy	-37	-20	-22	-20	-26	-25	246	113	122	111	157	143
Germany	-33	-19	-20	-18	-24	-22	2589	863	967	843	1392	1226
Poland	-34	-19	-20	-18	-24	-22	3508	1241	1391	1498	1936	2043
Saudi Arab	-87	-61	-64	-60	-73	-70	62	30	32	29	40	37
Rest of So	-67	-40	-42	-40	-51	-48	50	24	26	24	33	30
Rest of Ea	-36	-21	-22	-21	-26	-25	48	24	25	23	32	29
Rest of Ce	-35	-19	-20	-19	-25	-23	115	52	56	51	72	67
North Afric	-66	-38	-40	-37	-48	-45	74	36	38	35	49	45
West Afric	-100	-85	-87	-84	-93	-92	49	25	26	24	33	31
Southern a	-93	-71	-74	-71	-82	-79	103	50	53	49	68	62
Europe	-34	-19	-20	-19	-24	-23	277	124	134	122	173	159
South Ame	-56	-32	-34	-32	-41	-39	95	45	48	44	61	56
Central Am	-98	-82	-84	-81	-90	-88	95	47	50	46	63	58
Caribbean	-100	-100	-100	-100	-100	-100	55	28	30	27	37	34
Rest of Au	-37	-20	-21	-20	-26	-24	48	24	25	23	32	30
Middle Eas	-46	-26	-28	-26	-34	-31	80	39	41	38	52	49
Global	-39	-22	-23	-22	-28	-26	66	32	34	31	43	40

- **The effects of uncertainty in the global temperature change associated with a given emissions policy are greater than the effect of climate model uncertainty.** Figure 3 shows change in global heating and cooling degree days in 2050, under the HadCM3 pattern scaled to the 10, 50 and 90% global temperature change, and should be compared to Figure 2.



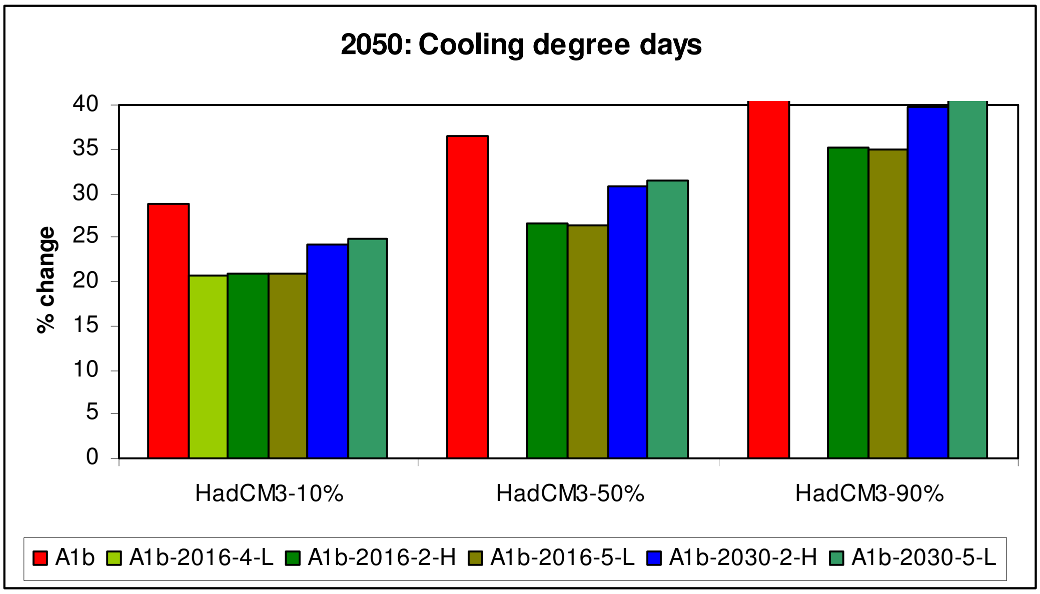


Figure 3: Change in global population-weighted heating and cooling degree days in 2050, assuming 10%, 50% and 90% temperature changes: HadCM3 pattern

Diaz, H.F., and R.G. Quayle, 1980: Heating Degree Day Data Applied to Residential Heating Energy Consumption. *Journal of Applied Meteorology*, 3, 241-246

9. ECONOMICS OF CLIMATE CHANGE IMPACTS

9.1 The PAGE model

The PAGE2002 model was used in the Stern review and its main function is to estimate economic damages due to climate change and provide estimates of uncertainty therein.

MODEL and e.g. of ref in literature.	Can accept prescribed emissions time series from AVOID scenarios	Model type	Model nature	Technological Change	Special features	Comments
PAGE (Hope et al. 2009)	Yes, and for each gas	Draws on material from both top-down and bottom-up	Marginal cost curves	N/A	Climate impacts damages included and valued; uncertainty analysis automatically output	Is an integrated model in itself

PAGE2002 is an updated version of the PAGE95 integrated assessment model. It takes as inputs the emissions of the primary greenhouse gases, CO_2 and methane, including changes in natural emissions stimulated by the changing climate. It also allows the explicit modelling of a third gas whose forcing is linear in concentration, and models other greenhouse gases such as N_2O and (H)CFCs as a time-varying addition to background radiative forcing.

PAGE2002 contains equations that model:

- The greenhouse effect. PAGE2002 keeps track of the accumulation of anthropogenic emissions of greenhouse gases in the atmosphere, and the increased radiative forcing that results, using a logarithmic relationship between concentration and forcing for CO_2, a square root form for methane, and a linear form for the third gas.
- Cooling from sulphate aerosols. The direct and indirect reductions in radiative forcing are separately modelled.
- Regional temperature effects. For the eight world regions in PAGE2002, the equilibrium and realised temperature changes are computed from the difference between greenhouse warming and regional sulphate aerosol cooling, and the slow response as excess heat is transferred from the atmosphere to land and ocean. Sulphate cooling is greatest in the more industrialised regions, and tends to decrease over time due to sulphur controls to prevent acid rain and negative health effects.
- Nonlinearity and transience in the damage caused by global warming. Climatic change impacts in each analysis year are modelled as a polynomial function of the regional temperature increase in that year above a time-varying tolerable level of temperature change, $(T-T_{tol})^n$, where n is an uncertain input parameter. Impacts are aggregated over time using time-varying discount rates.
- Regional economic growth. Impacts are evaluated in terms of an annual percentage loss of GDP in each region, for a maximum of two sectors; defined in this application as economic impacts and non-economic (environmental and social) impacts.

- Adaptation to climate change. Investment in adaptive measures (e.g. the building of sea walls; development of drought resistant crops) can increase the tolerable level of temperature change (T_{tol}) before economic losses occur and also reduce the intensity of both noneconomic and economic impacts.
- The possibility of a future large-scale discontinuity. This is modelled as a linearly increasing probability of a discontinuity that substantially reduces gross world product occurring as the global mean temperature rises above a threshold.
- Abatement costs. These are modelled for each region as cutbacks below a business as usual scenario, multiplied by a unit cost which increases once the cutbacks exceed a threshold for low-cost reductions.

In PAGE2002, the abatement cost depends on the percentage by which CO2 emissions in each region fall below the business as usual scenario. Three uncertain parameters are used to represent abatement costs in each region. The first is the cost of the cheapest control measures in $ per tonne of CO2 abated. The second is the maximum percentage of base year emissions that can be cut back by the cheap control measures. The third represents the additional cost in $ per tonne of CO2 for reductions in excess of this. Cost parameters in the non-focus regions differ from the values for the focus region by a regional multiplier. These abatement cost parameters have remained relatively unchanged in PAGE since the previous versions of the model, PAGE91 and PAGE95, and represent an attempt to span the range of estimates available in the literature, from the initially negative costs found by Barker et al. (1993), using recycled carbon taxes, to the higher values typically reported by top-down macro-economic models (Hope et al., 1993; Plambeck et al., 1997). The lower costs in other regions than the EU reflect the smaller remaining opportunities for low cost energy efficiency given the high energy prices already in place in the EU, and the possibility of lower cost construction and civil engineering works in the lower wage economies of the LDCs.

The abatement cost inputs are described in Hope C, 2008, Optimal carbon emissions and the social cost of carbon over time under uncertainty, Integrated Assessment, 8, 1, 107-122.

The PAGE2002 model uses relatively simple equations to capture complex climatic and economic phenomena. This is justified because the results approximate those of the most complex climate simulations, and because all aspects of climate change are subject to profound uncertainty. To express the model results in terms of a single 'best guess' could be dangerously misleading. Instead, a range of possible outcomes should inform policy. PAGE2002 builds up probability distributions of results by representing over 50 key inputs to the calcuations by probability distributions, making the characterization of uncertainty the central focus.

PAGE2002 models two damage sectors: economic and noneconomic. Impacts are assumed to occur only for temperature rise in excess of some tolerable rate of change, or that has a magnitude above the tolerable plateau. Adaptation can increase the tolerable temperature change or reduce the impact if the tolerable temperature change is exceeded.

Weights are used to monetise the impacts to allow for comparison and aggregation across economic and noneconomic sectors. The weights express the percentage of GDP lost for benchmark warming of 2.5°C above the tolerable level in each impact sector in the EU, with regional multipliers for other regions.

Note that weights may be negative, representing a gain, as in the case of Eastern Europe and the former Soviet Union. Impacts are computed for each region, sector, and analysis period as a power function of regional temperature increase above the tolerable level. The minimum and maximum values, particularly for the regional weights factors, involve a large amount of judgement to encompass the different studies cited by the IPCC.

In Clarkson and Deyes (2002), equity weighting is justified as follows: 'The effect of equity weighting is that it allows welfare equivalents to be compared since a dollar to a poor man is worth more than a dollar to a rich man. Therefore, it accounts for the fact that if a poor person were to be given an amount of money, then he/she would value that money far more than if it were given to a person who already was very rich.'
(Clarkson and Deyes, 2002, box 1).

The exact form used in the Eyre et al. (1999) study, on which Clarkson and Deyes (2002) is based, is to multiply the impacts in a region by:

(Yworld/Yregion)^(-elasticity)

where Y is the GDP per capita and 'elasticity' is the elasticity of marginal utility with respect to income. The effect is to increase the impacts in poor regions of the world, and reduce the impacts in rich regions'

Regions covered in PAGE2002 are: EU, FSU & Eastern Europe, USA, China & CP Asia , India & SE Asia, Africa & ME Latin America, Other OECD countries.
-China and CP Asia contains China, N.Korea, Vietnam and Mongolia,
-Africa and the Middle East contains all of Africa, and the middle east including Iran and Turkey.

In PAGE the Hadley derived emissions pathways are directly input to the model as multi-gas time series over the 21st century.

9.2 Simulations of climate change impacts from the PAGE model

The values quoted in this section are for avoided impacts only (i.e. they do not include mitigation costs).

Benefits accrue strongly the further into the 21st century one looks.

In the A1B SRES reference scenario, climate change impacts reach about $32 trillion year 2000 US$ (range 29-83 trillion $$) or some 4% of global GDP by 2100 (range 1 to 12%)

By 2100 policy scenarios in which emissions peak in 2016 avoid close to 20 trillion (19-19.7) US2000$ (5-95% range 4.6-54 trillion) of equity weighted climate change impacts globally compared to the A1B reference scenario. This amounts to 2.6-2.7% of year 2100 GDP (range 0.6-7.4%GDP). Thus some *two thirds* of the impacts may be avoided through such policies.

By 2060 they avoid mean impacts of 1.5-1.6 trillion (0.6% GDP) and a 5-95% range of 0.4-4 trillion (0.1-1.5% GDP)
By 2040 they avoid mean impacts of 0.16-0.17 trillion (0.1% GDP) and a 5-95% range of 0.04-0.4 trillion (0.02-0.2% GDP)

Policy scenarios in which emissions peak in 2030 avoid about 15 trillion (14-16) US2000$ (5-95% range 3.5--45 trillion)of equity-weighted climate change impacts globally compared to the A1B reference scenario by 2100. This amounts to 2.0-2.2% of year 2100 GDP (range 0.5-6.1%GDP). Thus some *half* of the impacts may be avoided through such policies.

By 2060 they save a mean of 1 (0.97-1) trillion (0.4%GDP) and a 5-95% range of 0.3-2.7 trillion (0.1-1% GDP).
By 2040 they save a mean of 0.1 trillion (0.04%GDP) and a 5-95% range of 0.03-0.2 trillion (0.02-0.15%GDP).

Unweighted impacts display a similar pattern, but values are slighty smaller (e.g. 13-14 trillion US2000$ by 2100 for the scenarios in which emissions peak in 2016. The equity-weighted impacts are, broadly speaking, the impacts that would be equivalent to the non-equity-weighted impacts for someone with average world GDP per capita.

The policies may be ranked in the following order of decreasing efficacy in avoiding impacts:

Equity-weighted:
1st-2016r5low, 2nd 2016r4low, 3rd 2016r2 high, all very close together
4th 2030r5low 5th 2030r2high

This shows that the **date at which global emission peak is much more important than the rate of subsequent emissions reduction in determining the impacts avoided**.

Figure 9.2.1

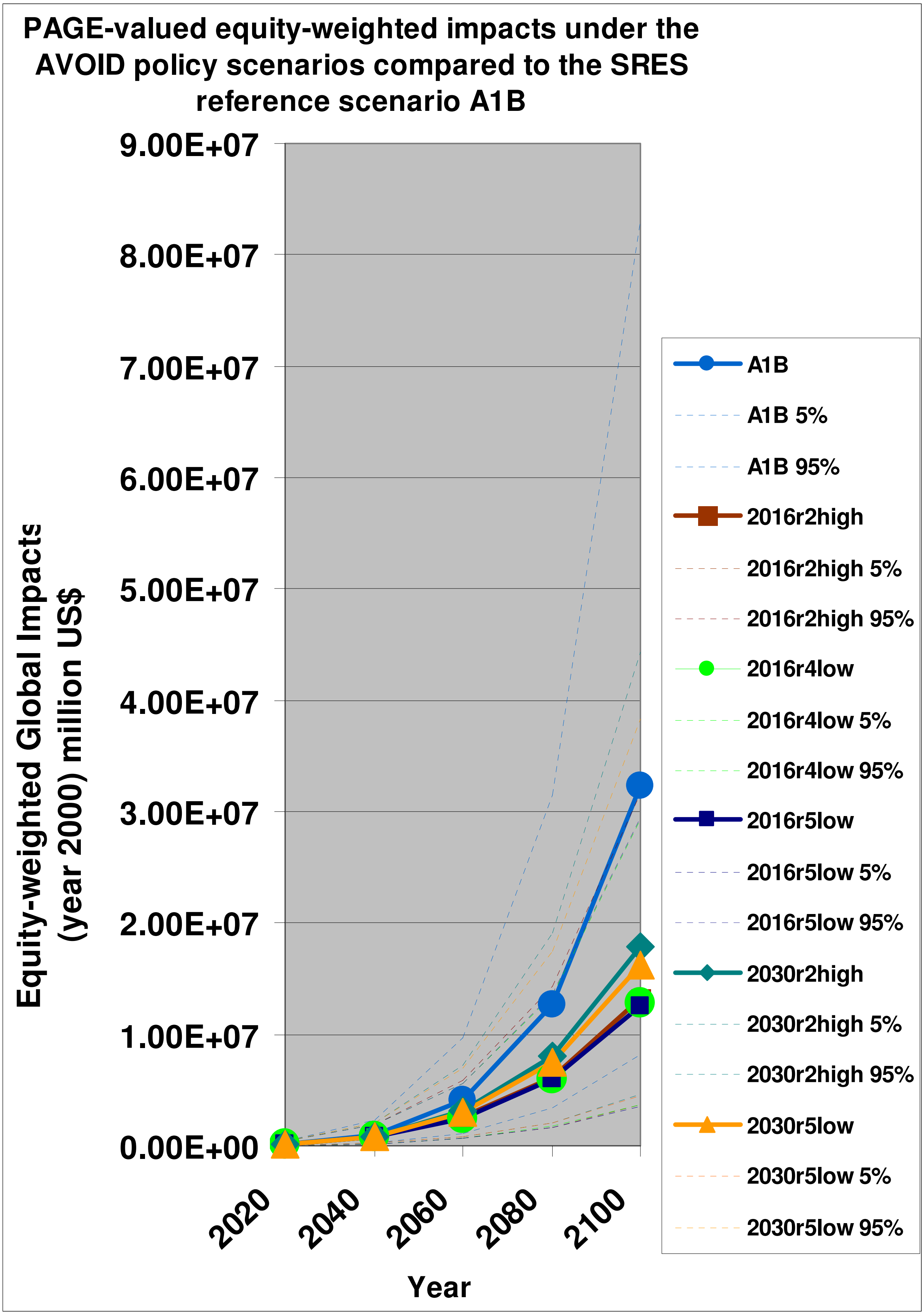

PAGE-valued equity-weighted impacts under the AVOID policy scenarios compared to the SRES reference scenario A1B
Equity-weighted Global Impacts (year 2000) million US$
9.00E+07
8.00E+07
7.00E+07
6.00E+07
5.00E+07
4.00E+07
3.00E+07
2.00E+07
1.00E+07
0.00E+00
2020
2040
2060
2080
2100
Year
A1B
A1B 5%
A1B 95%
2016r2high
2016r2high 5%
2016r2high 95%
2016r4low
2016r4low 5%
2016r4low 95%
2016r5low
2016r5low 5%
2016r5low 95%
2030r2high
2030r2high 5%
2030r2high 95%
2030r5low
2030r5low 5%
2030r5low 95%

Figure 9.2.2

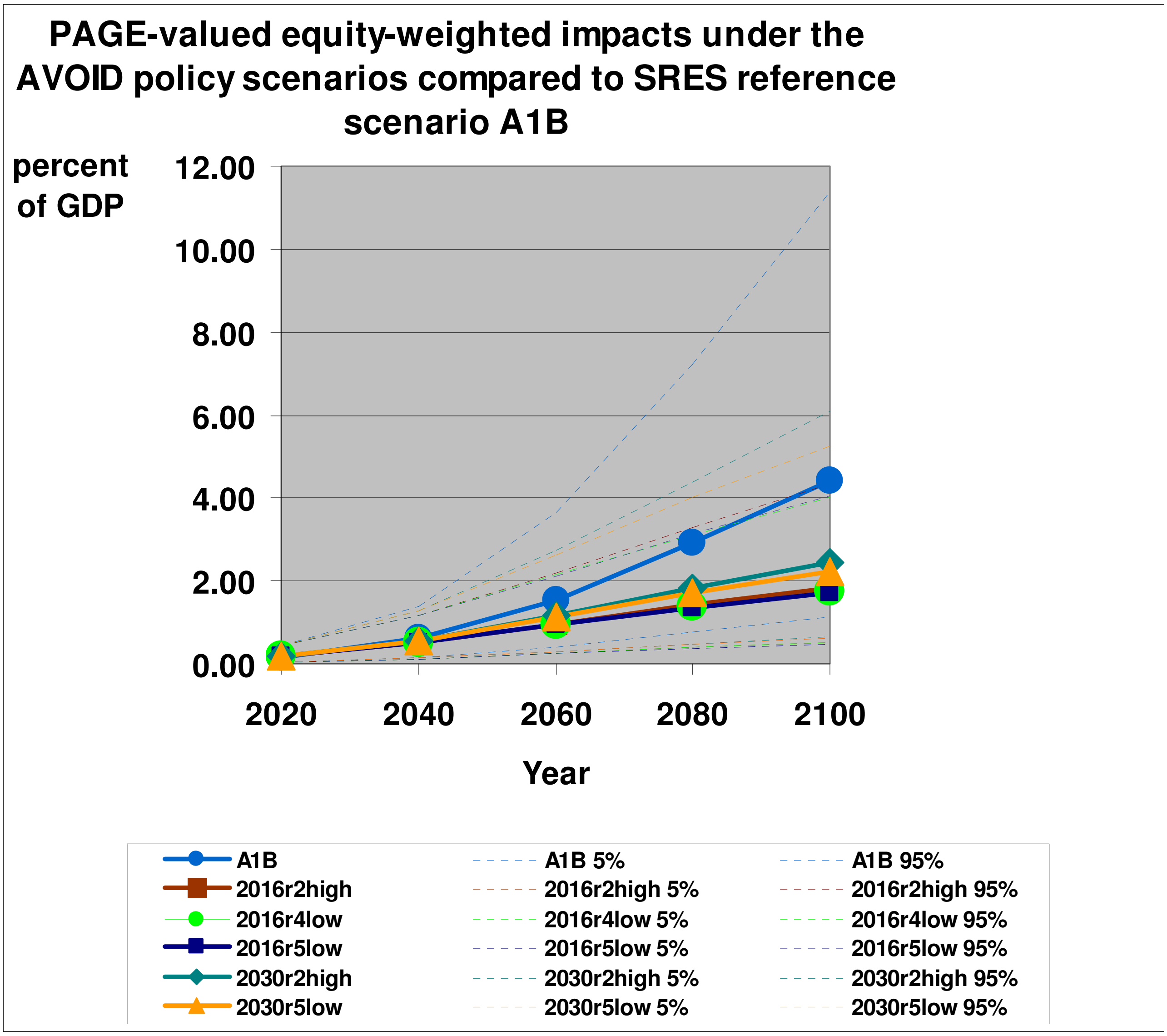

PAGE-valued equity-weighted impacts under the AVOID policy scenarios compared to SRES reference scenario A1B
percent of GDP
12.00
10.00
8.00
6.00
4.00
2.00
0.00
2020
2040
2060
2080
2100
Year
A1B
A1B 5%
A1B 95%
2016r2high
2016r2high 5%
2016r2high 95%
2016r4low
2016r4low 5%
2016r4low 95%
2016r5low
2016r5low 5%
2016r5low 95%
2030r2high
2030r2high 5%
2030r2high 95%
2030r5low
2030r5low 5%
2030r5low 95%

Figure 9.2.3

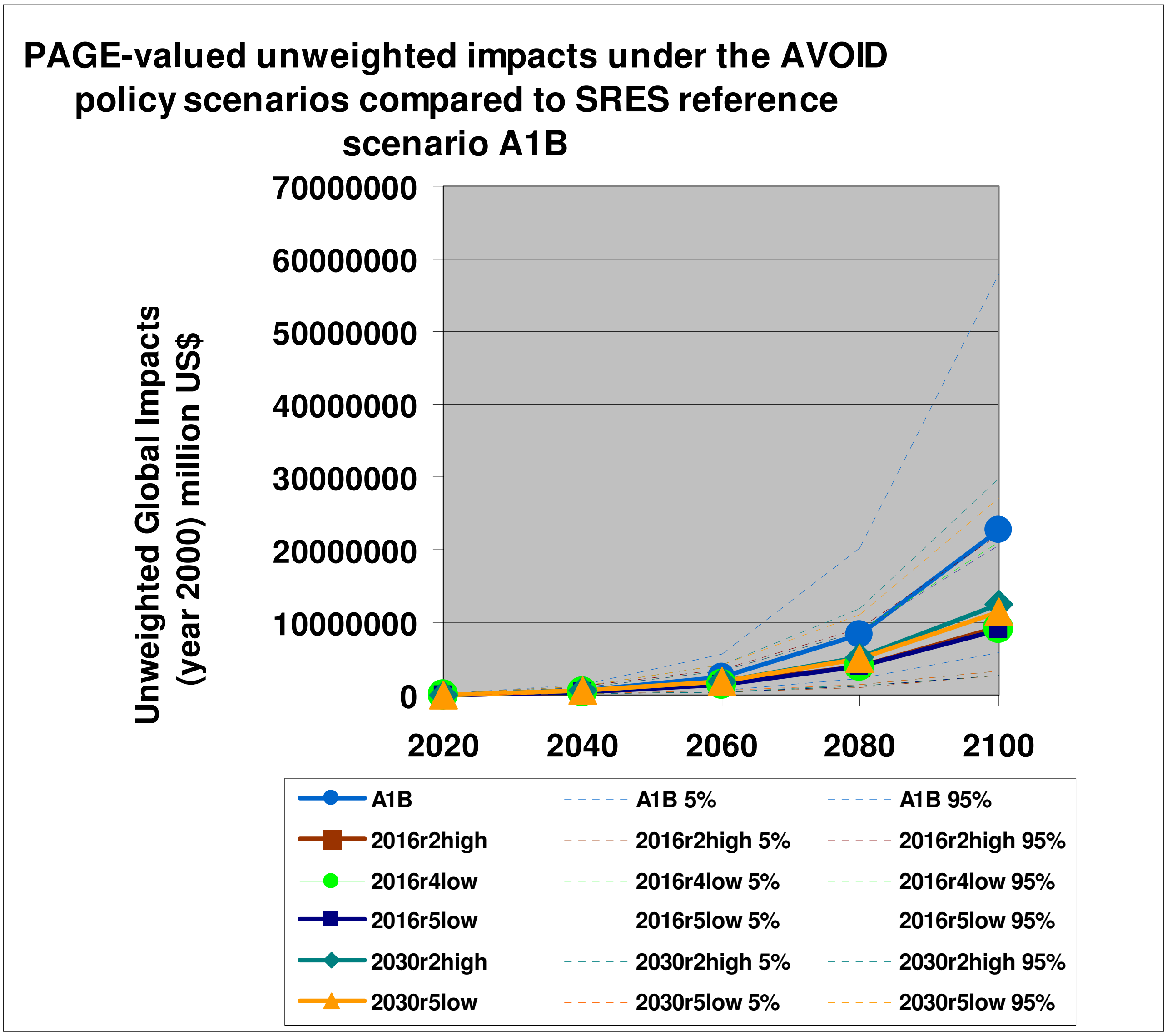
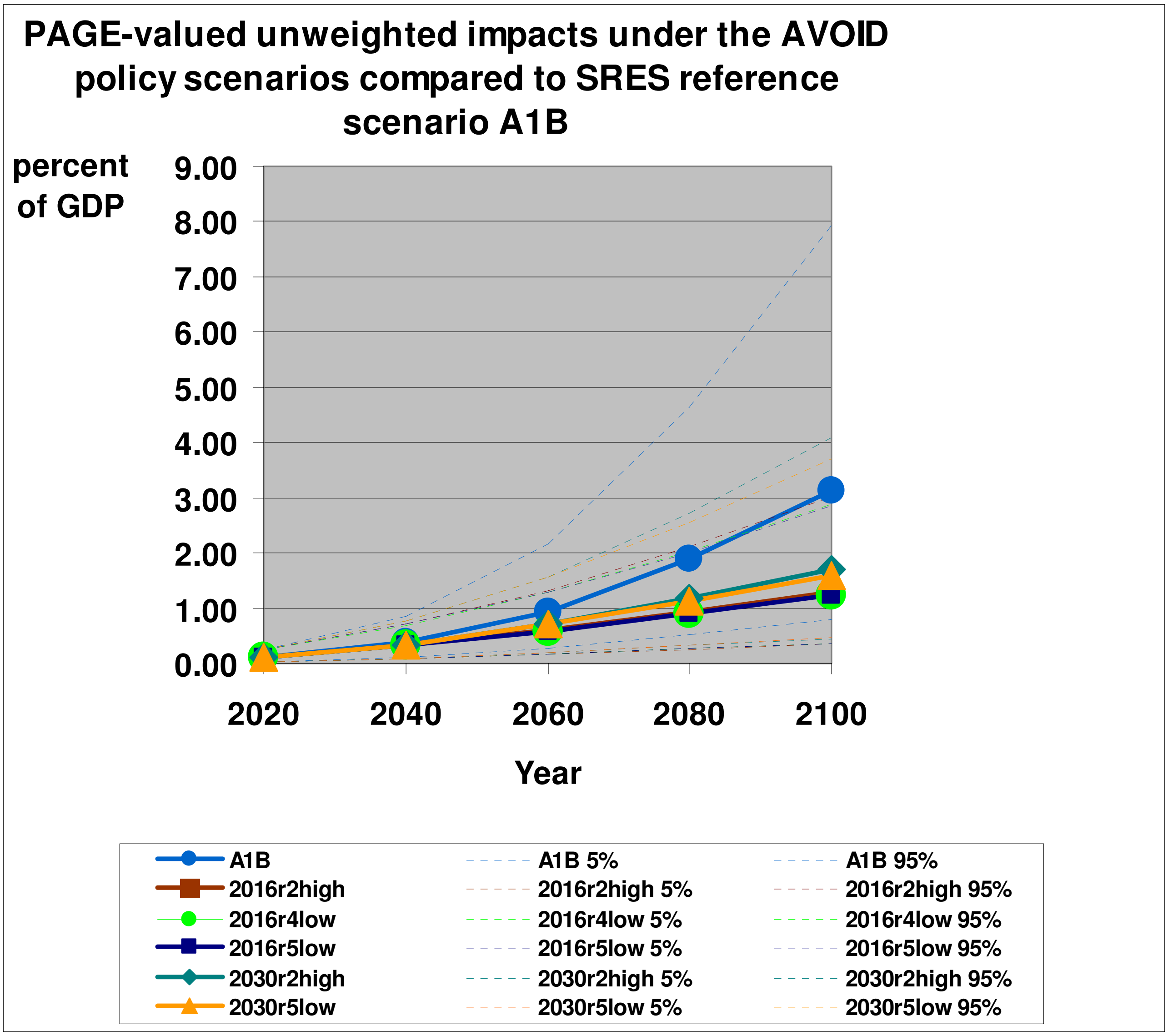

PAGE-valued unweighted impacts under the AVOID policy scenarios compared to SRES reference scenario A1B
Unweighted Global Impacts (year 2000) million US$
70000000
60000000
50000000
40000000
30000000
20000000
10000000
0
2020
2040
2060
2080
2100
A1B
A1B 5%
A1B 95%
2016r2high
2016r2high 5%
2016r2high 95%
2016r4low
2016r4low 5%
2016r4low 95%
2016r5low
2016r5low 5%
2016r5low 95%
2030r2high
2030r2high 5%
2030r2high 95%
2030r5low
2030r5low 5%
2030r5low 95%

Figure 9.2.4



Regionally, the strongest benefits of the policies are in IA, AF and LA (equity weighted) or IA, LA and AF (non-equity weighted). The reason that the order of regions is slightly different in the two weighting schemes is because average per capita income is lower in Africa than in Latin America, so the equity-weighting increases the valuation of impacts more in Africa.

Impacts appear smaller in other regions because China and OECD countries are assumed to be less vulnerable to climate change than poor tropical nations, and OECD nations are better able to adapt. Policies appear to have dis-benefits in EE because it is assumed that Russia benefits from increased agricultural production in a warmer world.

The PAGE regions are shown in Figure 9.2.5.

Figure 9.2.5 PAGE regions

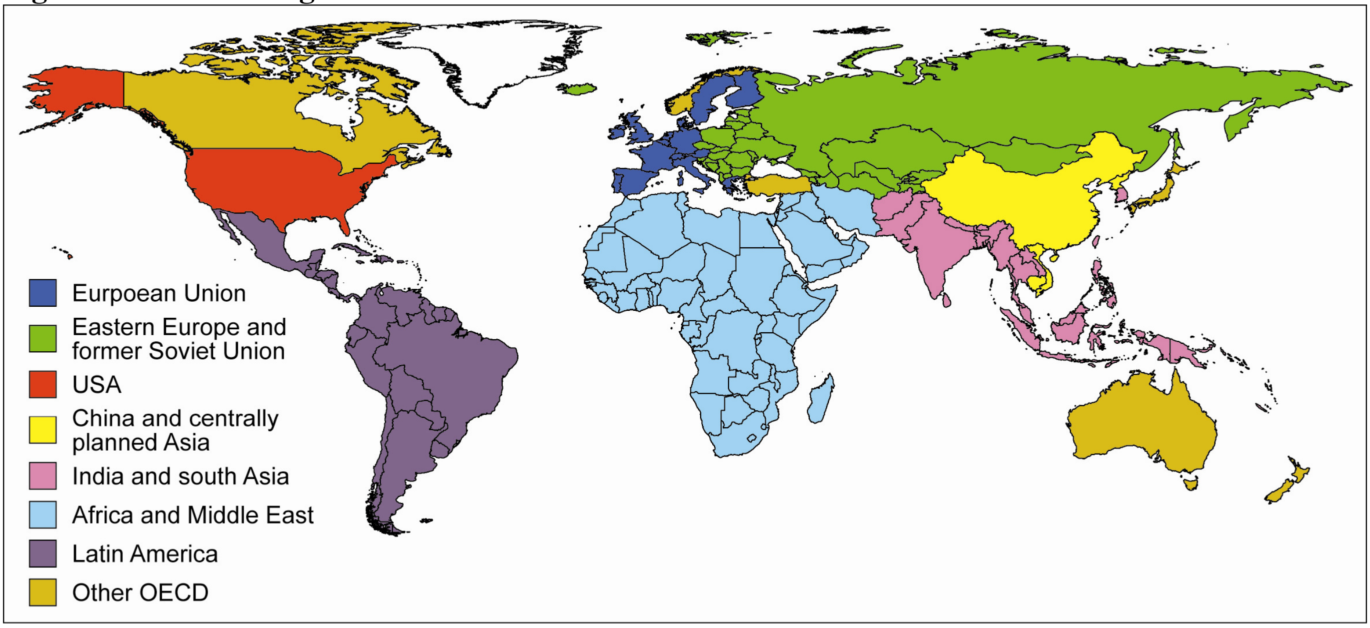


Figure 9.2.6 PAGE2002 equity weighted impacts by region in 2100 in the reference and policy scenarios

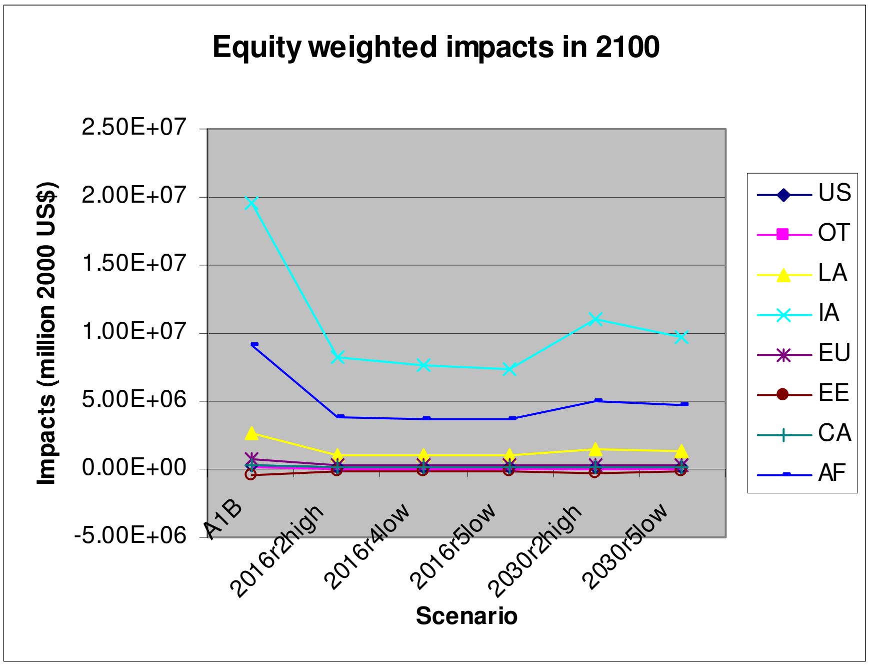


Figure 9.2.7 PAGE2002 unweighted impacts by region in 2100 in the reference and policy scenario

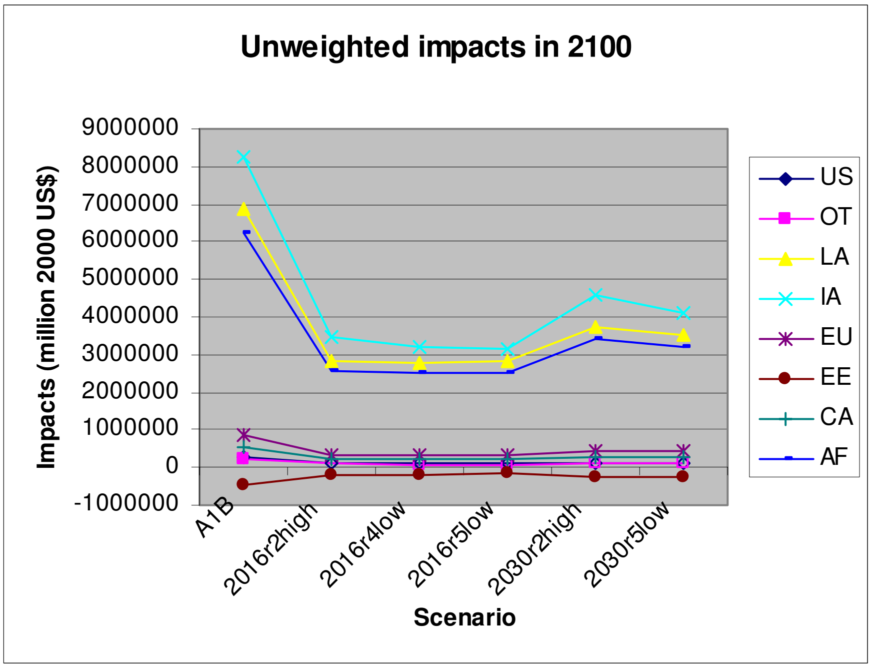


Figure 9.2.8 Avoided PAGE2002 unweighted impacts by region in 2100 in the policy scenarios

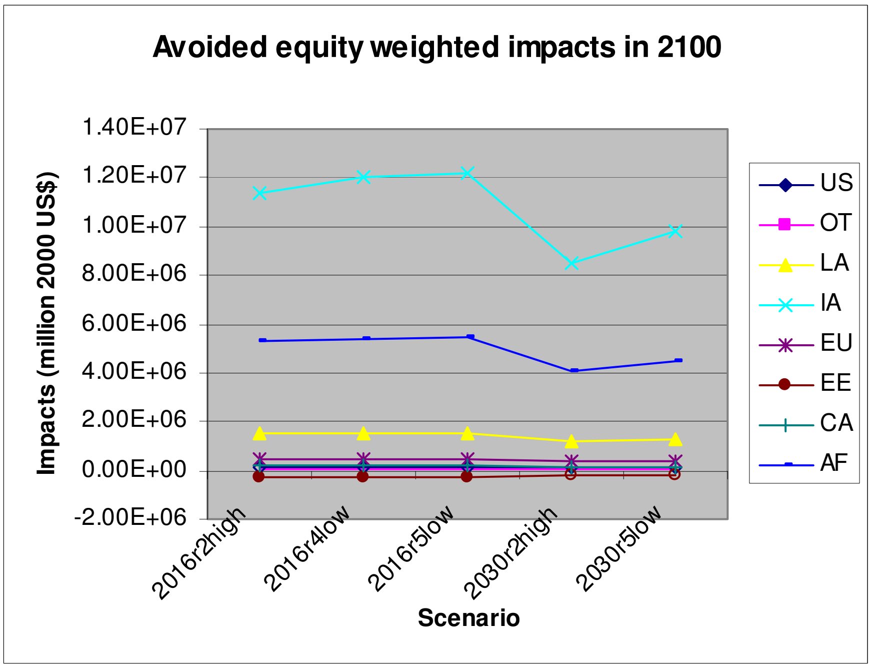
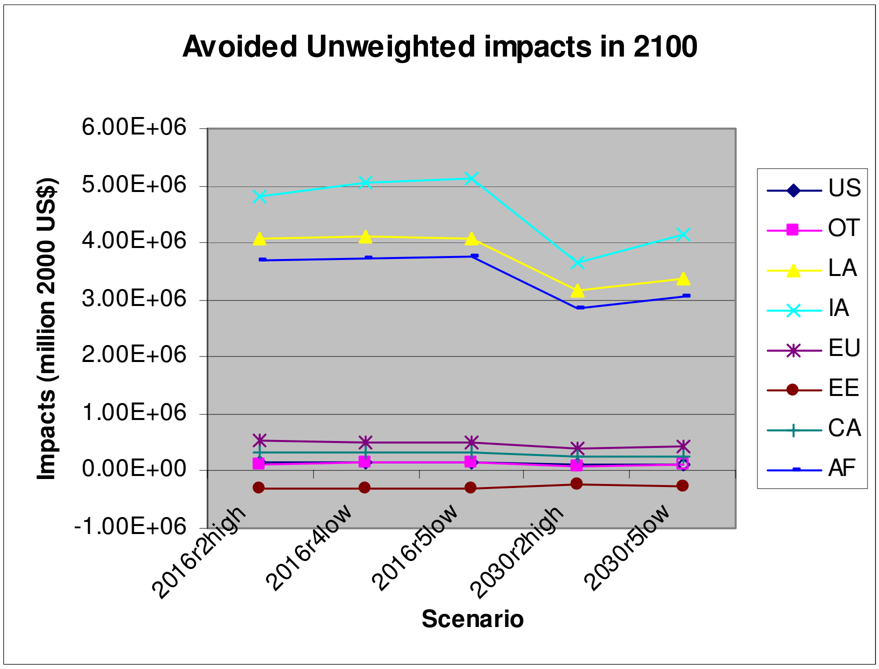


Figure 9.2.9 Avoided PAGE2002 equity-weighted impacts by region in 2100 in the policy scenarios



9.3 The economic costs of climate change impacts: results from Year 1 of the AVOID programme

This section is an extract from the AVOID Workstream 2 Report 9 by Alex Bowen.

It describes the results of the economic costs of climate change impacts from research conducted in the first year of the AVOID programme. The content is taken from the AVOID report *A review of the economic modelling for Workstream 1 of the AVOID programme*.

This report should be read along with the AVOID reports *Costs of different paths toward a low carbon world* (AV/WS2/D1/R4) and *The economics costs of climate change mitigation: results from Year 1of the AVOID programme* (AV/WS2/D1/R9), which together comprise all the economic modelling work of climate change impacts carried out in the first year of the AVOID programme.

9.3.1 INTRODUCTION

The AVOID programme is a UK government initiative designed to improve knowledge of the science of climate change, and its impacts on various aspects of society involved, among UK stakeholders. One goal of the project is to consider the implications of a range of potential policy-induced trajectories of greenhouse-gas emissions. Deliverable (3) of Work Stream (1) of the project was designed to provide, amonst other things, quantitative estimates of the climate change impacts avoided by reducing emissions relative to a baseline trajectory.

In pursuit of the this objective, one model (PAGE2002 – Chris Hope of the Judge Institute, Cambridge University) was used to assess the economic costs of the climate-change impacts likely to be associated with the chosen trajectories and the associated social costs of carbon.

The author of this report was commissioned to:

i. draw out the key messages from the modelling about the implications of the different trajectories for economic costs and feasibility;
ii. explore how the results fit with evidence from the wider literature, in particular on overall costs, the costs of delayed action and the trade-offs between trajectories and discuss the findings in relation to the findings of the Stern Review on the economics of climate change;
iii. identify and discuss the main characteristics, strengths and weaknesses of, and differences among, the economic models used in the work stream; and

iv. consider the implications for the specification of future economic modelling work for the work stream.

9.3.2 THE CHOICE OF MODELS

There are some major differences in the theoretical approaches taken by the economic models used in the AVOID project. Each has its strengths and weaknesses.

The modelling strategy of PAGE2002 focuses more on climate-change damage costs than on mitigation costs. It emphasises parameter uncertainty, drawing on a reading of the 'climate science' and 'economic impacts' literature to derive ranges for key parameters. As such, it is agnostic about some of the disagreements among economists about how to assess uncertain impacts up to a far distant time horizon. That may not be consistent with policy-makers' views, given the existence of official guidance on how to assess possible climate-change impacts when undertaking project appraisal in the public sector. PAGE2002 is discussed further in Box 4 in Section 7 ('The costs of climate-change impacts').

9.3.3 BASELINE AND POLICY SCENARIOS

The approach taken in the AVOID programme is to specify a range of emissions policy scenarios and to compare their climate-change impacts and economic implications with a baseline or 'business as usual' scenario. The policy scenarios are defined in terms of the year in which global emissions peak; the subsequent rate of emissions reductions; and the minimum level to which emissions are eventually reduced. The scenarios are not determined by a process of optimisation, trading off explicit quantified risks of climate-change impacts against the possible costs of mitigation. Instead, the idea is to examine a number of specific and easily described target scenarios, with differing intensities of climate-change policy, and to assess their implications for the atmospheric concentrations of greenhouse gases, impacts on the environment and human welfare, choice of technologies, the extent of other abatement activities and the costs of mitigation.

The baseline scenario chosen for the economic modelling in Workstream 1 of AVOID is the A1B scenario from the SRES family presented in the IPCC's Special Report on Emissions Scenarios (Nakicenovic and Swart, 2000). If the baseline scenario chosen were higher, the various policy scenarios would entail bigger emissions reductions. Hence they would be more costly in terms of

GDP foregone and would be associated with higher carbon prices; and the reverse would be the case if the appropriate baseline were lower.

The PAGE2002 model takes a multi-gas approach and includes all emitting sectors but in a very stylised, 'stripped down' way.

9.3.4 THE COSTS OF CLIMATE CHANGE IMPACTS

The PAGE2002 model is used to estimate probability distributions for the costs of climate change, whereas the other models focus on the costs of mitigation (although WITCH does include a feedback from temperature increases to output – a feedback that is suppressed in the mitigation cost estimates – and the WITCH team do discuss climate-change costs in their report). It was the PAGE2002 model that was used in Chapter 6 of Stern (2006) – and in subsequent work by the Stern team on discounting – to estimate expected utility in different scenarios, although its application in the AVOID project does not use the expected utility approach.

Box 4: The characteristics of PAGE2002

- PAGE2002 is an integrated assessment model (IAM) designed to focus on the probabilistic nature of climate change, climate-change impacts and mitigation costs. The basic structure of the model is fairly simple, but allows key parameters to be treated as if drawn from a probability distribution determined by the range of estimates in the literature (broadly as of the time of IPCC TAR – a new model release is imminent, which will update the ranges).
- On the one hand, the 'impacts' modelling is relatively sophisticated for an IAM, encompassing both market and non-market impacts and the risk of catastrophe. But, on the other hand, these phenomena are treated in a very abstract way and the form of the 'damage function' used constrains their representation. The approach taken with respect to parameter uncertainty means that the model is agnostic with respect to some of the arguments among economists about how to assess non-market impacts and how to allow for comparisons of individual welfare across time and space. These arguments are one reason why aggregate estimates of climate-change impacts and the social cost of carbon range so widely (see, for example, the 'metastudy' by Tol, 2005, and Chapter 20.6 of IPCC AR4 Working Group II (Yohe *et al*, 2007)). Policy-makers may be less agnostic about some of the judgements involved.

- The ‘mitigation costs’ side is relatively undeveloped, although the stochastic approach is potentially helpful. Stylised marginal abatement cost curves are used to generate probabilistic estimates of mitigation costs; a margin of ‘low-cost’ mitigation options (‘low-hanging fruit’) is included.
- Adaptation is also modelled, again in a simple stylised way.
- The PAGE2002 runs included in the AVOID project do not take on board all the features of estimates of the potential welfare costs of climate change deemed desirable in Chapter 6 of Stern (2006). In particular, risk aversion is not incorporated and expected welfare costs are not aggregated over time, so the importance of impacts beyond 2100 is not brought to the foreground.
- Stern also focused on just two climate-sensitivity scenarios (standard and high sensitivity), whereas in PAGE2002 these scenarios are subsumed in the probability distribution for the climate sensitivity parameter.

According to the PAGE2002 model, scenarios with a global emissions peak in 2016 result in considerably lower expected damage costs than those that peak in 2030. The time of peaking is more important than the subsequent rate of decline or the ultimate emissions level. In the A1B SRES reference scenario, climate change impacts reach some 4% of global GDP by 2100 in the central case (in a range 1 to 12% – some indication of the extreme uncertainty about the valuation of the impacts).

This figure cannot be compared directly with the so-called ‘balanced growth equivalent’ GDP losses often quoted from the Stern Review (Stern, 2006, p. 162): “the appropriate estimate of damages may well lie in the upper part of the range 5-20% [of per capita consumption.]” First, the PAGE2002 figures reported here refer to a particular point in time rather than to a summary measure of costs over time. That obviates the need to use a discount rate to aggregate costs incurred in different periods. The ‘balanced growth equivalent’ of Stern answered the question, what proportional reduction in consumption per head (and output per head in the PAGE2002 set-up), now and forever, would have the same impact on expected discounted utility for a benevolent utilitarian social planner as would the climate-change impacts considered? That calculation requires aggregation of utility across time.

Second, many of the costs contributing to the Stern estimate accrue further in the future. That is particularly the case for the paths with higher damages, because the discount rate (endogenous in the Stern exercise) is lower for paths with slower consumption growth. Stern’s choice of a very low rate for the pure rate of time discount also puts more weight on damages further away in time. The choice of a near-zero pure rate of discount has been controversial; see, among others, Weitzman (2007), Beckerman and Hepburn (2007), Dietz *et al* (2007) and Stern (2008).

Third, the Stern estimates use the probability distribution of possible GDP paths to weight utility along each of the paths, whereas the PAGE2002 outputs used here remain probability distributions over GDP. Utility weighting requires that value judgements are made about intertemporal, cross-country and intragenerational equity. A given loss of consumption inflicted on a low-income individual costs more in terms of loss of utility than the same loss of consumption inflicted on a high-income individual, because of declining marginal utility of income as income rises. The rate of decline in marginal utility of income assumed in the Stern Review was also a source of controversy, although the logarithmic utility function assumed for most of the calculations therein is standard in many macroeconomic applications. The PAGE2002 results include a set that are equity-weighted across regions to allow for differences in average per-capita income, but no results aggregating and weighting across time.

Fourth, the Stern calculations used the SRES A2 scenario, whereas PAGE2002 uses the AVOID-specified A1B scenario. Population growth is higher in the former and GDP growth lower, so that lower discount rates are appropriate in the former (income per capita grows more slowly). That means that Stern gives more weight to climate-change impacts in the far future.

Nevertheless, despite the lack of full comparability with the Stern estimates, the PAGE2002 runs for the AVOID project convey an impression of a lower impact of business as usual than does Stern. That is likely to reflect three main factors:

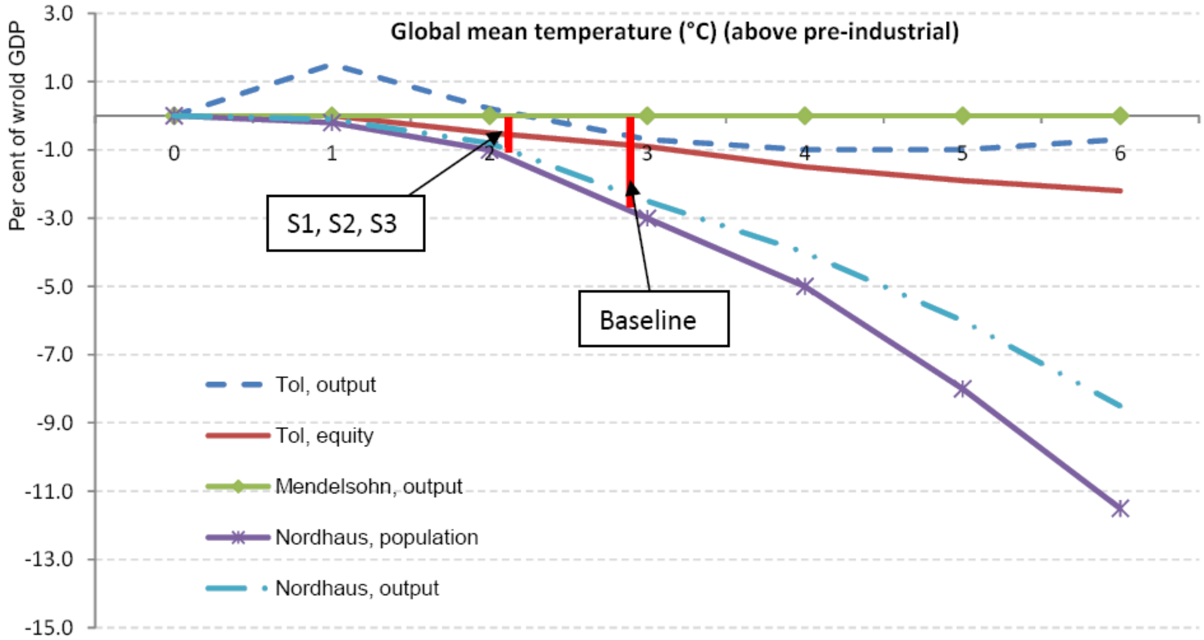
1 Stern aggregated climate-change damages into the indefinite future (but assuming that marginal impacts fell to zero from 2200), using a low pure rate of time discount – probably the most important factor;
2 Stern weighted low-growth paths more heavily, by working in terms of utility instead of GDP. To put this another way, Stern allowed for risk aversion with respect to the possible outcomes of climate change – subsequent work has shown that the risk of catastrophe, if the catastrophe is big enough, can dominate the calculation of expected utility (Dietz, 2009), although this factor was not key in the Stern PAGE2002 runs; and
3 Stern's 20% figure reflected scenarios in which the climate's sensitivity to a given increased in greenhouse gas concentrations was higher than in the standard runs, to allow for emerging research suggesting that climate sensitivity could be above that assumed in the base case.

Since the Stern Review was published, Stern himself has argued that the consequences of business as usual are likely to be worse than he had thought (Stern, 2008). There are several reasons why the impact on the 'balanced growth equivalent' level of consumption might be larger than the range given in Stern (2006) and bigger than suggested by the mean parameter values assumed in PAGE2002, which broadly reflects the range of parameter estimates in the literature at the time of the IPCC's Third Assessment Report (see Hope, 2006). Some of these are discussed in Richardson *et al* (2009):

i. More rapid-than-expected greenhouse gas emissions growth;
ii. Greater concern about positive feedbacks from climate change on natural stores of carbon and the performance of carbon sinks in the carbon cycle;
iii. Greater concern about other potential 'tipping points' in the global climate system
iv. Greater awareness of the potential social costs of climate-change impacts (e.g. enforced mass migration, more conflict over water resources); and
v. Greater awareness of the potential consequences for ecosystem services and the shortcomings of not modelling impacts on manufactured and natural capital separately (Neumayer, 2007; Sterner and Persson, 2007)

In the PAGE2002 runs for the AVOID project, policy scenarios in which emissions peak in 2016 avoid losses of 2.6-2.7% of year 2100 GDP in the central case (in a range of 0.6-7.4% GDP), reducing the magnitude of the impacts by some two thirds. Policy scenarios in which emissions peak in 2030 avoid losses of 2.0-2.2% of year 2100 GDP in the central case (in a range of 0.5-6.1% GDP), reducing the impacts by around a half. Hence, in the central case, peaking in 2016 instead of 2030 'buys' an additional reduction in impacts in 2100 equivalent to around 0.5% of year 2100 GDP. This figure can be compared with the mitigation cost estimates in the AVOID study – although one would prefer to use estimates drawn from a single modelling framework, so that assumptions about growth processes, damage functions and other factors were consistent..

The report of the modellers using WITCH includes (Appendix 2) a discussion of damage functions. They refer to a chart of selected damage functions, reproduced below (the WITCH report cites IPCC AR4, but the results were published in AR3). That can be compared with the damage functions derived from PAGE2002 in Stern (2006) shown in the subsequent chart (note that this chart focuses on mean changes in income per capita, not changes in 'balanced growth equivalent' consumption per capita, and so does not take into account risk aversion about particularly bad outcomes).



Estimates represent the annual GDP impact (relative to a no-climate-change scenario) of a given increase in temperature, as observed at the time when this increase in temperature is reached. They come from studies by Tol (2002), Mendelsohn (1998), Nordhaus and Boyer (2000) and Stern (2007). In "Tol, output", impacts across regions are simply added while in "Tol, equity", they are weighted by regional per capita income. In "Nordhaus output", impacts are weighted by GDP while in "Nordhaus equity", they are weighted by population. *Source*: IPCC (2007).

Figure: Selected damage functions (N.B. the chart does not include any Stern review estimates despite the footnote)

Source: IPCC AR3 via the WITCH report AV/WS2/D1/04

The baseline temperature increase by 2100 in the WITCH exercise is 3.7°C, which, using these damage functions, would imply a world GDP loss of 0-2.8% – below PAGE2002's 4% central estimate (the PAGE2002 estimates in Stern (2006) are slightly lower than 4%, as the following chart illustrates). Using the damage function in Nordhaus' more recent calibration (DICE2007), the estimated GDP loss is 3.8% of GDP, much closer to that from PAGE2002. WITCH's scenario S2, which brings the temperature increase in 2100 down to 2.02°C and has emissions peaking in 2016, saves an estimated 73% of the climate change costs in 2100. In contrast, scenario S7, which only limits the 2100 temperature increase to 3°C and has emissions peaking in 2030, saves an estimated 34% of the costs. Hence moving from S7 to S2 saves about 1.5% of 2100 world GDP in 2100; WITCH's estimates imply that the increased mitigation costs involved would be of the order of 4-6% of discounted world GDP. Thus a comparison of costs and benefits of adopting the tougher trajectory suggests that it is not worth the costs. In my view, that is likely to reflect the inadequate treatment of potential costs discussed above, the discount rate used and the time horizon chosen, but in the absence of a full reworking with updated 'Stern-style' assumptions that is difficult to demonstrate conclusively.

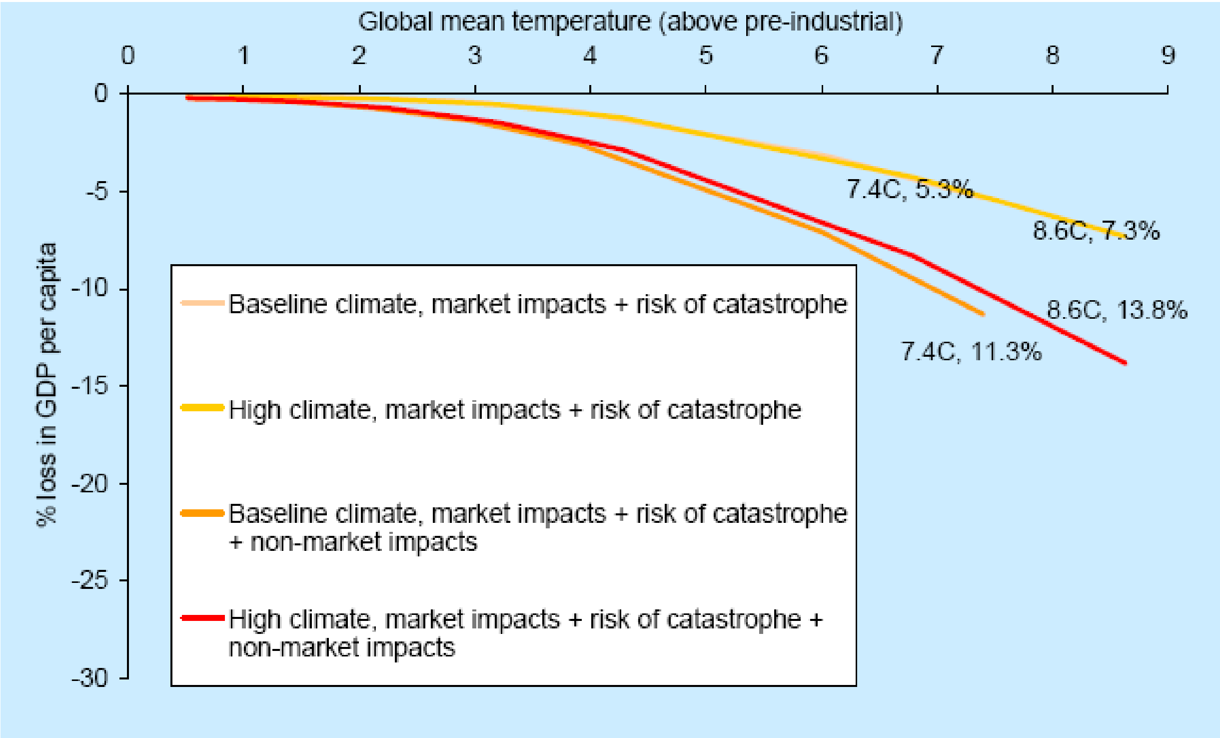


Figure: Mean losses in income per capita from four scenarios of climate change and economic impacts, plotted against average increases in global mean temperature (above pre-industrial levels – using the PAGE2002 model). This figure traces mean losses in per capita GDP due to climate change as a function of increasing global mean temperature, according to four of the scenarios of climate change and economic impacts. Losses are compared with baseline growth in per capita GDP without climate change. Because temperature is one of the probabilistic outputs of the PAGE2002 model, increases in temperature in each scenario are averaged across all 1000 runs. Source: Stern (2006), Figure 6.6, p. 180

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