UNIVERSITY OF SUSSEX
ECONOMICS

Working Paper Series

No. 100-2016

DANGEROUS INTERFERENCE WITH THE CLIMATE SYSTEM: AN ECONOMIC ASSESSMENT

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Abstract: This paper combines uncertainty about the impact of climate change on human welfare with the distribution of impacts over space and time. The best guess of world average impacts shows a relatively small impact, but with an uncertainty is large and skewed towards negative surprises. Poorer countries are more vulnerable to climate change. There is a 1% chance of a total loss in some countries at warming above 3°C. Generally, economic growth would reduce vulnerability, but this may not be true for the tail of the distribution for warming above 3°C. Thus, 3°C global warming appears as a critical threshold above which climate change is dangerous.

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Abstract

This paper combines uncertainty about the impact of climate change on human welfare with the distribution of impacts over space and time. The best guess of world average impacts shows a relatively small impact, but with an uncertainty is large and skewed towards negative surprises. Poorer countries are more vulnerable to climate change. There is a 1% chance of a total loss in some countries at warming above 3°C. Generally, economic growth would reduce vulnerability, but this may not be true for the tail of the distribution for warming above 3°C. Thus, 3°C global warming appears as a critical threshold above which climate change is dangerous.

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1. Introduction

Article 2 of the United Nations Framework Convention on Climate Change binds the countries of the world to avoid dangerous anthropogenic interference with the climate system. While noble in its intent, there is no objective definition of what is or is not dangerous (Tol & Yohe, 2006). Estimates of the impact of climate change on human welfare suggest that climate change is not the biggest problem in the world (Arent et al., 2014; Pearce et al., 1996), while other remedies than greenhouse gas emission reduction may be more effective in reducing those impacts (Anthoff & Tol, 2012; Schelling, 1992). This paper sheds new light on this by studying the uncertainty about the distribution of the impacts of climate change.

There is a substantial literature on what would constitute dangerous anthropogenic inference with the climate system (Dessai et al., 2004; Dietz, Hope, & Patmore, 2007; Gupta & van Asselt, 2006; Hansen, 2005; Knutti, Rogelj, Sedlácek, & Fischer, 2016; Kriegler, 2007; Leiserowitz, 2005; Lorenzoni, Pidgeon, & O'Connor, 2005; Mastrandrea & Schneider, 2004; New, Liverman, Schroder, & Anderson, 2011; O'Neill & Oppenheimer, 2002; Oppenheimer, 2005; Parry, Carter, & Hulme, 1996; Schneider, 2001; Shaw, 2015; Smith et al., 2009). This is not the place to review that literature. The natural sciences focus on what-if questions, predicting climate change and its impacts conditional on scenarios of greenhouse gas emissions and, occasionally, vulnerability to climate change. The social sciences also study so-what questions – including the question at what point a predicted impact of climate change would be deemed dangerous – but Arrow (1950) and Harsanyi (1955) showed that it would be an illusion to think a definition of dangerous could be universally agreed upon. I here follow Weitzman (2009) and consider climate change as dangerous if it leads to a welfare impact equivalent to a total loss of income.

The paper proceeds as follows. In Section 2, I discuss the data and set-up a simple model that captures the distribution of the welfare impacts over space and time, and the uncertainty about those impacts. Section 3 presents the results. Section 4 concludes.

2. Data and model

Tol (2015) reviews the literature on the total welfare impacts of climate change, and conducts a meta-analysis. Twenty-seven estimates of the total welfare impact of climate change were taken from twenty-two studies (Berz; Bosello, Eboli, & Pierfederici, 2012; d'Arge, 1979; Fankhauser, 1995; Hope, 2006; Maddison & Rehdanz, 2011; Maddison, 2003; Mendelsohn, Schlesinger, & Williams, 2000; Nordhaus, 1982, 1991, 1994a, b, 2006, 2008, 2013; Nordhaus & Boyer, 2000; Nordhaus & Yang, 1996; Plambeck & Hope, 1996; Rehdanz & Maddison, 2005; Roson & van der Mensbrugghe, 2012; Tol, 1995, 2002). Various impact functions were fitted to the data shown in Table A1. A piecewise linear function is, by far, the best fit to the global estimates. This three-parameter function defines an optimal temperature, the climate at which average welfare is maximised. Welfare falls linearly, with different slopes, if the temperature is above or below the optimum.

Ten estimates report regional detail, for six regions or more, and three have results for individual countries. The remaining fourteen only show a global total. A weighted regression of the regional estimates on the natural logarithm of per capita income and annual mean temperature, both regionally averaged, suggests that the welfare loss due to a 2.5°C warming is 1.2% of income less, with a standard deviation of 0.6%, for a country that is twice as rich and 0.4% less, with a standard deviation of 0.1%, for a country that is 1°C colder. In other words, richer and colder countries are less vulnerable to climate change.

The function estimated using the regional results is used to impute national impact estimates. The national imputations are forced to add up to the estimated regional and global totals of the original studies by shifting the imputed values, that is, by changing the intercept.

Having thus obtained twenty-seven estimates of the national welfare impact of climate change, a piecewise linear impact function is fitted for each country. This was done in Matlab, using the code in Appendix B. The global estimates suggest an optimum temperature of 0.5°C above pre-industrial temperature, or 0.3°C colder than today's climate. The national optima are on average 0.1°C with a error of 0.1°C, assuming that every country weights equally. The cold slope of the global impacts is 0.6 per cent Gross Domestic Product per degree Celsius (%GDP/°C), that is, there is a welfare loss equivalent to a 0.6 income loss for every degree Celsius of cooling. This is 3.8(0.3)%GDP/°C when averaged over the countries. The warm slope is -0.7%GDP/°C for the global results: Welfare falls by 0.7%GDP for every degree warming. For the country results, the warm slope is -3.3(0.1)%GDP/°C. The different results highlight that the world economy is concentrated in the temperate zone while the world population is concentrated in the tropics and subtropics. The large standard deviations highlight the diversity in the effects of climate change across the world.

The country-specific parameters vary systematically. The optimum temperature increase by 3.7(0.4)°C if the average income increases by $10,000 per person per year; and it is 0.11(0.01)°C lower in countries that are 1°C warmer. The cold slope is steeper in richer countries, by 0.8(0.2)%GDP/°C per $10,000/p/yr, and shallower in warmer countries, by 0.08(0.04)%GDP/°C per °C. The warm slope is shallower in richer countries, by 2.3(0.5)%GDP/°C per $10,000/p/yr, and steeper in warmer countries, by 0.06(0.01)%GDP/°C/°C. In other words, as countries grow richer, they will become less vulnerable to climate change.

A bootstrap was used to estimate the standard deviation of the country-specific parameters. 25,000 samples of 27 impact estimates were drawn, with replacement, from the original impact estimates, and the bilinear model was fitted to the pseudo-observations. The Matlab code is in Appendix B.

3. Results

Figure 1 shows the global impact for climate change ranging from a 3°C global cooling to a 8°C global warming. Figure 1 shows three alternative estimates. First, the impact function is calibrated to the global average impact. The welfare impacts are modest, equivalent to the loss of a few percent of income. The picture changes if instead we calibrate separate impact functions for each country. Figure 1 shows that if we do that and add the results up to the global average, impacts are substantially larger. At 8°C warming, the global average impact is equivalent to a 5% income loss, whereas the global average of the country-specific impacts is 13%.

There are two ways of interpreting the latter result. If we estimate country impacts in dollar terms and add them up to the globe, then we are either indifferent to the distribution of income and welfare; or we assume that transfers are paid by the relative winners to the relative losers. The third estimate in Figure 1 discards that interpretation and apply equity weights, correcting for the fact that a dollar is worth more to a poor woman than to a rich woman. Impacts go up further. At 8°C, the average welfare loss would be equivalent to a 33% income loss.

The impact function also changes qualitatively. The first two estimates show modest net gains from warming up to 1°C. As this is relative to pre-industrial times, these impacts are largely in the past. However, with equity weighting, warming always has a negative impact, while cooling has a positive impact. This is because equity weights put greater emphasis on the impacts in poorer countries, which tend to be in hotter climate and thus prefer cooling.

Figure 1 shows the best estimates of the impacts of climate change. Figure 2 shows the uncertainty about the impacts evaluated at the global average. As detailed above, the uncertainty was assessed with a bootstrap with 25,000 replications. Figure 2 compares the bootstrap mean to the best guess. The mean estimate is more pessimistic than the mode, reflecting the non-linearity of the bilinear model and suggesting that the uncertainty is asymmetric, and skewed in the wrong way. The median lies between the mode and the mean.

Figure 2 also shows the confidence intervals. Figure 2 reveals relatively high confidence in the estimated impacts around 2.5°C to 3.0°C global warming. Many of the primary estimates are for these levels of global warming. By construction, we are certain about the impact of no warming. The impact estimates between 0 and 3°C are therefore well-constrained on both sides. Note, however, that the impact estimates do not significantly deviate from zero.

The impact estimates for global cooling are essentially uninformative. This is no surprise as there is one primary estimate only. Above 2.5°C of warming, the impact estimates are significantly different from zero. Focussing on the lower bounds of the confidence intervals, it is clear that there are substantial risks of global warming. At 8°C, the lower bound of the 99% confidential interval of the welfare loss would be equivalent to a 20% income loss.

Combined, Figures 1 and 2 show that, although we should not worry too much about the best-guess impact of climate change on the average person, there are concerns about the risks of climate change to vulnerable groups. Figure 3 highlights this. It shows the fraction of the world population who live in countries where the welfare impact, at the 10th, 5th and 1st percentile, is equivalent to a total loss of income. If we want to be 90% sure that no country will be hit so hard, the world can warm 6.5°C. If we want to be 95% sure that this does not happen, warming should be limited to 3.5°C. And if we want to be 99% sure, 3.0°C is the limit.

Figures 1-3 show the impact if climate is the only thing that changes. This is unrealistic. If poorer countries are more vulnerable to climate change, then they would become less vulnerable as they grow richer. For maximum flexibility, I separately regress, for each percentile and for each global warming scenario, the country-specific impacts on country-average income. The results are show in Figure 4. Between a cooling of 3°C and a warming of 3°C, the results are as expected: Countries become less vulnerable to climate change as they grow richer. This is true for the 90th percentile throughout. Deeper in the tails, however, vulnerability to warming above 3°C increases with income. Not shown in Figure 4, the same is true for the standard deviation of the impacts: Below 3°C of warming, the spread of the impacts is smaller for richer countries; above 3°C, it is larger.

Figure 5 shows the implications. It repeats Figure 3, but now imposes scenarios of economic growth. I assume that 3°C warming occurs in 80 years' time, and that current warming is

1°C. In other words, global warming is 0.25°C per decade. (I assume the same for cooling.) In the three panels of Figure 5, economic growth per capita is assumed to be 1%, 2% and 3%. Qualitatively, the results follow immediately from Figure 4. Below 3°C, economic growth reduces vulnerability. Above 3°C, vulnerability increases.

The numbers are striking. Below 3°C, the risks shown in Figure 3 essentially disappear. Above 3°C, however, risks rapidly escalate until everyone lives in a country where, on average, the welfare loss is equivalent to a total loss of income.

The results in Figure 4 and 5 are surprising. The Schelling Conjecture – that economic development would reduce vulnerability to climate change (Schelling, 1992, 1995; Tol, 2005, 2007) – is widely accepted although occasionally disputed (Hoel & Sterner, 2007; Sterner & Persson, 2008). Here, the Schelling Conjecture breaks down in the tail for high warming. This result may be an artefact of the data and method used here. Of all the studies included, there is one (Hope, 2006) that assumes that vulnerability increases with income. However, this does not dominate the results in the tail. Instead, the imputation for the estimates by Maddison and Rehdanz (2011) is the cause. This study has the highest impacts – and the impacts imputed for the countries without observations there deviate most from the average pattern. This is particularly the case for richer countries. For poorer countries, the Maddison & Rehdanz imputations foresee large negative impacts and so do the other estimates. For richer countries, the Maddison & Rehdanz imputations also foresee large negative impacts, but other estimates are small and negative if not positive. Thus, Maddison & Rehdanz inflates the standard deviation and fattens the tail particularly for richer countries. This is particularly pronounced for more profound warming as Maddison & Rehdanz is one of the only three estimates of climate change above 3°C.

The dashed lines in Figure 4 show the income sensitivities if the Maddison & Rehdanz estimates are excluded. They are always positive. The dashed lines in Figure 5 shows the implications for the fraction of people living in countries suffering welfare collapse due to climate change. Using the income sensitivities without the Maddison & Rehdanz estimates, economic growth does not take away the dangers of climate change – but it does substantially reduce the number of people affected by these dangers, increasing the political feasibility of the international transfers needed to alleviate these concerns.

4. Discussion and conclusion

This paper casts old data in a new light. Previous meta-analyses of the total impact of climate change focussed on best estimate of the average impact of climate change, or on the uncertainty about the global average impact, or on the distribution across countries of the average impact. Here, I combine uncertainty and distribution. The results show that the best guess of world average impacts are relatively small, but that the uncertainty is large and skewed towards negative surprises. Poorer countries are more vulnerable to climate change. The uncertainty about country-specific impact estimates is such that there is a 1% chance of a welfare loss equivalent to total income loss in some countries at warming above 3°C. A total loss would count as catastrophic in Weitzman's sense of the word. While economic growth would reduce vulnerability in general, this may not be true for the tail of the distribution for warming above 3°C. There, vulnerability may increase with economic growth. Thus, 3°C global warming appears as a critical threshold above which climate change could be dangerous, although this result is based on a single study. Nonetheless, a non-zero probability of an infinite loss is sufficient to dominate the welfare calculus.

The results presented above come with caveats that require further research. It is by now widely accepted that the dangers of climate change lie not in the best forecast of what would happen to the average person, but rather in the tail-risks for selected countries. As international compensation is unlikely (Tol & Verheyen, 2004), this does not take away the concerns about climate change. The pattern of vulnerability that is seen between countries, is likely to hold within countries as well. This would strengthen the worries about climate change, but there has hardly been any research on the quantification of the intra-country distributional implications of the impacts of climate change.

The apparent overturning of the Schelling Conjecture, albeit based on a single study, calls for more research into the relationship between vulnerability to climate change and development. The empirical basis for estimates of the economic impacts of climate change has been growing steadily (Dell, Jones, & Olken, 2014), but studies of how economic growth, development, institutions, culture and technology shape that relationship have been lagging behind.

Acknowledgements

Financial support by the RISES-AM project is gratefully acknowledged.

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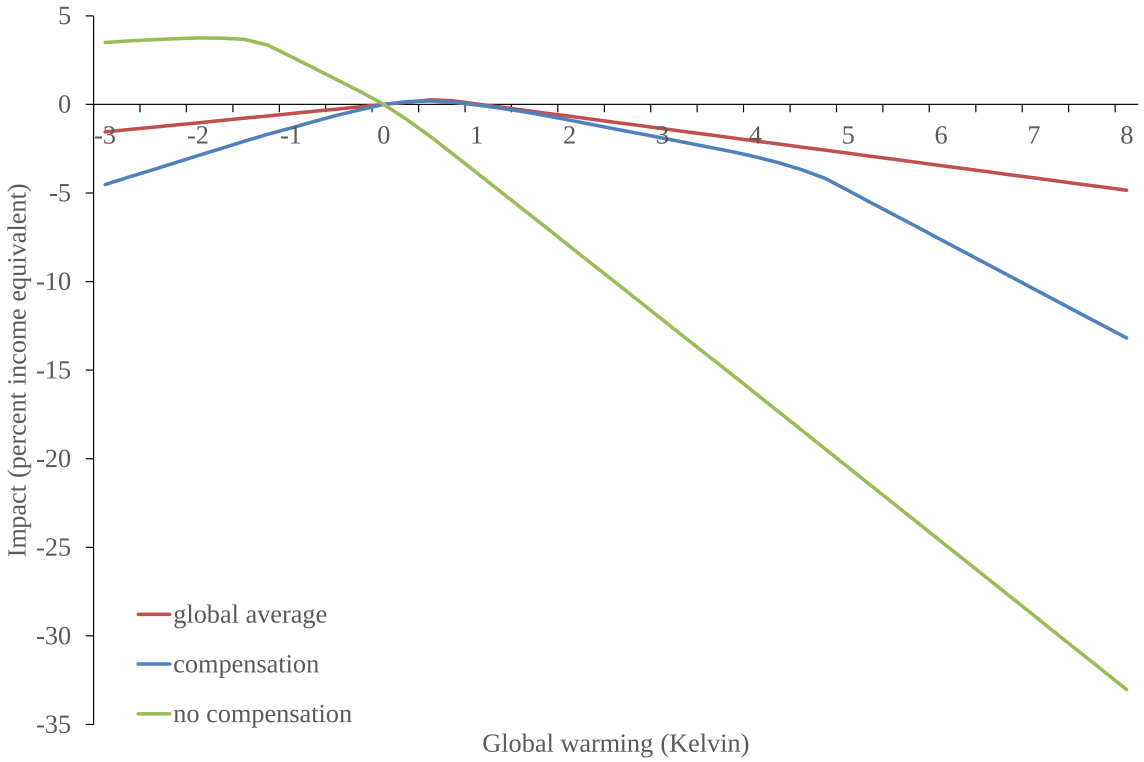


Figure 1. The total impact of climate change as a function of the degree of global warming, evaluated at the global average, and evaluated at country averages aggregated to the global average with and without assuming compensation between countries.

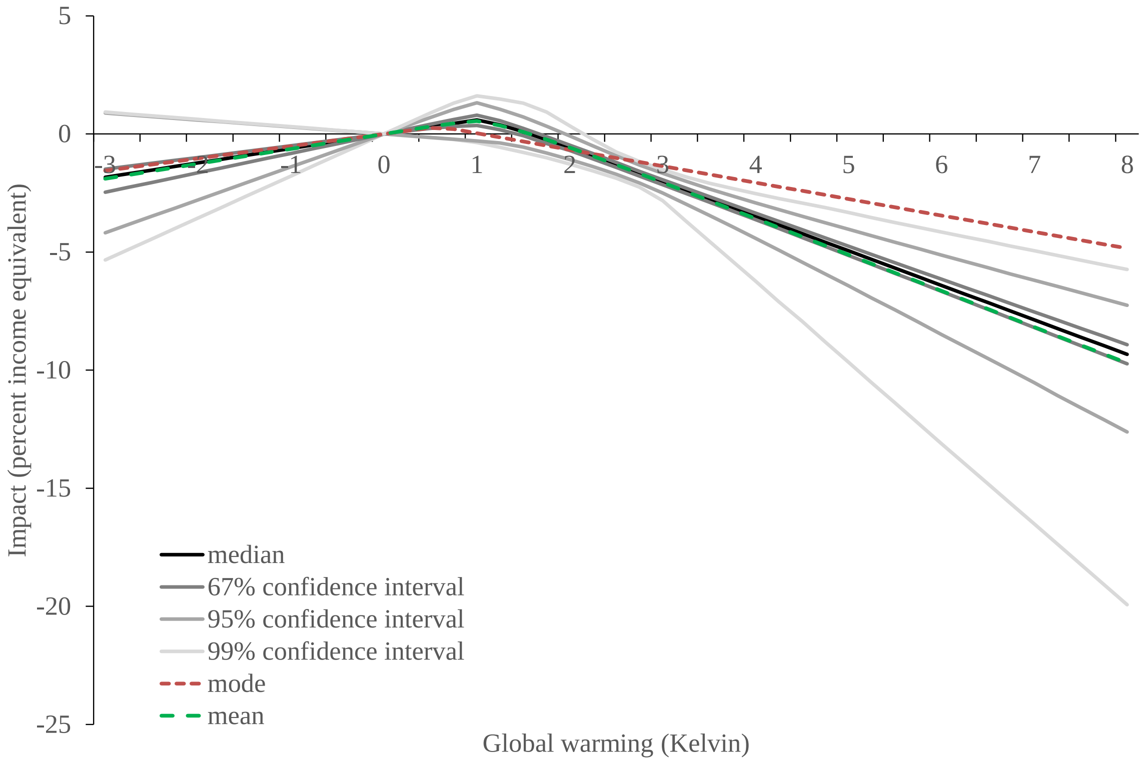


Figure 2. The central tendencies and selected confidence intervals of the total impact of climate change as a function of the degree of global warming, evaluated at the global average.

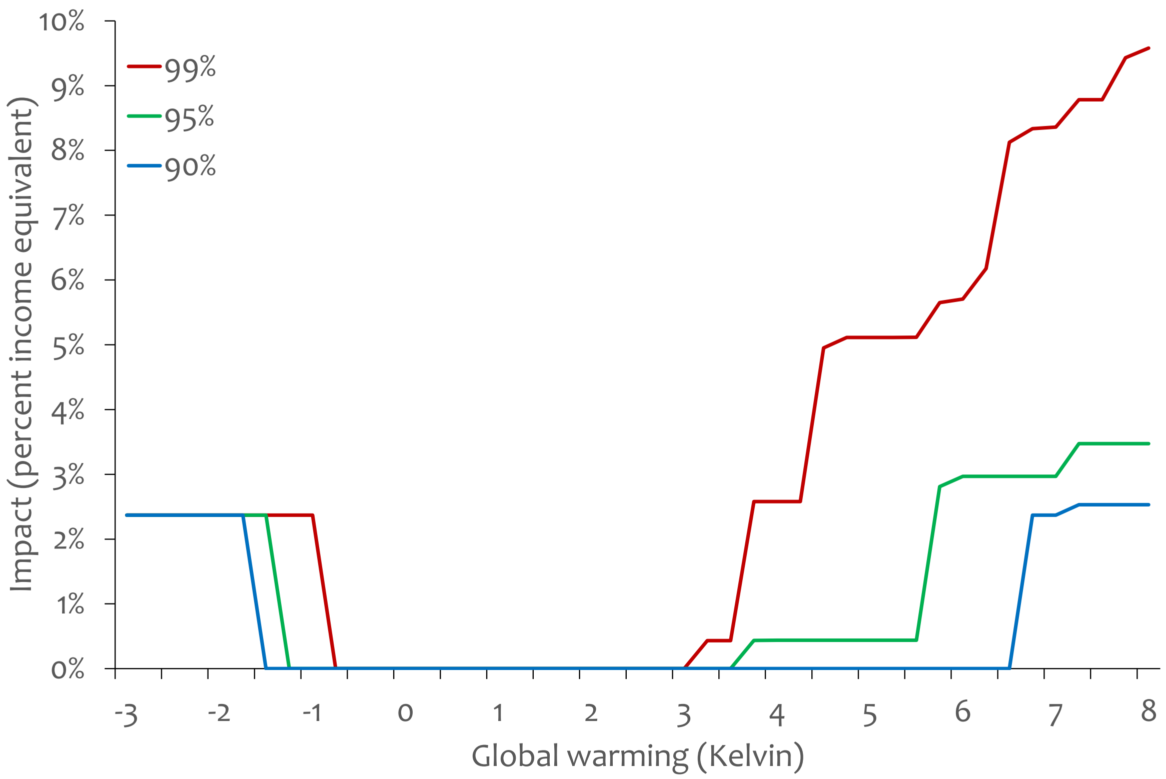


Figure 3. The fraction of the world population living in a country where the welfare impact of climate change is equivalent to a total loss of income, as a function of the degree of global warming, for a 10%, 5% and 1% chance of occurrence.

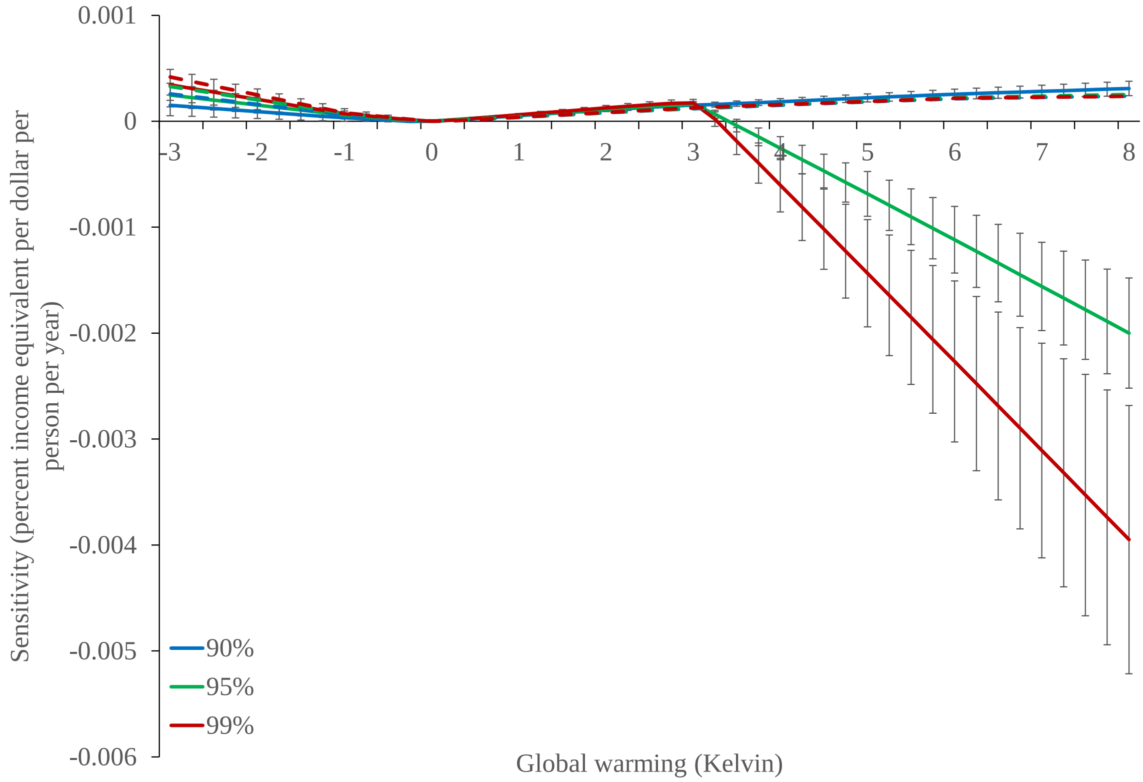
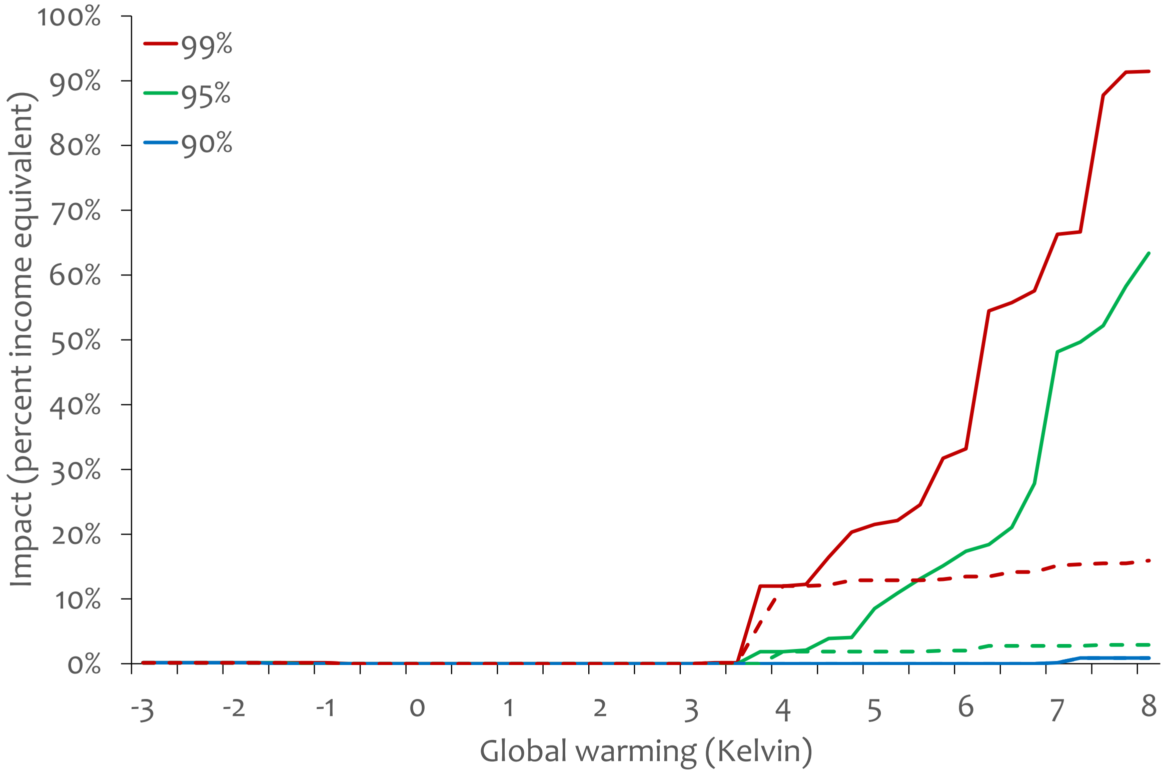


Figure 4. The sensitivity of the impact of climate change to changes in per capita income at various degrees of global warming and at various points in the tail of the distribution. The solid (dashed) lines include (exclude) the Maddison & Rehdanz estimates.


100%
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70%
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50%
40%
30%
20%
10%
0%
Impact (percent income equivalent)
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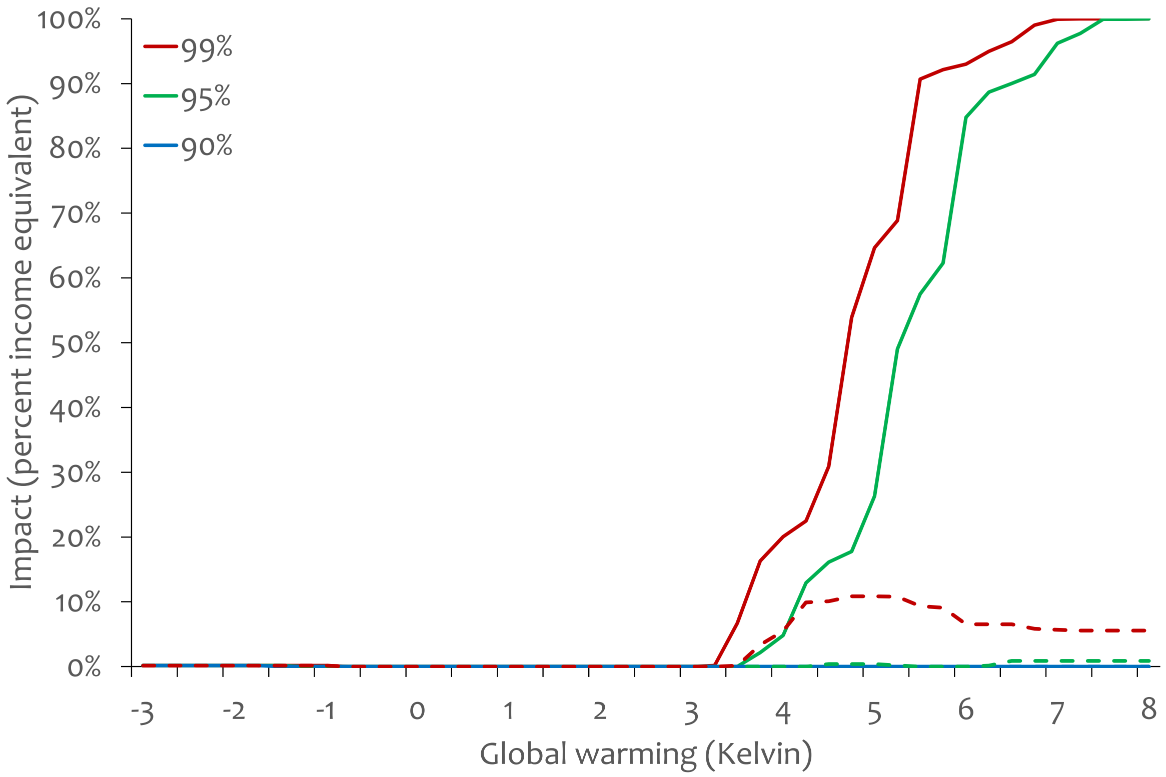
Global warming (Kelvin)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Impact (percent income equivalent)
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Global warming (Kelvin)

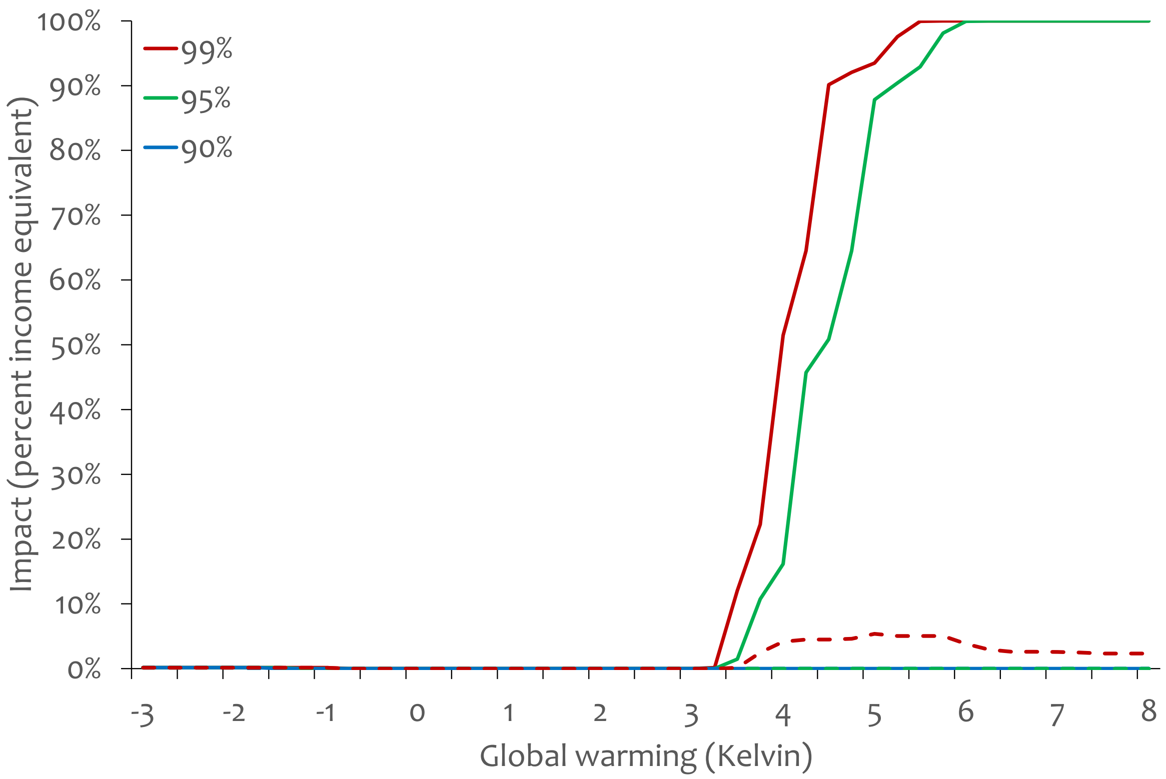

Figure 5. The fraction of the world population living in a country where the welfare impact of climate change is equivalent to a total loss of income, as a function of the degree of global warming, for a 10%, 5% and 1% chance of occurrence, for an income growth rate of 1% per year (top panel), 2% per year (middle panel) and 3% per year (bottom panel). The solid (dashed) lines include (exclude) the Maddison & Rehdanz estimates in the estimation of the income sensitivities.

APPENDIX A – IMPACT ESTIMATES

Table 1. Estimates of the welfare impact of climate change[a, b]

Study	Warming (°C)	Impact (%GDP) Best	SD	Low	High	Regions #
d'Arge 1979	-1.0	-0.6				1
Nordhaus 1982	2.5	-3.0		-12.0	5.0	1
Nordhaus 1991	3.0	-1.0				1
Nordhaus 1994b	3.0	-1.3				1
Nordhaus 1994a	3.0	-3.6		-21.0	0.0	1
	6.0	-6.7				
Fankhauser 1995	2.5	-1.4				6
Berz undated	2.5	-1.5				6
Tol 1995	2.5	-1.9				9
Nordhaus and Yang 1996	2.5	-1.4				6
Plambeck and Hope 1996	2.5	-2.9		-13.1	-0.5	8
Mendelsohn et al. 2000	2.5	0.0				1
	2.5	0.1				
Nordhaus and Boyer 2000	2.5	-1.5				13
Tol 2002	1.0	2.3	1.0			9
Maddison 2003	2.5	0.0				83
Rehdanz and Maddison 2005	0.6	-0.2				63
	1.0	-0.3				
Hope 2006	2.5	-1.0		-3.0	0.0	8
Nordhaus 2006	3.0	-0.9	0.1			1
	3.0	-1.1	0.1			
Nordhaus 2008	3.0	-2.5				1
Maddison and Rehdanz 2011	3.2	-5.1				79
Bosello et al. 2012	1.9	-0.5				14
Roson and van der Mensbrugghe 2012	2.9	-2.1				15
	5.4	-6.1				
Nordhaus 2013	2.9	-2.0				1

[a] Impact is measured as welfare-equivalent income loss, and expressed as percentage of income. Climate change is characterised by the increase in the global annual mean surface air temperature. Estimates are best guesses. Where available, either the standard deviation (SD) of the estimate or an indication of lower (low) and upper (high) bound of its confidence interval are given.

[b] Data are at http://users.sussex.ac.uk/~rt220/totalimpactreep.xlsx

APPENDIX B – MATLAB CODES

Function bilinear.m

```
function imp = bilinear(temp,par);
%calculates the impact imp of warming temp
%par(1) = cold slope
%par(2) = optimal temperature
%par(3) = warm slope

if par(2) > 0,
    if temp <= par(2),
        imp = par(1)*temp;
    else
        imp = par(1)*par(2) + par(3)*(temp-par(2));
    end
else
    if temp > par(2),
        imp = par(3)*temp;
    else
        imp = par(3)*par(2) + par(1)*(temp-par(2));
    end
end

end
```

Function SSRbilinear.m

```
function SSR = SSRbilinear(temp,impobs,par)
%calculates the sum of squared residuals for the bilinear impact model
%temp = vector of temperatures
%impobs = vector of corresponding impacts
%par = parameters of bilinear model

for i=1:length(temp)
    impmod(i) = bilinear(temp(i),par);
end

SSR = (impmod-impobs)*(impmod-impobs)';

end
```

Script calibcountry.m

```
%% read data
vFileToOpen = 'dangerousimpact.xlsx';
tempdata = xlsread(vFileToOpen, 'country', 'S1:AR1');
globaldata = xlsread(vFileToOpen, 'country', 'S2:AR2');
countrydata = xlsread(vFileToOpen, 'country', 'S4:AR191'); %AS to include
Maddison and Rehdanz

%% calibration for individual countries
n = length(countrydata);
parinit = [0.5964 0.5181 -0.6959];
options  =  optimset('MaxFunEvals',100000,'MaxIter',100000);

for i=1:n,
    disp(i)
    impdata = countrydata(i,:);
    [parest(i,:),SSR(i)] =
fminsearch(@(par)SSRbilinear(tempdata,impdata,par),parinit,options);
end
```

```
%% bootstrap
m = length(tempdata);
b = 25000; %number of bootstraps
randindex = randi(m,b,m);
tempeval = [-3.5 -3.25 -3.0 -2.75 -2.5 -2.25 -2.0 -1.75 -1.5 -1.25 -1.0 -
0.75 -0.5 -0.25 0.0 0.25 0.5 0.75 1.0 1.25 1.5 1.75 2.0 2.25 2.5 2.75 3.0
3.25 3.5 3.75 4.0 4.25 4.5 4.75 5.0 5.25 5.5 5.75 6.0 6.25 6.5 6.75 7.0
7.25 7.5 7.75 8.0]
e = length(tempeval);

parbs = zeros(n,3);
parb2 = zeros(n,3);
parall = zeros(n,3,b);
impeval = zeros(n,e);
impeva2 = zeros(n,e);
impall = zeros(n,e,b);

for j=1:b,
    disp(j)
    tempbs = tempdata(randindex(j,:));
    for i=1:n,
        impdata = countrydata(i,:);
        impbs = impdata(randindex(j,:));
        [parbst,SSR] =
fminsearch(@(par)SSRbilinear(tempbs,impbs,par),parinit,options);
        parall(i,:,j) = parbst;
        parbs(i,:) = parbs(i,:) + parbst;
        parb2(i,:) = parb2(i,:) + parbst.*parbst;
        for l=1:e,
            vimp = bilinear(tempeval(l),parbst);
            impall(i,l,j) = vimp;
            impeval(i,l) = impeval(i,l) + vimp;
            impeva2(i,l) = impeva2(i,l) + vimp*vimp;
        end
    end
end

parbs = parbs/b;
parb2 = parb2/b;
impeval = impeval/b;
impeva2 = impeva2/b;

%the worrisome impacts are large and negative, so we need the lower
percentiles
imp01 = prctile(impall,1,3);
imp05 = prctile(impall,5,3);
imp10 = prctile(impall,10,3);

%% bootstrap global
randindex = randi(m,b,m);

parbsg = zeros(1,3);
parb2g = zeros(1,3);
parallg = zeros(3,b);
impevalg = zeros(1,e);
impeva2g = zeros(1,e);
impallg = zeros(e,b);

for j=1:b,
```

```
    disp(j)
    tempbs = tempdata(randindex(j,:));
    impbs = globaldata(randindex(j,:));
    [parbst,SSR] =
fminsearch(@(par)SSRbilinear(tempbs,impbs,par),parinit,options);
    parallg(:,j) = parbst;
    parbsg = parbsg + parbst;
    parb2g = parb2g + parbst.*parbst;
    for l=1:e,
        vimp = bilinear(tempeval(l),parbst);
        impallg(l,j) = vimp;
        impevalg(l) = impevalg(l) + vimp;
        impeva2g(l) = impeva2g(l) + vimp*vimp;
    end
end

parbsg = parbsg/b;
parb2g = parb2g/b;
impevalg = impevalg/b;
impeva2g = impeva2g/b;
```