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THE UNCERTAINTY ABOUT THE TOTAL ECONOMIC IMPACT OF CLIMATE CHANGE

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Abstract: This paper uses a vote-counting procedure to estimate the probability density function of the total economic impact as a parabolic function of global warming. There is a wide range of uncertainty about the impact of climate change up to 3ºC, and the information becomes progressively more diffuse beyond that. Warming greater than 3ºC most likely has net negative impacts, and warming greater than 7ºC may lead to a total welfare loss. The expected value of the social cost of carbon is about $29/tC in 2015 and rises at roughly 2% per year.

Keywords: climate change, economic impact, meta-analysis, social cost of carbon

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The Uncertainty about the Total Economic Impact of Climate Change

1. Introduction

Climate change is generally accepted as one of the largest externalities of our times. However, its impact on human welfare is poorly understood. Some argue that climate change would have devastating consequences (Stern et al. 2006) while others conclude that climate change is a minor nuisance (Mendelsohn et al. 2000a). In this paper, I use the available estimates in the literature to assess the uncertainty about the total economic impact of climate change.

In previous papers (Tol 2010;Tol 2005;Tol 2008;Tol 2009), I assess the uncertainty about the marginal impact of carbon dioxide emissions. This is relatively straightforward as there are now more that 300 estimates of the social cost of carbon. However, there are only 14 estimates of the total impact of climate change. Therefore, as a second contribution, this paper offers a method to objectively estimate a probability density function with few data.

The method is not particularly complicated or advanced. It uses basic probability and statistical theory but applies it in an unconventional way. The main concern is that standard methods, such as Bayesian updating, lead to overconfidence. The method used here respects the weak empirical basis that implies a wide range of uncertainty, which grows with extrapolation.

The paper proceeds as follows. Section 2 surveys the literature on the total economic impact of climate change. Section 3 takes the 14 static point estimates and turns them into a probability density function of the dynamic impacts. Section 4 derives the implied social cost of carbon. Section 5 concludes.

2. Estimates of the Total Economic Effect of Climate Change

The first study of the global welfare impacts of climate change was done by (Fankhauser 1994;Fankhauser 1995). Table 1 lists that study and a dozen other studies of the worldwide effects of climate change.

Any study of the economic impact of climate change begins with some assumptions on future emissions, the extent and pattern of warming, and other possible aspects of climate change, such as sea level rise and changes in rainfall and storminess. The studies must then translate from climate change to economic consequences. A range of methodological approaches are possible. (Nordhaus 1994a) interviewed a limited number of “experts”[1], asking them directly about the total economic impact.

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[1] While these people were experts in other fields, there was no literature on the economic impacts of climate change at that time.

The studies by Fankhauser (1994, 1995), (Nordhaus 1994b), (Tol 1995;Tol 2002a;Tol 2002b) use the *enumerative method*. In this approach, estimates of the "physical effects" of climate change are obtained one by one from natural science papers, which in turn may be based on some combination of climate models, impact models and laboratory experiments. The physical impacts must then each be given a price, and added up. For traded goods and services, such as agricultural products, agronomy papers are used to predict the effect of climate on crop yield, and then market prices or economic models are used to value that change in farm productivity. As another example, the impact of sea level rise constitutes the costs of coastal protection and land lost, estimates of which can be found in the engineering literature; the economic input in this case is not only the cost of dike building and the value of land, but also decisions about which properties to protect. For non-traded goods and services, other methods are needed. An ideal approach might be to study how climate change affects human welfare through health and nature in each area around the world, but a series of "primary valuation" studies of this kind would be expensive and time-consuming. Thus, for enumerative studies, the monetisation of non-market climate change impacts relies on "benefit transfer," in which epidemiology papers are used to estimate effects on health or the environment, and then economic values are applied from studies of the valuation of mortality risks in other contexts than climate change.

The *statistical approach* is an alternative (Mendelsohn et al. 2000b;Mendelsohn et al. 2000a). It is based on direct estimates of the welfare impacts, using observed variations (across space within a single country) in prices and expenditures to discern the effect of climate. Mendelsohn assumes that the observed variation of economic activity with climate over space holds over time as well; and uses climate models to estimate the future impact of climate change. Mendelsohn's estimates are done per sector for selected countries, extrapolated to other countries, and then added up, but physical modelling is avoided. Other studies (Maddison 2003;Nordhaus 2006) use versions of the statistical approach as well. Nordhaus uses empirical estimates of the *aggregate* climate impact on income across the world (per grid cell), while Maddison looks at patterns of *aggregate* household consumption (per country). Like Mendelsohn, Nordhaus and Maddison rely exclusively on observations, assuming that "climate" is reflected in incomes and expenditures – and that the pattern of impact of variation of climate over space is the same as the pattern of impact of variation of climate over time. (Rehdanz and Maddison 2005) also empirically estimate the aggregate impact, using self-reported happiness (an entirely independent data-set) for dozens of countries.

The *enumerative approach* has the advantage that it is based on natural science experiments, models and data; the results are physically realistic. However, the enumerative approach also raises concerns about extrapolation: economic values estimated for other issues are applied to climate change concerns; values estimated for a limited number of locations are extrapolated to the world; and values estimated for the recent past are extrapolated to the remote future. Tests of benefit transfer methods have shown time and again that errors from such extrapolations can be substantial (Brouwer and Spaninks 1999). But perhaps the main disadvantage of the enumerative approach is that the assumptions about adaptation may be unrealistic—as temperatures increase, presumably private and public-sector reactions would occur to both market and non-market events.

In contrast, the statistical approach relies on uncontrolled experiments. These estimates have the advantage of being based on real-world differences in climate and income, rather than extrapolated differences. Therefore, adaptation is realistically, if often implicitly, modelled. However, statistical studies run the risk that all differences between places are attributed to climate. Furthermore, the data often allow for cross-sectional studies only; and some important aspects of climate change, particularly the direct impacts of sea level rise and carbon dioxide fertilization, do not have much spatial variation.

Given that the studies in Table 1 use different methods, it is striking that the estimates are in broad agreement on a number of points. Table 1 shows selected characteristics of the published estimates. The first column of Table 1 shows the underlying assumption of warming, measured as the increase in the global average surface air temperature. The impact studies in Table 1 are comparative static, and they impose a future climate on today's economy. One can therefore not attach a date to these estimates. The second column of Table 1 shows the impact on welfare at that future time, expressed as a percentage of income. For instance, (Nordhaus 1994b) estimates that the impact of 3˚C global warming is as bad as losing 1.4% of income. In some cases, a confidence interval (usually at the 95 percent level) appears under the estimate; in other cases, a standard deviation is given; but most studies do not report any estimate of the uncertainty.

A first area of agreement between these studies is that the welfare effect of a doubling of the atmospheric concentration of greenhouse gas emissions on the current economy is relatively small—a few percentage points of GDP. It is roughly equivalent to a year's growth in the global economy—as the estimates in Table 1 are the impacts of a century or so of climate change, the economic loss from climate change is not all that large. However, the damage is not negligible. An environmental issue that causes a permanent reduction of welfare, lasting into the indefinite future, would certainly justify some steps to reduce such costs.

A second finding is that some estimates (Hope 2006;Mendelsohn et al. 2000b;Mendelsohn et al. 2000a;Tol 2002b) point to initial benefits of a modest increase in temperature, followed by losses as temperatures increase further. There are no estimates of costs for a warming above 3˚C, although climate change may well go beyond that. All studies published after 1995 have regions with net gains and net losses due to global warming, while earlier studies only find net losses. Figure 1 illustrates this pattern. The horizontal axis shows the increase in average global temperature. The vertical index shows the central estimate of welfare loss. The central line shows a best-fit parabolic line from an ordinary least squares regression. Of course, it is something of a stretch to interpret the results of these different studies as if they were a predictive time-series of how climate change will affect the world economy over time, and so this graph should be interpreted more as an interesting calculation than as hard analysis. But the pattern of modest economic gains due to climate change, followed by substantial losses, appears also in the few studies that report likely impacts over time (Mendelsohn et al. 2000b;Mendelsohn et al. 2000a;Nordhaus and Boyer 2000;Smith et al. 2001;Tol 2002b).

The initial benefits arise partly because more carbon dioxide in the atmosphere reduces "water stress" in plants and may make them grow faster (Long et al. 2006). In addition, the output of the global economy is concentrated in the temperate zone, where warming reduces heating costs and cold-related health problems. Although the world population is concentrated in the tropics, where even the initial effects of climate change are probably negative, the relatively smaller size of the economy in these areas means that gains for the high-income areas of the world more than offset losses in the low-income areas. However, even though, initially, net economic impacts may well be positive, it does not follow that greenhouse gas emissions should be subsidized. The climate responds rather slowly to changes in greenhouse gas emissions. The initial warming can no longer be avoided; it should be viewed as an inevitable "sunk" benefit.

Third, the uncertainty is vast. For example, consider only the studies that are based on a benchmark warming of 2.5ºC. These studies have an average estimated effect of climate change on average output of -0.7 percent of GDP, and a standard deviation of 1.2 percent of GDP. Only five of the 14 studies in Table 1 report some measure of uncertainty. Two of these report a standard deviation only—which suggests symmetry in the probability distribution. Three studies report a confidence interval – of these, two studies find that the uncertainty is right-skewed, but one study finds a left-skewed distribution. Although the evidence on uncertainty here is modest and inconsistent, it seems that undesirable surprises are more likely than desirable surprises. While it is relatively easy to imagine a disaster scenario for climate change – for example, involving massive sea level rise or monsoon failure that could even lead to mass migration and violent conflict – it is not easy to imagine that climate change will be a huge boost to human welfare.

The kinds of studies presented in Table 1 can be improved in numerous ways, some of which have been mentioned already. In all of these studies, economic losses are approximated with direct costs, ignoring general equilibrium and even partial equilibrium effects. There may be some overlap between impact estimates—for example, losses in water resources and losses in agriculture may actually represent the same loss. Estimates are often based on extrapolation from a few detailed case studies, and extrapolation is to climate and levels of development that are very different from the original case study. Realistic modelling of adaptation is problematic, and studies typically either assume no adaptation or perfect adaptation. Willingness to pay (WTP) is the basis for valuation, but as climate change is an involuntary risk imposed by a previous generation, willingness to accept compensation cannot be ruled out as a more appropriate basis.

Many effects are unquantified, and some of these may be large. The effects of climate change that have been quantified and monetized include the impacts on agriculture and forestry, water resources, coastal zones, energy consumption, air quality, tropical and extratropical storms, and human health. Obviously, this list is incomplete. Even within each category, the assessment is incomplete. Many of the omissions seem to be relatively small –

such as saltwater intrusion, cooling water, fisheries, wind and wave energy, Arctic navigation and exploitation, disruptions of traffic and construction. There are large unknowns too: extreme climate scenarios, the very long term, biodiversity loss, the possible effects of climate change on economic development and even political violence.

Examples of extreme climate scenarios include an alteration of ocean circulation patterns and the disintegration of major ice sheets. Exactly what would cause these sorts of changes or what effects they would have are not at all well-understood but the costs could be substantial. Another big unknown is the effect of climate change in the very long term. Most static analyses examine the effects of doubling the concentration of atmospheric CO_2; most studies looking at effects of climate change over time consider only the time period up until 2100. Of course, climate change will not suddenly halt in 2100. In fact, most estimates suggest that the negative effects of climate change will grow, and even accelerate, in the years up to 2100. Climate change could have a profound impact on biodiversity, not only through changes in temperature and precipitation, but in the ways climate change might affect land use and nutrient cycles, ocean acidification, and the prospects for invasion of new habitats by alien species. However, there are few quantitative studies of the effects of climate change on ecosystems and biodiversity and valuation of ecosystem change is difficult, particularly if that change is not marginal. There is an open question about the possible effects of climate change on annual rates of economic growth. Accumulated over a century or more, even a small impact of the growth rate would dominate all earlier estimates of the economic effects of climate change.

3. The uncertainty about the total costs of climate change

3.1. Methods

Table 1 has 14 estimates of the total costs of climate change. Ten of those are comparable as they refer to the same warming, while two estimates consider less warming and two estimates greater warming. In order to reconcile the estimates and assess the uncertainty, the following procedure was followed. First, a parabola was fitted, through least squares, to the 14 observations. The result is shown in Figure 1. Initial warming has positive effects – associated with carbon dioxide fertilization, reduced winter heating costs, and lower cold-related mortality and morbidity – but impacts reach their peak at a warming 1.1ºC and fall thereafter to turn negative at 2.2ºC. As the world is committed to one and probably two degrees of warming (Clarke et al. 2009), the initial benefits are sunk benefits: The net benefits of climate change will be reaped regardless of climate policy. The incremental impacts of the climate change than can be avoided are negative.

Second, 14 parabolas were fitted to all but one of the observations (single bootstrap); and 91 parabolas were fitted to all but two of the observations (double bootstrap). These bootstraps give a first indication of the uncertainty about the fitted curve. Third, 44 parabolas were fitted that exactly go through two of the observations (double fit).[2] Fourth, 14 parabolas were fitted that exactly go through one of the observations and minimise the squared deviation with the remaining 13 observations (single fit).

Thus, a total of 164 parabolas were fitted. While these span a wide range of results, this does not reflect the true uncertainty. The most pessimistic parabola (in the long run) goes through the most optimistic estimate for 2.5ºC and the most pessimistic estimate for 3.0ºC; while the most optimistic parabola goes through the most pessimistic estimate for 2.5ºC and the most optimistic estimate for 3.0ºC. That is, the range of point estimates in Table 1 is treated as the range of uncertainty. Put differently, the uncertainty about the point estimates is ignored.

I therefore construct a probability density function (PDF) for the total impact of climate change at 1.0ºC, 2.5ºC and 3.0ºC warming. This is readily done with the 10 observations for 2.5ºC, but there are only 2 observations each for 1.0ºC and 3.0ºC. Therefore, I use the parabolas that exactly go through one estimate while minimising the squared distance with the remaining 13 estimates (method 4, single fit, above). Thus, there are 14 “observations” for each scenario.

There are various PDFs that can be constructed from 14 point estimates. (1) One can assume Normality and use the sample statistics. (2-3) One can use the sample standard deviation and assign this uncertainty to each of the point estimates. The 14 individual PDFs can be then combined using (2) Bayesian updating or (3) vote-counting. As vote-counting gives the widest range of uncertainty, I prefer this method.

From each of the 3 PDFs (one each for 1.0ºC, 2.5ºC and 3.0ºC), 9 points were selected: the 1st, 5th, 10th, 33rd, 50th, 67th, 90th, 95th, and 99th percentile (see Table A1). Picking one point each from two PDFs, 243 combinations result. I exactly fit a parabola to these two “observations”. The result is a set of parabolas that gives a wide range of results which is not inconsistent with the 14 primary studies (sample).

A total number of 407 parabolas is the result. These parabolas are not equally plausible. Each of the parabolas was given a likelihood equal to the increment of the Cumulative Distribution Function (CDF)[3] derived above for the impact at 1.0ºC, 2.5ºC and 3.0ºC. The probability of each parabola follows from adding the three probabilities and guaranteeing that the 407 probabilities sum to one. Adding (vote-counting) probabilities again leads to a wider and therefore more appropriate range of uncertainty than multiplying probabilities. Furthermore, as all 14 observations were each used in the construction of each of the three PDFs, multiplying the probabilities would imply that the same information is used thrice.

Two alternative probability assignments were used as a sensitivity analysis. First, I compute the sum of squared deviations of the parabolas from the 14 observations. From that follows

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[2] As the assumed warming is the same for many of the studies, many of the 182 combinations are infeasible.

[3] The derivative of the CDF is used rather than the PDF to correct for importance sampling.

the prediction error (assuming 12 degrees of freedom as 2 parameters are estimated), and the likelihood (assuming a normal distribution). Second, I compute the likelihood of the parabolas using the 14 observations as the mean and the sample standard deviation (cf. Table A1). These two methods lead to a narrower range of uncertainty; these are regression methods and can therefore be interpreted as Bayesian updating of information (but not as vote-counting).

Furthermore, the sample of parabolas is not random: I oversample in the centre and in the tails. I am not aware of a method to correct for importance sampling with the two alternative PDFs. In order to illustrate the impact, I use a fourth method. The likelihood of each parabola equals the normalised sum of likelihoods according to the PDFs for the impact of 1.0ºC, 2.5ºC and 3.0ºC of warming.

3.2. Results

Figure 1 shows the PDF of the economic impact of 2.5ºC warming. For comparison, the 10 observations are marked (by dots), as are the 4 extrapolated point estimates (by diamonds). The extrapolated estimates in fact fall in the middle of the distribution. Figure 1 also shows the PDF from Bayesian updating. It is very narrow, and in fact treats most of the observations as outliers. This is clearly inappropriate. Finally, Figure 1 depicts the PDF based on the sample statistics. The two most extreme observations are at the 4.5% and 97.8% for the sample CDF and at the 11th and 92nd percentile for the vote-counting PDF. The sample frequency has the extrema at 1/(2*14)=3.5% and 96.5%.The vote-counting PDF gives the widest range of uncertainty, and it is the only PDF that does not discount the probability of the largest point estimate. The vote-counting PDF is therefore used as the default PDF in the remainder of the paper.

Figure A1 shows the vote-counting PDFs for 1.0ºC, 2.5ºC and 3.0ºC of warming. These PDFs together imply a bivariate PDF for the parameters of the impact function (see above). This is displayed in Figure 2. The bivariate distribution is the sum of three degenerated distributions, each with a small spread around what is almost a straight line in the parameter space. At the same time, the location on that line is much more uncertain. Figure A2 displays the modal lines and the modal probabilities of Figure 2. While Figure 1 shows that the economic impact of climate change within sample (1.0-3.0ºC) is reasonably well-constrained, Figure 2 reveals that this information is consistent with a wide range of parameters, and hence with impacts outside sample (>3.0ºC).

Figure 3 shows the best fit parabola and the two extreme parabolas in the short run as well as in the long run (although minimum and maximum swap position). Figure 3 also shows the minimum and maximum across all parabolas. Figure 3 compares this to the 14 observations. By construction, the set of parabolas encompasses the observations. As Figure 2, Figure 3 shows that the relatively tight evidence for the impacts of warming of up to 3.0ºC implies a diffuse set of impacts beyond 3.0ºC.

73 of the 407 parabolas show positive impacts in the long run, but only 10% of the probability mass is assigned to this possibility. 26 of the 407 parabolas show negative impacts for any warming, but the probability is only 5%. Therefore, the qualitative pattern suggested by the central curve in Figure 3 – net gains in the short run, net losses in the long run – is fairly robust.

Figure 4 shows the survival curves for the total impact at 2ºC, 3ºC, 5ºC and 10ºC warming.[4] At 2ºC, the impact could be positive as well as negative. There is a probability of 37% of a net negative impact. This changes at 3ºC. There is a probability of 93% of a net negative impact. At 5ºC, the impact lies with 90% probability between 4% and -43% of income. At 10ºC, there is a 12% chance of positive impacts, while there is a 48% chance that the impact exceeds -100% of income – that is, a total loss of welfare. The most pessimistic parabola in the sample hits a total welfare loss at 5.7ºC warming.

Figure A3shows the probability density functions at 1-10ºC, at 1ºC intervals. This reveals the same pattern as above. The information is relatively sharp within sample, but rapidly diffuses when extrapolated. At 4ºC and 5ºC, the PDF is still recognisably bell-shaped but there is little information beyond that.

The wide range of impact estimates for very large warming seems appropriate. These results are based on ultrapolation[5] from a weak evidence base. But there is also a wide range of uncertainty about the impact of more modest warming, reflecting the literature which indeed does not agree on the sign of the impact at 2.5ºC warming.

Figure 5 shows four alternative estimates of the survival function of the total economic impact of a 3ºC warming. The first method uses the vote-counting PDF (cf. Figure 1) to assign probabilities to the parabolas and hence the impact at 3ºC. This is method used in Figure 4. The second method does not correct for the non-random sampling of parabolas. This particularly affects the 10-40 and 60-90 percentiles, as parabolas were sample in the centre and the tails. The third method uses the sample standard deviation (cf. Table A1) as prediction error, and the 14 observations. The fourth method uses the fit of the parabola to the 14 observation to estimate the prediction error. The vote-counting method leads to the widest range of uncertainty and this method is therefore used as the default. This implies that, indeed, net negative impacts are reasonably certain at 3ºC warming.

Figure A4 compares the survival function for the impact of 2.5ºC of warming as the derived above (i.e., based on the derivative of the CDFs for 1.0ºC, 2.5ºC and 3.0ºC warming) to the survival function for 2.5ºC (see Figure 1). Figure A4 shows that the joint survival function contains by and large the same information as a key point of calibration.

Figure A5 gives seven alternative ranges for the total economic impact of 5.0ºC warming. At the extreme left, there is the best-fit parabola and its 99% confidence interval (from the

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[4] Survival curves contain the same information as cumulative distribution functions, but are easier to read in this case.

[5] Ultrapolation is beyond extrapolation.

forecast error). At the extreme right, there is the 99% confidence interval of the vote-counting PDF. The other ranges are the minimum and maximum of the five methods used to generate the set of parabolas (single/double bootstrap/fit, sample). The bootstrap and fit methods generate a range that is too narrow, while the sample method yields results that are very far in the tail. Figure A5 also shows the averages and expectations. The vote-counting PDF, although build up from symmetric components, is skewed towards more negative impacts.

4. Estimates of the marginal cost of carbon dioxide emissions

4.1. Methods

DICE99 (Nordhaus and Boyer 2000) is the only integrated assessment model that assumes the global economic impact of climate change is a parabolic function of the global mean surface air temperature. The model code is readily available[6] and convenient in use. I therefore use DICE99 to explore the implications of the estimates of the total costs of climate change for the social cost of carbon. I use the exact same version of DICE99 as (Nordhaus and Boyer 2000), except for the parameters of the climate change impact parabola.

The 407 parabolas discussed in Section 3 were put in DICE99. The first partial derivative of the total impact to a change in emissions is approximated analytically in the model code. The social cost of carbon equals the discounted sum of partial derivatives, using a pure rate of time preference that starts at 2.85% per year in 2015 and gradually falls over time (to 2.20% in 2115).

4.2. Results

The mean social cost of carbon starts at \$29/tC in 2015, rises to \$116/tC in 2065, to \$208/tC in 2115, and to \$379/tC in 2215. Figure 6 shows the survival functions at these points in time. In 2015, the uncertainty is relatively tight with 90% of the probability mass between -\$1/tC and \$65/tC. The uncertainty appropriately widens as we look further into the future. For 2065, the 90% confidence interval spans -\$30/tC to \$279/tC. For 2115, the range is from -\$70/tC to \$483/tC. For 2215, the 90% confidence interval of the social cost of carbon is from -\$182/tC to \$802/tC.

The growth rate of the mean social cost of carbon over the 21st century is 1.99% per year. This is indistinguishable from the IPCC estimate of 2% (Yohe et al. 2007). Figure A6 shows that the uncertainty about this estimate is rather narrow. This is because the growth rate of the social cost of carbon is not just driven by the total impact of climate change (the only uncertain variable in this analysis) but also by the discount rate, the rate of degradation of

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[6] http://www.econ.yale.edu/~nordhaus/homepage/web%20table%20of%20contents%20102599.htm

carbon in the atmosphere, the rate of warming, the rate of economic growth, and the rate of emissions growth – all of which are kept constant between scenarios in the current analysis.

5. Discussion and conclusion

In this paper, I survey the estimates of the total economic impacts of climate change. While climate change is initially positive, incremental impacts are negative for any warming that can be avoided. Climate change is therefore a negative externality. Published estimates suggest that climate change is not a particularly large problem. However, estimates are available for a global warming of up to 3.0ºC while actual warming may well be (much) larger than that. I combine the primary estimates to form probability density functions for the impact of 1.0 ºC, 2.5ºC and 3.0ºC of warming. I use vote-counting rather than Bayesian updating so as to preserve the wide range of uncertainty. The primary suggests that the impacts follow a parabola and the PDFs are used to derive the probability distribution of the parabola's parameters. This is in turn used for extrapolation. Impacts of warming of 3.0ºC or more are most likely negative. Beyond 7.0ºC, there is a reasonable chance that climate change would imply a total loss of welfare – although the PDF is very diffuse. The uncertainty about the social cost of carbon is fairly wide too and grows over time. Although it cannot be excluded that greenhouse gas emissions should be subsidized, the expected value of the social cost of carbon points to a carbon tax that starts around $30/tC and rises at 2% per year.

There are a number of caveats to these results. First, I only consider the uncertainty about the economic impact of climate change. I disregard the uncertainty about climate change itself, and the uncertainty about future emissions and concentrations (Weitzman 2007;Weitzman 2009). The conditional uncertainty shown in this paper necessarily underestimates the actual uncertainty. Second, I disregard changes in the vulnerability of society to climate change (Horowitz 2002;Yohe and Tol 2002). This is known to substantially modulate the impact of climate change, but as the 14 studies do not consider this, it is omitted here. Third, I fit a single functional form to the 14 primary estimates. As the 14 studies together assess only 3 scenarios of warming, a parabola is the most complex polynomial one can fit while maintaining some degrees of freedom – but that does not imply, of course, that the impact function is truly parabolic. Fourth, I use Normal distributions as the basic components of the vote-counting procedure. Although the final PDF is skewed towards the bad tail, one may argue that this should reasonably be assumed (rather than emerge). Fifth, I do not assess the policy implications. While I estimate the social cost of carbon, I do not impose a carbon tax in the model. Nor do I estimate the risk premium on the social cost of carbon, which could be considerable as the impact of climate change reaches a total welfare loss at greater warming. All these matters are deferred to future research.

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Table 1. Estimates of the welfare loss due to climate change (as equivalent income loss in percent); estimates of the uncertainty are given in bracket as standard deviations or 95% confidence intervals.

Study	Warming	Impact
	(˚C)	(%GDP)
(Nordhaus 1994b)	3.0	-1.3
(Nordhaus 1994a)	3.0	-4.8 (-30.0 to 0.0)
(Fankhauser 1995)	2.5	-1.4
(Tol 1995)	2.5	-1.9
(Nordhaus and Yang 1996)a	2.5	-1.7
(Plamberk and Hope 1996)a	2.5	-2.5 (-0.5 to –11.4)
(Mendelsohn et al. 2000a)a,b,c	2.5	0.0[b] 0.1[b]
(Nordhaus and Boyer 2000)	2.5	-1.5
(Tol 2002a)	1.0	2.3 (1.0)
(Maddison 2003)a,d	2.5	-0.1
(Rehdanz and Maddison 2005)a,c	1.0	-0.4
(Hope 2006)a,e	2.5	0.9 (-0.2 to 2.7)
(Nordhaus 2006)	2.5	-0.9 (0.1)

[a] Note that the global results were aggregated by the current author.

[b] The top estimate is for the "experimental" model, the bottom estimate for the "cross-sectional" model.

[c] Mendelsohn et al. only include market impacts.

[d] Maddison only considers market impacts on households.

[e] The numbers used by Hope are averages of previous estimates by (Fankhauser 1995) and (Tol 2002a); Stern *et al*. (2006) adopt the work of Hope.

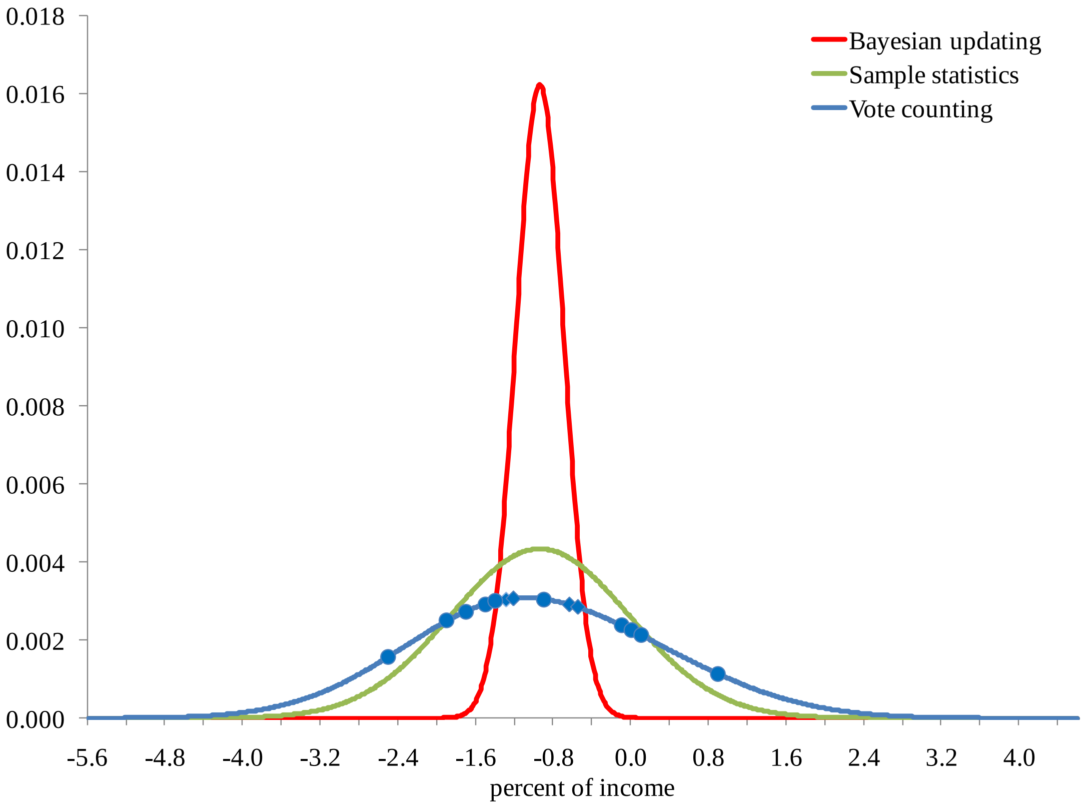

Figure 1. Three alternative probability density functions of the total economic impact of 2.5ºC warming; the dots are the 10 primary estimates; the diamonds the impacts extrapolated from the primary estimates for 1.0ºC and 3.0ºC of warming.

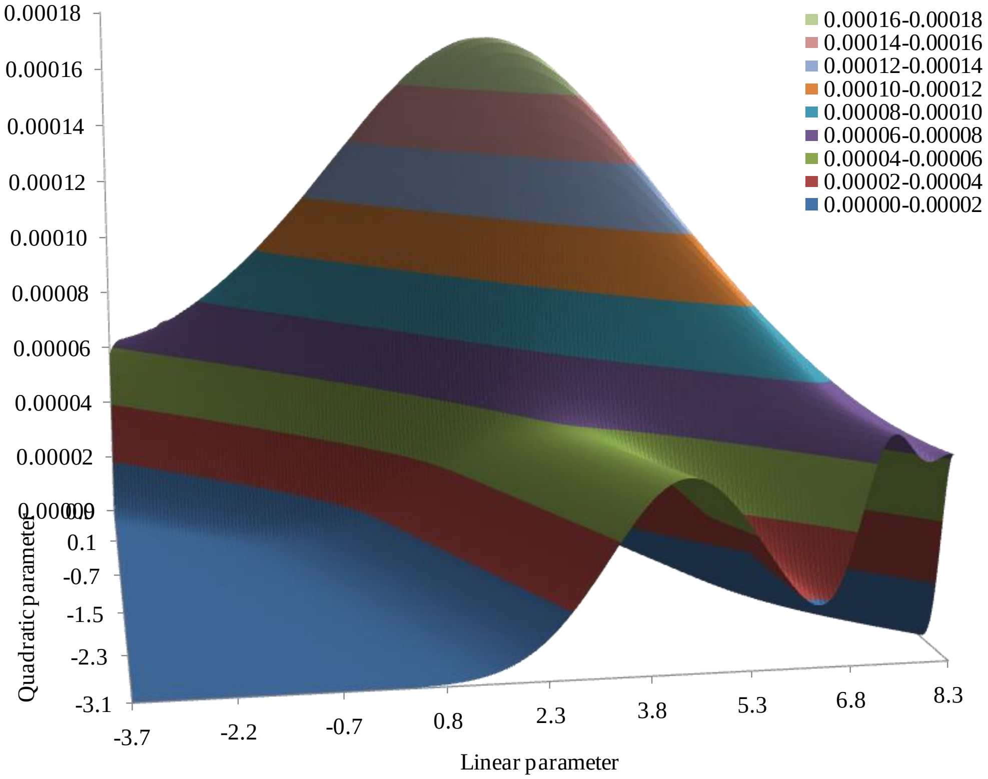

Figure 2. The bivariate probability density function of the parameters of the impact parabola.

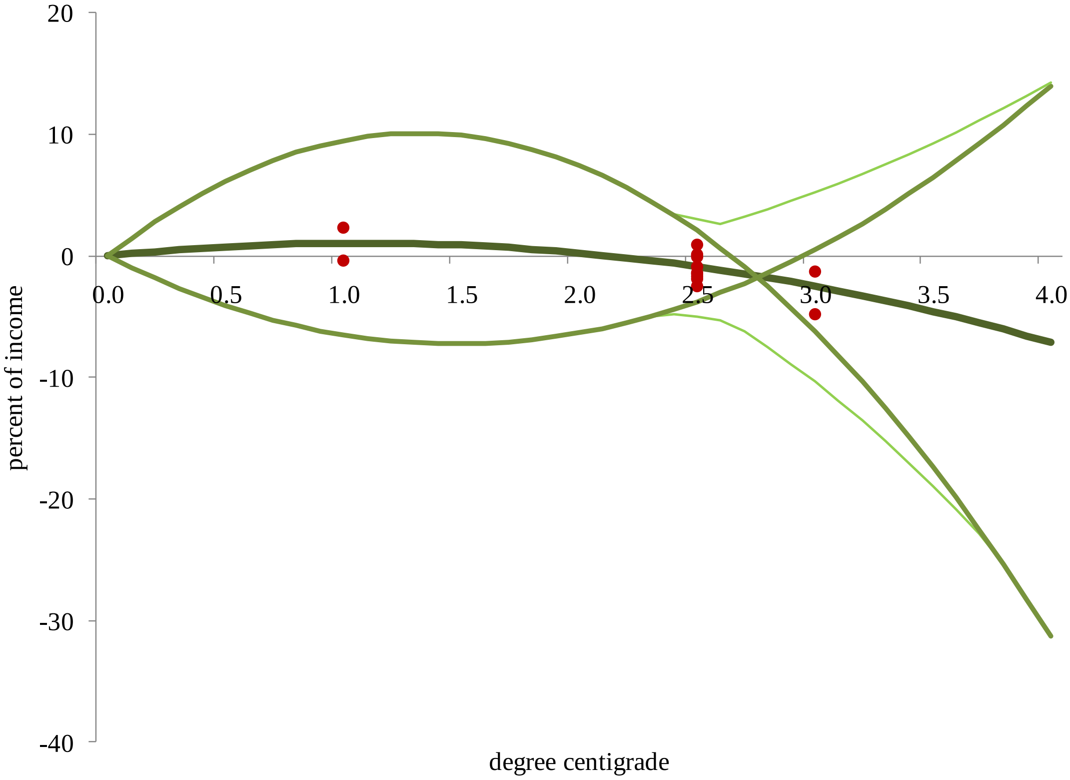

Figure 3. The best-fit impact function (fat, centre line), the extreme impact functions, the extreme impacts (thin lines), and the primary impact estimates (dots).

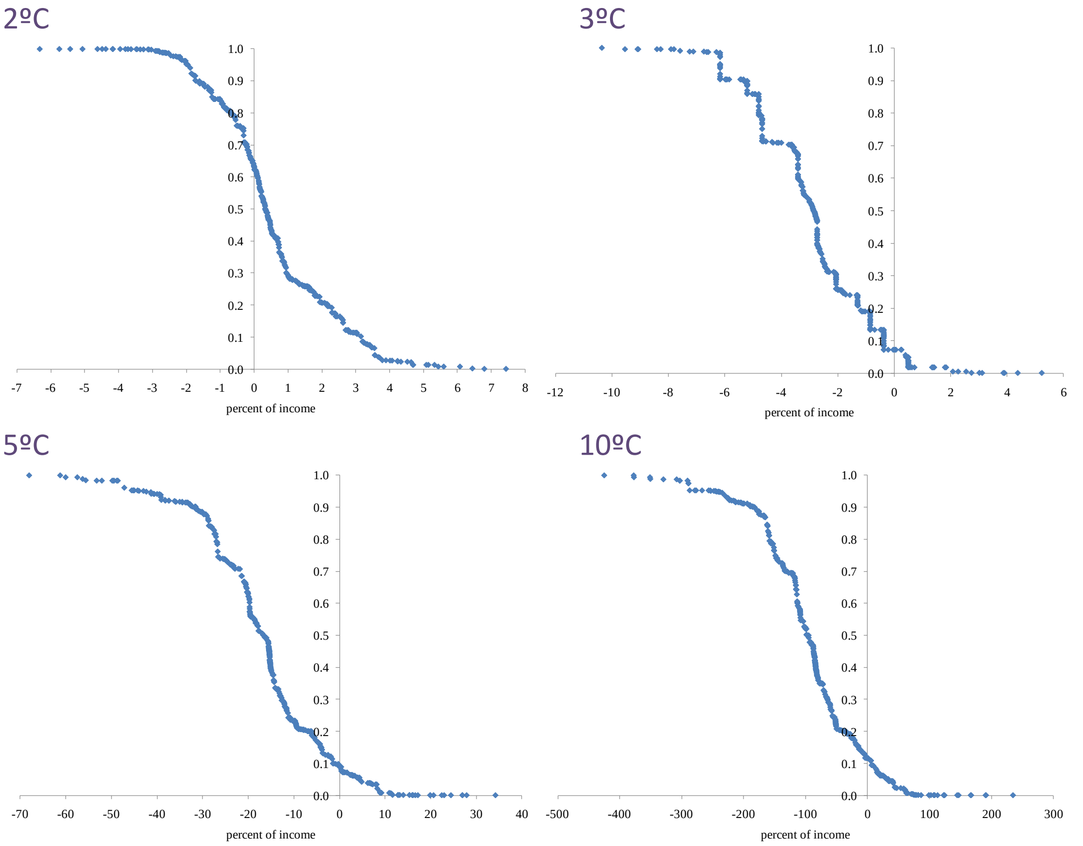

Figure 4. The survival functions of the total economic impact of climate change for different degrees of global warming.

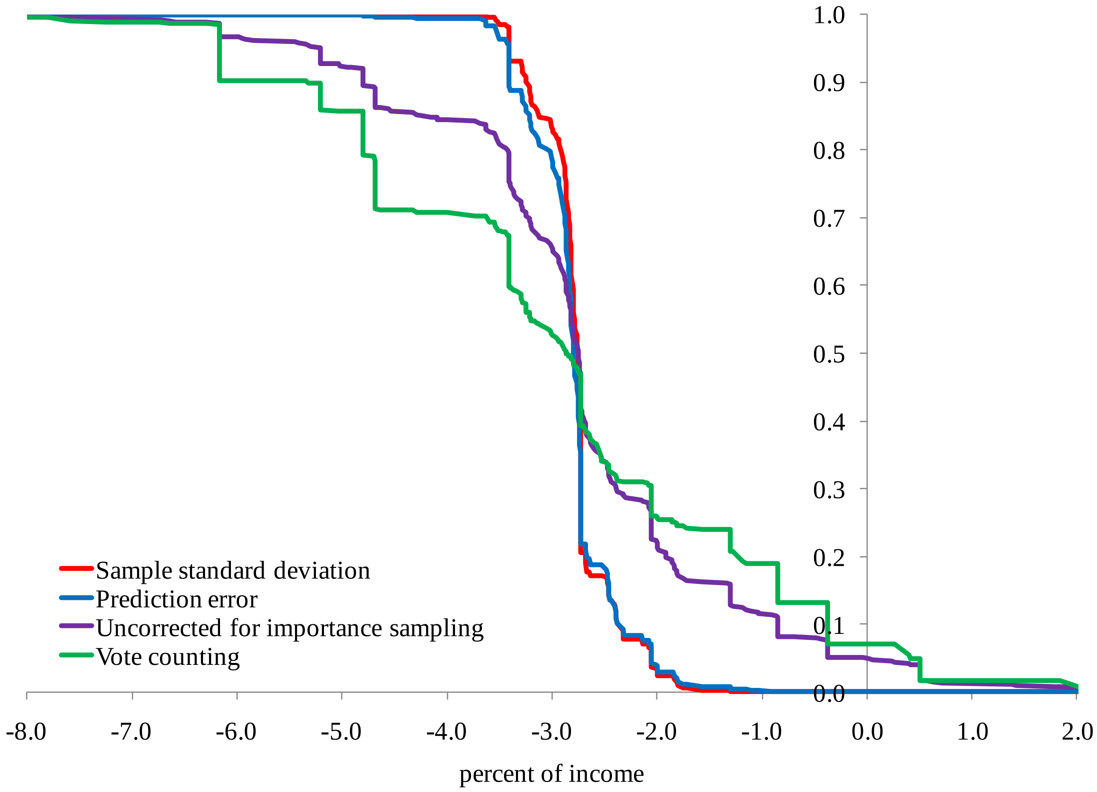

Figure 5. Four alternative survival functions for the total economic impact of 3ºC warming.

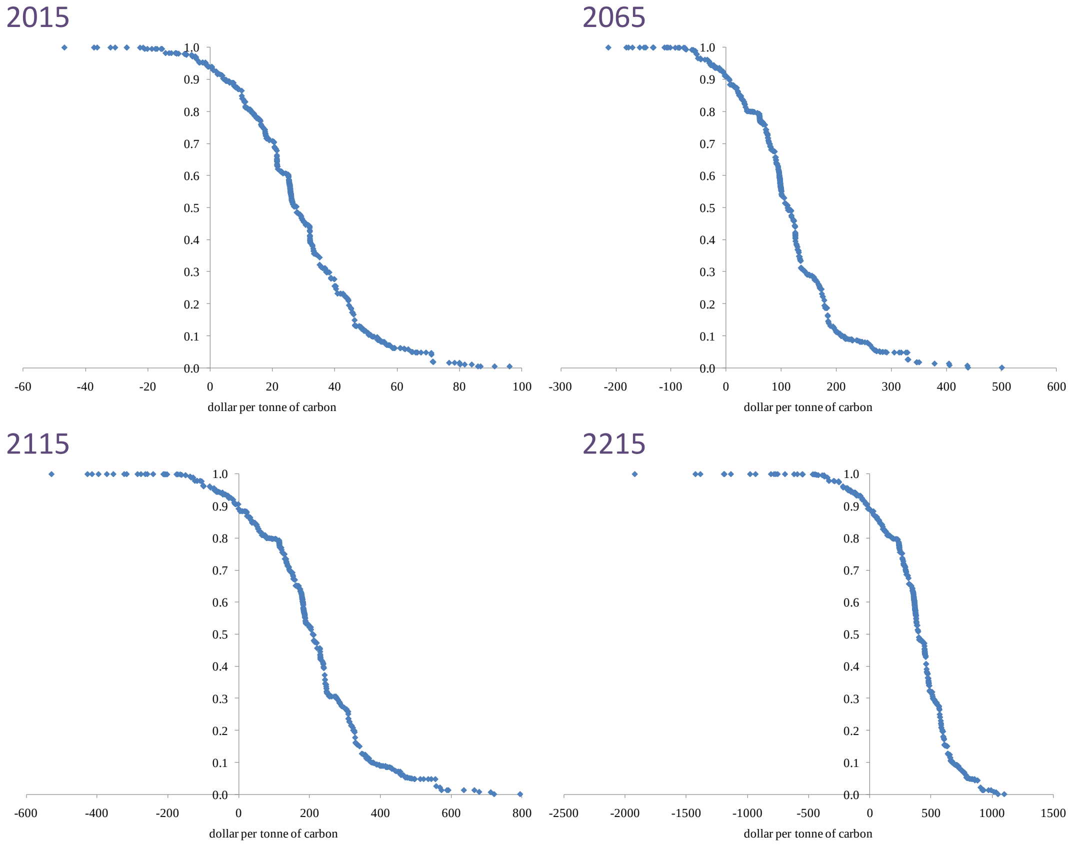

Figure 6. The survival functions of the social cost of carbon for different points in time.

Table A1. Observed and *extrapolated* estimates of the total economic impact of climate change, their mean and (standard deviation), and selected percentiles of the vote-counting PDF.

	1.0ºC	2.5 ºC	3.0 ºC
Tol 02	2.30	-0.75	-3.51
Rehdanz	-0.40	-1.33	-1.72
Fankhauser	0.88	-1.40	-3.12
Tol 95	0.48	-1.90	-3.52
Yang	0.64	-1.70	-3.36
Plambeck	0.00	-2.50	-4.00
Mendelsohn	2.00	0.00	-2.00
Mendelsohn	2.08	0.10	-1.92
Boyer	0.80	-1.50	-3.20
Maddison	1.92	-0.10	-2.08
Hope	2.72	0.90	-1.28
Nordhaus 06	2.72	0.90	-1.28
Nordhaus 94b	0.23	-0.67	-1.30
Nordhaus 94a	2.54	-1.41	-4.80
Primary	0.95	-0.90	-3.05
N=2,10,2	(1.91)	(1.08)	(2.47)
Sample	1.25	-0.94	-2.75
N=14	(1.01)	(0.92)	(1.06)
Bayesian	1.25	-0.94	-2.75
N=14	(0.27)	(0.25)	(0.28)
Vote-counting	1.25	-0.94	-2.75
N=14	(1.40)	(1.28)	(1.48)
1%	-1.90	-3.75	-6.17
5%	-1.05	-2.96	-5.21
10%	-0.58	-2.53	-4.68
33%	0.59	-1.49	-3.41
50%	1.25	-0.93	-2.73
67%	1.91	-0.35	-2.06
90%	3.07	0.76	-0.85
95%	3.54	1.23	-0.37
99%	4.36	2.08	0.50

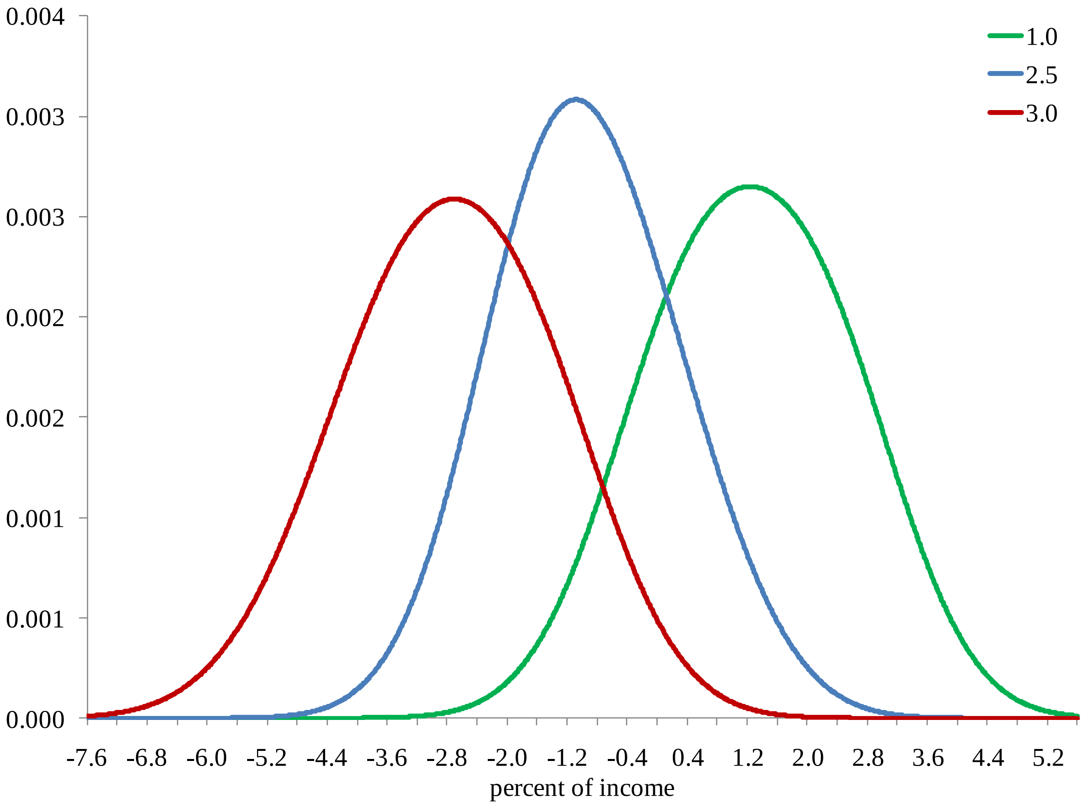

Figure A1. The probability density function of the total economic impact of 1.0ºC, 2.5ºC and 3.0ºC of warming.

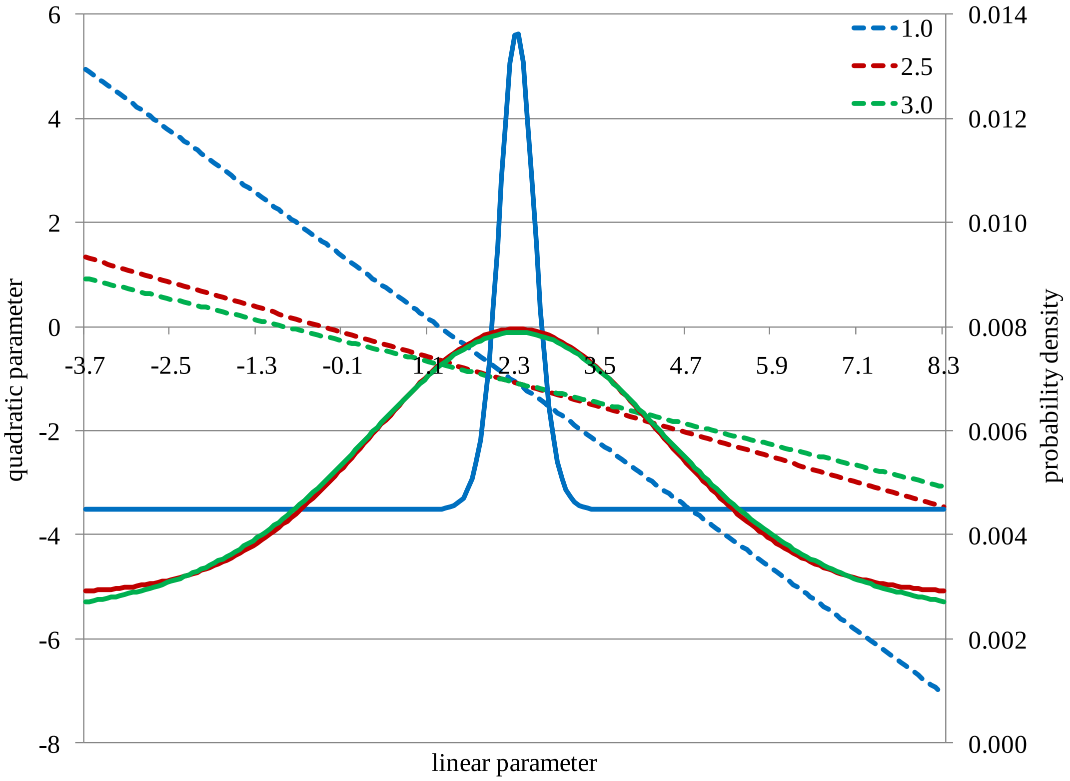

Figure A2. The most likely quadratic parameter as a function of the linear parameter for three alternative calibration points (1.0ºC, 2.5ºC and 3.0ºC), and the conditional probability of the linear and quadratic parameters according to the bivariate probability density function of Figure 2; note that the vote-counting procedure implies that there is a constant, minimum probability (visible for 1.0ºC only) of the calibration line.

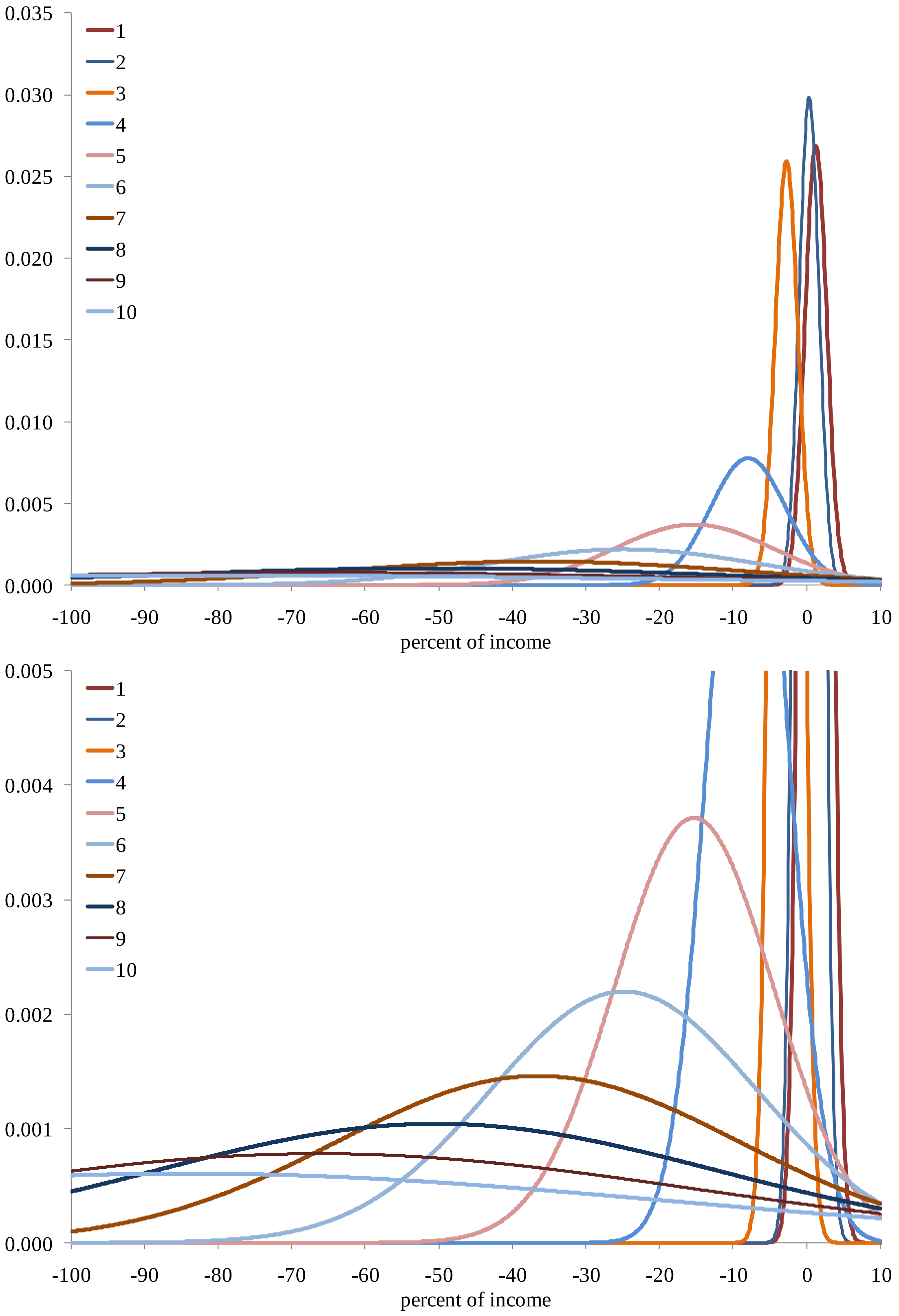

Figure A3. The probability density functions of 1-10ºC warming at 1ºC intervals. The top and bottom graph are identical except for the scale of the vertical axis.

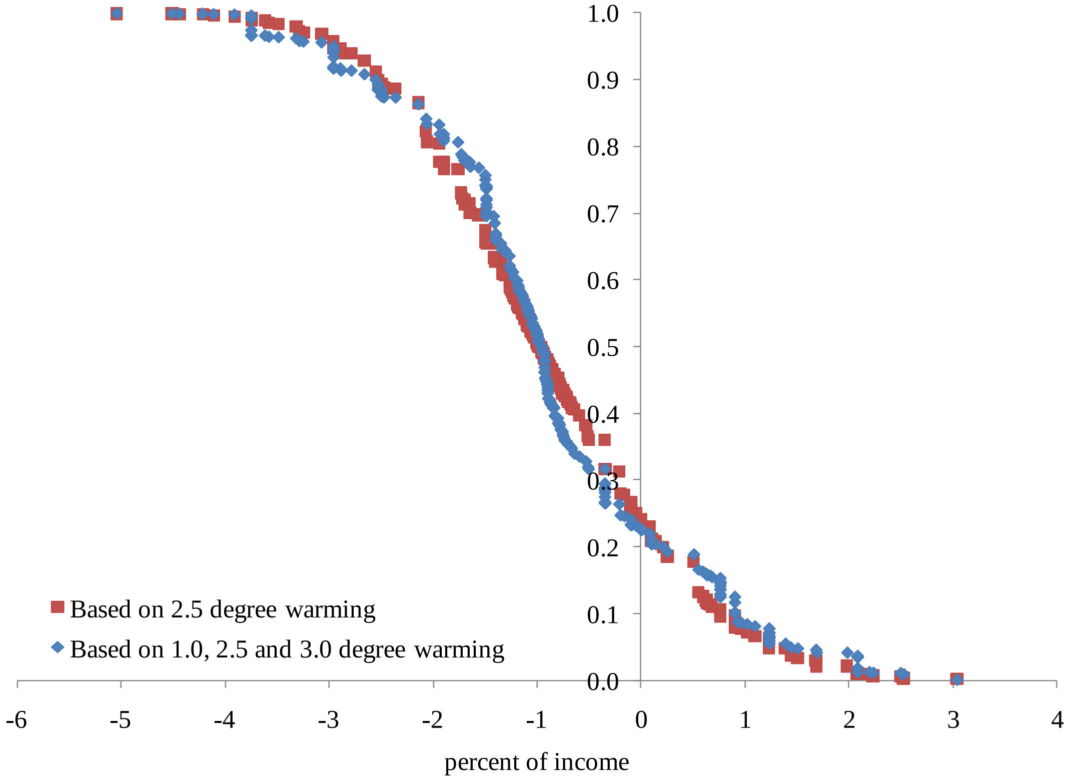

Figure A4. Four alternative survival functions for the total economic impact of 3ºC warming.

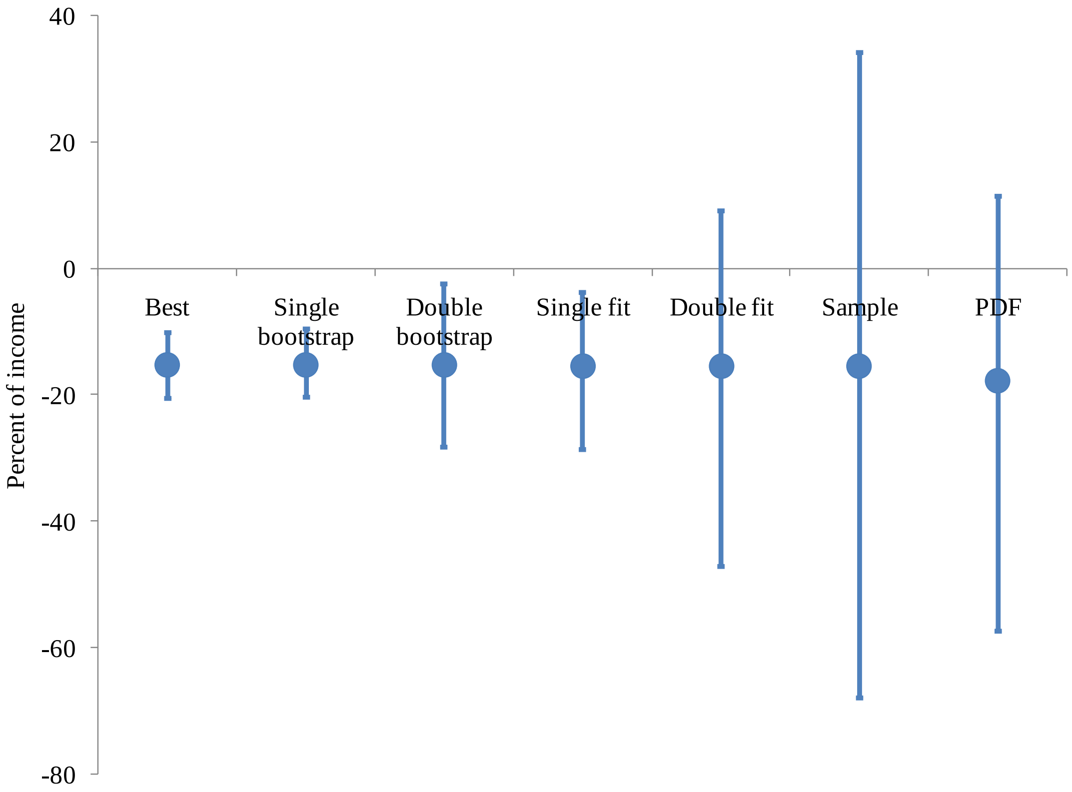

Figure A5. Alternative ranges of impact estimates for 5.0ºC warming.

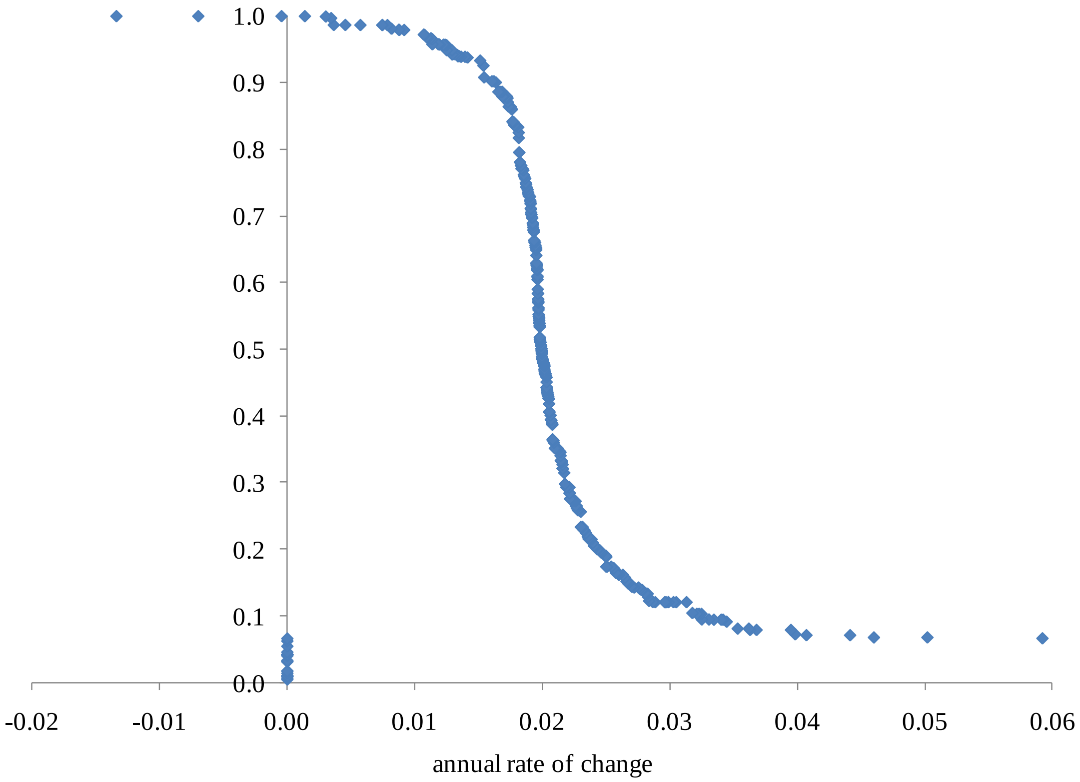

Figure A6. The survival function of the growth rate of the social cost of carbon over the 21st century.

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