

**Uncertainty and Climate Sensitivity:
Revised estimates of the Social Cost of Carbon Dioxide**

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Abstract

This paper contributes to the literature on estimating the social cost of carbon dioxide (SCCO₂) using integrated assessment models (IAMs). Several critiques have been raised against IAMs. In particular Weitzman noted in recent articles that standard IAMs do not appropriately capture key and critical features of the climate change problem; among them, the large potential impacts due to low probability events.

We changed the probability of temperature rise in response to an increase in greenhouse gas concentration (climate sensitivity) of the default PAGE09 Model, modifying the probability distribution of the two parameters that determine climate sensitivity (transient climate response and half-life of global warming). Keeping the main part of the distribution of these parameters unchanged, but modifying the tail of the distribution, we match Weitzman's figures that the climate sensitivity could be higher than 10°C with 5% probability and higher than 20°C with nearly 1% probability. With the new probability distributions, the mean value for the SCCO₂ rises from US\$104/tCO₂ (in the default PAGE09 model) to US\$290/tCO₂, while the 95th percentile rises from US\$238/tCO₂ to US\$1,370/tCO₂.

1. Introduction

This paper uses the PAGE09 Model (Policy Analysis for the Greenhouse Effect)¹ to investigate the uncertainty surrounding ‘dangerous’ climate change by introducing various assumptions as to the likelihood of extreme climate events. PAGE09 is an integrated

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¹ The model is a development of the PAGE2002, explained in Hope (2006).

assessment model incorporating uncertainty in the input variables (which allows investigation through Monte Carlo simulation), and so it is well-suited to address this issue.

Extreme climate events or ‘dangerous’ climate change can be defined as “any process that produces losses in consumption-equivalent welfare, which are both rapid and large-scale relative to global trend consumption” (Dietz et al., 2007:314). Within the PAGE09 Model, damage from climate change is modelled firstly as combination of specified damage functions for sea level rise, economic effects and non-economic effects. And secondly, there is a possibility of a discontinuity in consumption trends, which suggests a ‘dangerous’ climate ‘tipping point’. Whether such a discontinuity occurs is determined in a probabilistic fashion, but becomes more likely with higher temperature rises (temperature itself is determined probabilistically).

Theoretically, this paper is framed against the background of debates about the uncertainty of extreme climate events, in particular, one of the suggestions made in Weitzman (2009b) about the climate sensitivity parameter. As explained in more detail below, he argues that given the uncertainty surrounding the upper tail of the probability distribution of this parameter, some positive probability ought to be placed on very high values.

The approach taken in this paper is to modify the assumptions in the PAGE09 model about the climate sensitivity parameter, which itself is determined by the transient climate response and the half-life of global warming gases. We explore the case where these probability distributions have a longer tail than in the standard model assumptions. Note that there is no strong prior for the precise shape of such a distribution.² We choose to employ a ‘general’ function, which allows us to approximate the values suggested by Weitzman. In this way, one can investigate the importance of this key area of uncertainty, and address the resulting expected impacts from these new assumptions.

The paper is structured as follows. Section 2 discusses the related debate on standard approaches to economic assessment of climate change impacts and their limits in capturing uncertain features. Section 3 focuses on the specific issue of the climate sensitivity parameter and Weitzman’s analysis. Section 4 provides a note about the SCCO2. Section 5 presents the PAGE09 model and describes its main features. Section 6 discusses the model developments we performed in order to give more emphasis to the uncertainty of climate sensitivity. Section

² Indeed some, e.g. Allen and Frame, 2007, argue that it is ‘inherently’ difficult to predict such probabilities.

7 comments on the results obtained for the estimate of social cost of carbon and other relevant variables, and section 8 concludes.

2. Assessing Climate Change Impacts: Integrated Assessment Models (IAMs)

The economic assessment of climate change impacts is a challenging research area because of the enormous data needs and complex methodological issues (Carter et al., 2007). Relevant methodological difficulties arise due to the complexity of the climate problem, mainly related to a number of uncertainties, ranging from the driving forces of climate change to the economic valuation of impacts. Three main types of uncertainty surrounding the estimation of climate change economic impacts can be identified (Jamet and Corfee-Morlot, 2009):

- 1) *Techno-economic uncertainty*, deriving from macroeconomic projections (GDP, population growth, technological progress) and energy mix impact on emission forecasts.
- 2) *Environmental uncertainty*, due to GHG projections and concentration impacts on the physical climate (physical link between emissions and concentrations, sensitivity parameter).
- 3) *Economic valuation uncertainty*, related to climate change impacts on economy and society, mainly due to difficulties in the economic valuation of non-market impacts (e.g. health) and the risk of irreversible effects (e.g. disturbance of thermohaline circulation, melting of Greenland and West Antarctic ice sheets).

Integrated Assessment Models (IAMs) incorporate output from the various scientific disciplines relevant to the climate change issue, notably taking into account the interactions and feedback mechanisms of the human-climate system. Many IAMs have a module dealing with the assessment of the economic impacts of climate change. These modules (e.g. in the simplified or stylised IAMs family, such as DICE-RICE, WITCH, FUND, and PAGE) usually take into account market impacts and non-market impacts and, some of them, catastrophic impacts. Through the economic framework, they assess benefits, residual damages and in some case they also perform uncertainty analysis (e.g. Monte Carlo analysis in the PAGE model). They may differ for both their assumptions on relevant input variables (e.g. climatic³ and socio-economic⁴ scenarios, uncertainty treatment, regional effects aggregation, effects type considered⁵) and the estimation approach they follow.

³ GHG emissions and temperature projections, carbon cycle representation.

⁴ GDP and population growth projections, discount rate.

⁵ Monetized or utility-equivalent effects.

An important reason for their implementation as analytical tools for policy making might mainly be found in their flexibility, allowing for a variety of beliefs about environmental impacts to be addressed (Cantore, 2009). They integrate the analysis of economic and environmental processes related to climate change, through simulation scenarios dealing with intergenerational fairness, the distribution of wealth, and some of them, at least to a certain extent, the management of risk and uncertainty (Dietz et al., 2007).

IAMs have nevertheless been criticized because they are technically complex and the parameter choice is not always clear and independently validated (Lorenzoni and Adger, 2006). These represent important shortcomings as the results of the studies depend strongly on models assumptions and structure. As already noted in recent reviews, these models might be seen as too distant to a good representation of real world adaptation policy and cost, as their nature is highly theoretical and they heavily rely on simplifying assumptions using highly aggregated variables and data (Ackerman et al., 2009; Patt et al., 2010).

An interesting challenge to the methodology of IAMs comes from a series of papers from Weitzman (2009a, 2009b, 2009c). In these papers, he puts forward a number of critiques of the current cost-benefit analysis of climate change, especially the approach embodied in IAMs. Weitzman's observations go even further with the elaboration of what is referred to as the 'dismal theorem'. The idea is basically that under certain conditions, the expected loss from high-consequence, low-probability events can be infinite. In such a situation, standard cost-benefit analysis is therefore no longer an appropriate tool. Weitzman argues that, given the extent of our current understanding, these conditions apply to climate change. Taking this idea to its limit would suggest that IAMs have little relevance for policy, as the response ought always to be to choose policies that do everything possible to avoid an infinite loss, even if there is only a small probability of such an outcome.

Of particular importance is the specification of the damage function, which as Weitzman notes, is inherently difficult to determine. Weitzman argues that the damage function is "fat tailed", which in general terms, means that the probabilities of rare events decline relatively slowly as the event moves far away from its central tendency. The reduced form probability density function (PDF) of log disutility tends to be fat tailed because structural parameters are unknown. From past samples alone, it is not possible to learn enough about the probabilities of extreme future events to thin down the tail of the PDF, because we don't have enough data about analogous past extreme events. In other words, exact predictions are impossible and climate change impacts assessment is surrounded by uncertainty as usually defined in

Knighian terms (Knight, 1921)⁶. A fat upper tail of the PDF of log disutility makes the willingness to pay to avoid extreme climate changes very large, indeed arbitrarily large. A highly precautionary approach is suggested as a logical implication of Weitzman's dismal theorem.

Even though Weitzman's critiques are generally applicable to a number of models dealing with the economics of climate change, Nordhaus' DICE model (Dynamic Integrated model of Climate and the Economy) and its results have often been the implicit and sometimes the explicit target. Nordhaus acknowledges Weitzman's contribution, whilst defending the use of DICE and IAMs in general (2009). In a response specifically targeted to the dismal theorem, Nordhaus (2009) defends the principle of using IAMs, by contesting the general applicability of such a theorem. In his view, none of the extreme parameter values singularly taken produces catastrophic economic outcomes due to climate change. For the dismal theorem to hold it is instead necessary that high temperature sensitivity, catastrophic damages and absence of effective policy measures occur together. Therefore, CBA does not break down anytime there are fat tails in the distribution.

Though it may not be possible to take full account of all aspects of Weitzman's critique, it is the argument of this paper that some of his points can be incorporated within the flexible structure of an IAM. Moving from this debate and aware of the general limits and weaknesses of IAMs, we still find them the strongest tools available to date for carrying out the analysis of the economic effects of climate change. As noted in Dietz et al. (2007:323), IAMs can be thought of as a "canvas" on which debates about the parameters can be "painted". This paper uses the PAGE09 model to address a specific debate about the climate sensitivity parameter, which is explained in the next section.

3. Weitzman's Critique of the Climate Sensitivity Parameter

One of the key critiques from Weitzman (2009b) concerns the climate sensitivity parameter, which is the global average surface warming following a doubling of carbon dioxide concentrations. The actual temperature rise would then depend on the carbon dioxide concentration. Weitzman argues that little is known about the upper end of this distribution (i.e. the possibility of extreme temperature rises), and that peer reviewed studies suggest the

⁶ According to Knight's distinction, uncertainty differs from risk, which corresponds, as the possibility of an unfavourable contingency, to the possible negative consequences of an uncertain action.

possibility that the probability of the most extreme few percent is higher than current IAMs allow for.

This argument is made in two stages. The first stage is that a rough analysis of the 22 peer-reviewed studies cited in IPCC-AR4 (2007) suggests that the climate sensitivity parameter ought to have a 5 percent probability of being above 7 °C and a 1 percent probability of being above 10 °C.⁷

The second stage is concerned with feedback effects. For example, a rise in temperatures could cause the release of GHGs currently trapped in arctic permafrost, boggy soils and/or methane clathrates (ibid.). Thus the initial rise in GHGs could cause a further rise in GHGs. Though this is not technically speaking a higher climate sensitivity, this would be a consequence of the initial human-induced rise in GHGs. In the context of an IAM, it would be appropriate to include this multiplier effect within the sensitivity parameter. Again using rough calculations, Weitzman suggests that taking feedback effects into account, the probability distribution of the "climate sensitivity parameter" (as defined in most IAMs)⁸ could have a *5 percent probability of being above 10 degrees and a 1 percent probability of being above 20 degrees.*

To be clear about how to treat these figures, Weitzman himself emphasises that these are "wildly-uncertain unbelievably-crude ballpark estimates." Therefore, the precise values are not important. However, the general notion that there are small (but decidedly nonzero) probabilities of extreme events is certainly one that can be incorporated into an integrated assessment model framework. This is a belief that can be "painted" onto the "canvas" of an integrated assessment model.

4 The Social Cost of Carbon Dioxide (SCCO2)

The SCCO2 refers to the cost to society caused by one additional tonne of carbon dioxide released into the atmosphere. A number of studies have attempted to place a monetary value on this, most of which focus on the estimate of the monetary damage due to an increase of 1 tonne in emission, the damage being aggregated over time and discounted back to the present day (Hope, 2007).

⁷ Weitzman freely admits that these are very rough estimates.

⁸ The term "climate sensitivity parameter" has been placed in quotations as defining it in this way implies a slightly different interpretation than the strict scientific meaning. Nevertheless, it is a workable definition with respect to entering the parameter into an IAM.

Such estimates primarily aim to incorporate the social benefits of reducing carbon dioxide emissions into cost-benefit analyses of regulatory actions having small or marginal impacts on cumulative global emissions (Interagency Working Group on Social Cost of Carbon, US Government, 2010).

Two alternative approaches have been used in existing studies: the cost benefit analysis (CBA) approach and the marginal cost approach (Clarkson and Deyes, 2002). In the CBA approach, the SCCO₂ corresponds to the level of carbon tax necessary to achieve the optimum level of emissions, i.e. the level at which the marginal cost of reducing emissions is equal to the marginal damage they cause (marginal benefits of abatement). The marginal cost approach directly calculates how a marginal change from the current level of emissions impacts on future damages.

Among the SCCO₂ estimates proposed so far within the literature, Fankhauser (1994) reports marginal impacts of between 6\$/tC and 45\$/tC with a mean value of 20\$/tC (all figures in US\$1990). The IPCC (1996) estimates range from 5\$/tC to 125\$/tC (also in 1990 dollars). Tol, (1999) estimates the marginal impact to be between 9\$/tC and 23\$/tC. Clarkson and Deyes (2002) propose a central value of 105\$/tC (in year 2000 prices) for the SCC, with upper and lower values of 50\$/tC and 210\$/tC. Pearce (2003) argues that the probable range of the SCC in 2003 is in the region of \$4–9/tC.

Tol (2005) gathered over 100 estimates of the SCC from 28 published studies and combined them to form a probability density function with a median of \$14/tC, a mean of \$93/tC, and a 95th percentile of \$350/tC. The effect of the discount rate on estimates of the SCC is striking. In Tol's survey, the 90th percentile SCC, for instance, is \$62/tC for a 3% pure rate of time preference, \$165/tC for 1%, and \$1610/tC for 0% (Tol, 2005). The Stern Review (Report on the Economics of Climate Change; Stern et al., 2006) gives a mean estimate of the SCC today of \$85 per tonne of CO₂ (\$312/tC). Had it been included in the Tol (2005) survey, its estimate would have fallen around the 95th percentile of all estimates. This has drawn some comments at the time of publication of the report (Nordhaus, 2006; Tol and Yohe, 2006; Yohe, 2006), together with others concerning the pure time discount rate.

Others such as Stanton & Ackerman (2009) and Ackerman (2010) argue that some estimates based on IAMs reflect the weaknesses of the models used (e.g. the way in which positive human health impacts from warming & rises in agricultural productivity are taken into account in FUND and how benefits from more outdoor recreation at higher temperatures have been analysed in DICE).

A US interagency working group (involving 12 agencies) has recently estimated the global SCC, in order to be incorporated into cost-benefit analysis of regulatory actions that have small or marginal impacts on cumulative global emissions (Interagency Working Group on Social Cost of Carbon, US Government, 2010). The group selected four values for use in regulatory analysis. The values are the average SCC from three IAMs, (DICE, FUND and PAGE), at discount rates of 2.5%, 3% and 5%, with the SCC being 35.1, 21.4 and 4.7 $\$/\text{tCO}_2$, respectively. The fourth proposed value is 64.9 $\$/\text{t CO}_2$ and represents the 95th percentile SCC estimate at a 3% discount rate.

5. The PAGE09 Model

PAGE is an integrated assessment model that is widely respected and has been used in a number of major studies. As well as being one of the models used by the US interagency working group (see previous section), it was the base model used in the Stern Review (Stern, 2007). In this paper we use the latest available version of the model, PAGE09, which keeps the general structure unchanged, but introduces further developments reflecting the IPCC Fourth Assessment Report (2007).

PAGE09 uses a simple economic module model (Hope et al., 1993; Plambeck et al., 1997; Hope, 2006; Hope, 2008) and expands it to consider climate issues and the interlinkage between the economic and the climate systems through some stylized equations within the climate module. It is one of the first models developed to explicitly take into account both mitigation and adaptation, with their trade-offs and strategic complementarities. Uncertainty is taken into account through a Monte Carlo analysis. Each uncertain input parameter (e.g. equilibrium warming from a doubling of CO_2) is represented by a probability distribution. PAGE09 has about 80 uncertain impact parameters, the exact number depending on the regions and impact sectors used for a given run of the model. A full run of the model involves repeating the calculations of the following output variables: global warming over time, damages, adaptive costs and abatement costs.

The climate module considers four different types of gases (carbon dioxide, methane, nitrous oxide and linear gas). The climate sensitivity ($^{\circ}\text{C}$) is calculated from two other uncertain inputs, the transient climate response ($^{\circ}\text{C}$) and the half-life global warming (years). A linear feedback is introduced from global mean temperature to the excess concentration of CO_2 . Sea level is explicitly modelled.

Four impact categories, specified as the percentage loss of GDP and subtracted from consumption,⁹ are defined within the economic module: sea level impact (corresponding to the difference between current and tolerable sea level rise), economic and non-economic impacts based on regional temperature rise, discontinuity impact. Eight regions are identified: Europe is the focus region with respect to which impacts are calculated for all the others through specific weights.

Climate change economic and non-economic impacts before adaptation are captured as a proportion of GDP by the climate change damage function. As do all the other main IAMs with the exception of MERGE, damage is defined as a non-linear function (Bosello and Roson, 2007). Welfare impacts (*WI*) are expressed as a polynomial function of the difference between regional and tolerable temperature levels (*RTT*) as follows:

$$WI(t, d, r) = [RTT(t, d, r) / 2,5^{POW}] * W(d, 0) * [WF(r)/100] * GDP(t, r)$$

where *t* corresponds to time, *d* identifies the damage type (economic, non-economic, sea level rise) and *r* the region; 2.5 are the °C corresponding to the tolerable increase in temperature due to global warming; *POW* is the power of the polynomial impact function; *W(d, 0)* is the impact in the focus region (i.e. EU) at 2.5 °C and *WF(r)* is the regional weight applied to EU impact to calculate the impact in other world regions.

Unit costs of adaptation, defined as "tolerable" amount of climate change, are calculated for each region, for all impact categories except discontinuity, where there is no adaptation. Adaptation can give a certain tolerable climate change, and reduce the adverse impacts when temperature or sea level exceeds these levels.

The total effect of climate change is equal to the sum of impacts, abatement costs and adaptive costs. If total effects exceed the statistical value of civilisation, they are capped.

6. Model Developments

The modifications to the model we introduced concerned the probability density functions of two input variables: transient climate response (*TCR*) and half-life of global warming gases, also referred to as the feedback response time (*FRT*). The former refers to the temperature

⁹ Saturation applies if more than a certain consumption percentage is lost.

change (in °C) at the time of CO₂ doubling, the latter indicates how many years greenhouse gases persist in the atmosphere. In PAGE09, these variables determine the equilibrium warming for a doubling of CO₂, better known as 'sensitivity' (*SENS*). The relationship among the three variables is indicated by the following equation:¹⁰

$$SENS = TCR / ((1 - FRT / 70) * (1 - EXP(-70 / FRT)))$$

In other words, the probabilistic distributions of *TRC* and *FRT* affect the variable capturing the global temperature increase due to a doubling of CO₂ concentration in the atmosphere. In the PAGE09 model, these variables are assumed to follow a triangular probability distribution, with lower and upper bounds. The existence of an upper limit does drastically reduce the possibility of the occurrence of catastrophic events.

In the modified version of PAGE09 we are proposing, we therefore assumed that the considered variables are distributed according to a general function (see Appendix A for further details), keeping the same minimum and mode values as when triangularly distributed. In fact, the distribution up to the 80th percentile has been left unchanged, with the upper 20 percent being reallocated up to a higher maximum value.¹¹ The advantage is that we introduced a tail, allowing for more realistic states of the world to be included in the analysis. Table 1 shows the values defining the probability density functions for the two considered variables.

Table 1- Modified PAGE09 inputs

	<i>Min</i>	<i>Mode</i>	<i>Mean</i>	<i>Max</i>
Transient climate response (TCR; degC)				
Default PAGE09	1.000	1.300	1.700	2.800
Modified PAGE09	1.000	1.300	2.073	8.400
Half-life of global warming (FRT; years)				
Default PAGE09	10.00	30.00	35.00	65.00
Modified PAGE09	10.00	30.00	43.66	195.00

Figures 1 and 2 present the differences in shape among the two distribution types for the two considered variables. The Figures represent the triangular distribution of the default PAGE09

¹⁰ Note: this is an innovation of PAGE09 based on IPCC 4AR and research by Andrews and Allen (2008).

model, and the alternative distribution here proposed in the modified PAGE09 model (called 'general' in the figures).

Figure 1 – Transient climate response probability density functions

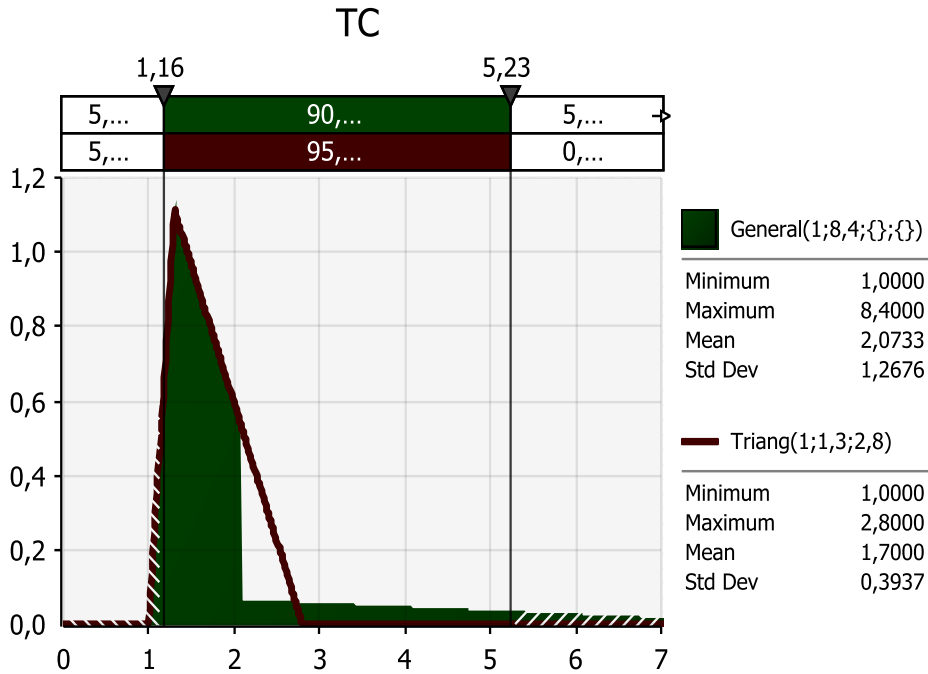
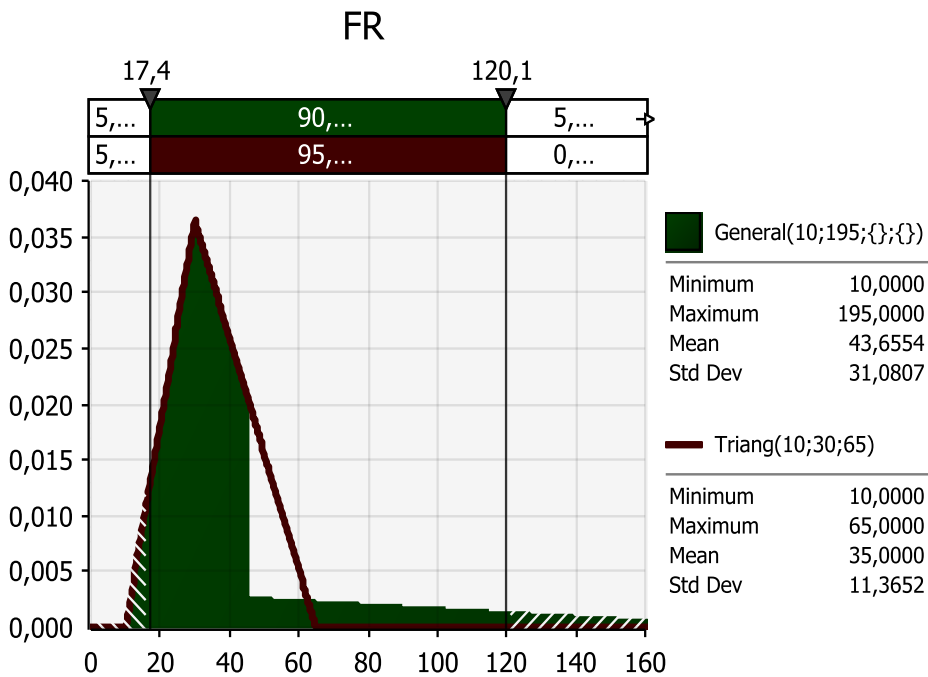


Figure 2 – Half-life of global warming probability density functions



¹¹ Such amount has been arbitrarily chosen as three times bigger than the original one.

For the sensitivity parameter, the run of the modified version of PAGE09 resulted in higher values for the average, but especially for the events lying in the extreme right tail of the distribution. The values obtained for the 95% and 99% percentiles (respectively 10.4 and 18.5) are close to the ones suggested by Weitzman (10 °C and 20 °C, respectively), and they are much higher than the ones obtained of the original PAGE09 model (Figure 3). Figure 4 shows a representation of the frequency distribution for the sensitivity parameter in the modified PAGE09 model.

Figure 3 – Sensitivity parameter descriptive statistics

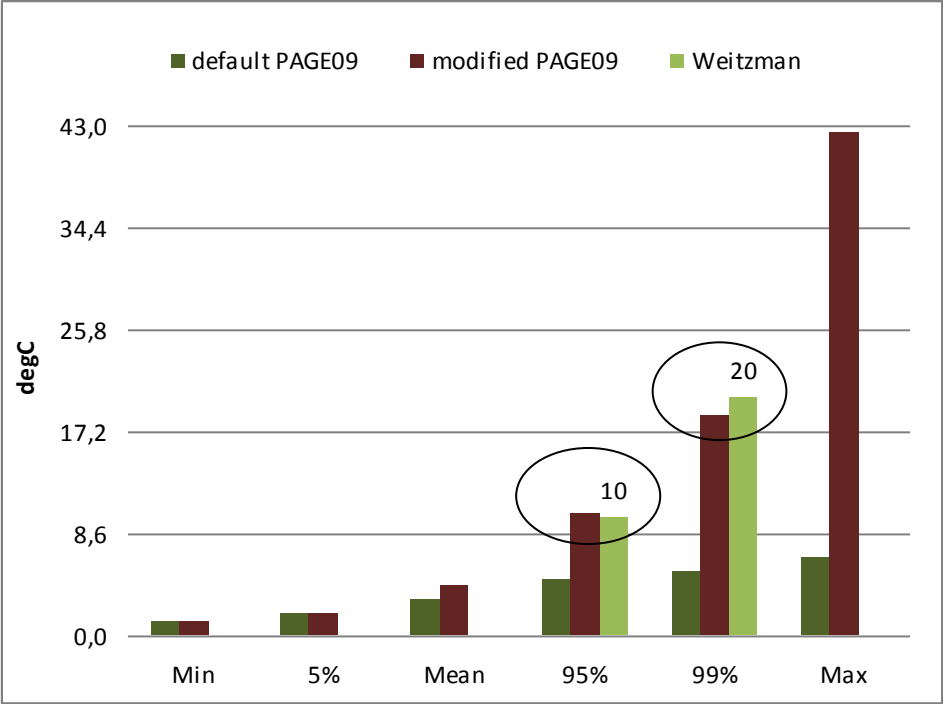
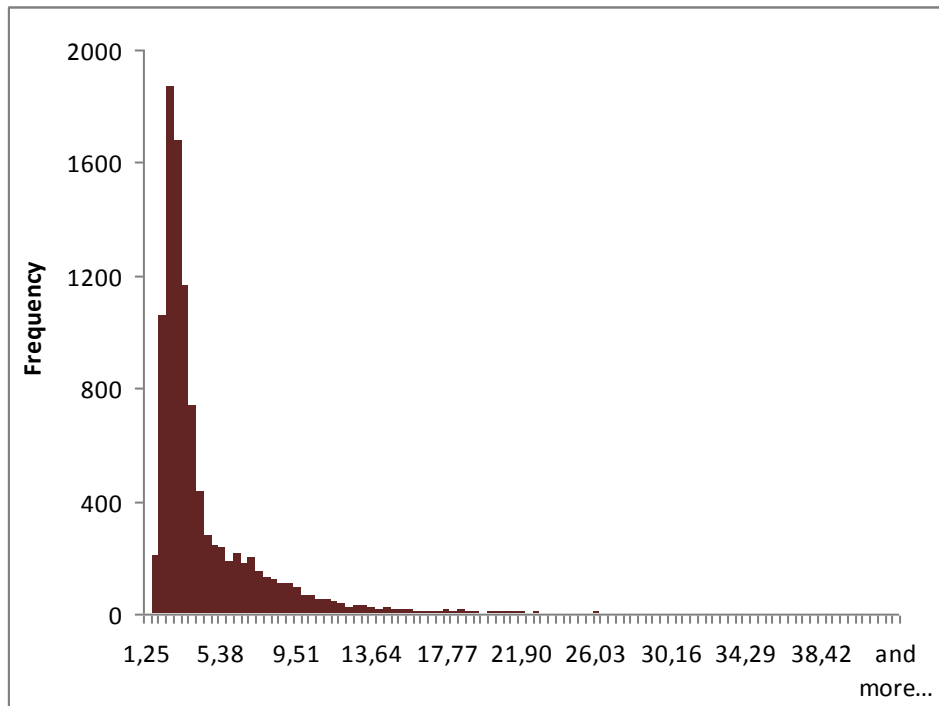


Figure 4 – Frequency of the Sensitivity variable in the modified PAGE09 model



7. Results and Comments

PAGE09 combines the regional temperature changes with the impact parameters to calculate the mean total climate change impacts of the business-as-usual scenario (the A2 scenario in the fourth IPCC Assessment Report) over the next two centuries, from 2009 to 2200. The marginal impact of CO₂ is calculated by reducing the emissions of the gas by 10GT in the first analysis year (2009) only, and finding the difference in impacts that this creates. The difference in impacts was divided by the number of tonnes of the gas that this represents, 800 Mt C as CO₂, to get the marginal impact per tonne. The structure of the model allows a probability distribution for the difference in impacts to be calculated.

We performed 10,000 iterations of both the default and the modified version of the PAGE09 model and the results show a relevant increase in the mean value of SCCO₂ with respect to the default version. As Table 2 shows, the SCCO₂ increased almost three times (+179%), compared to the default PAGE09 model.

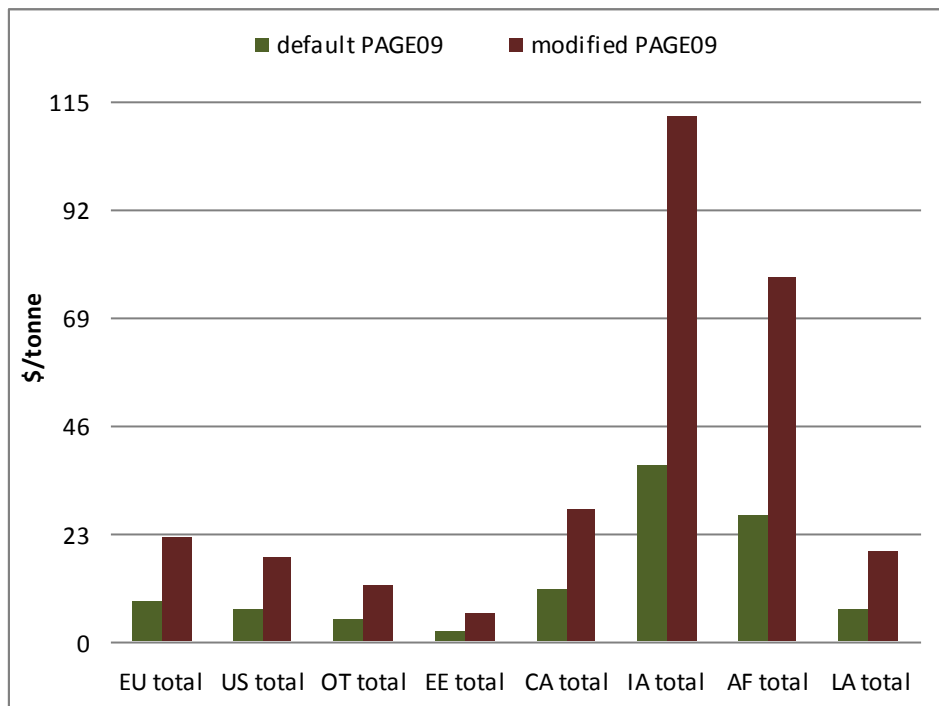
Table 2 – SCCO2 (\$/tCO₂)

	Min	5 th percentile	Mean	95 th percentile	Max
Default PAGE09	0.3	11.1	104.2	238.3	41,434.8
Modified PAGE09	0.5	11.6	290.1	1,369.6	32,961.3

The 95% percentile value increases from 238 \$/ tCO₂ (default model) to 1370 \$/ tCO₂s (modified model). However, the modified version reached a maximum which is lower than the default model's one. The minimum values for SCCO2 are nearly the same in the two models.

It is possible to decompose this result geographically. Figure 5 the mean SCCO2 by region. The bulk of the increase in the mean is mainly driven by the India and South-East Asia region (IA), and by the Africa and Middle East region (AF).

Figure 5 – SCCO2 geographical details (mean)

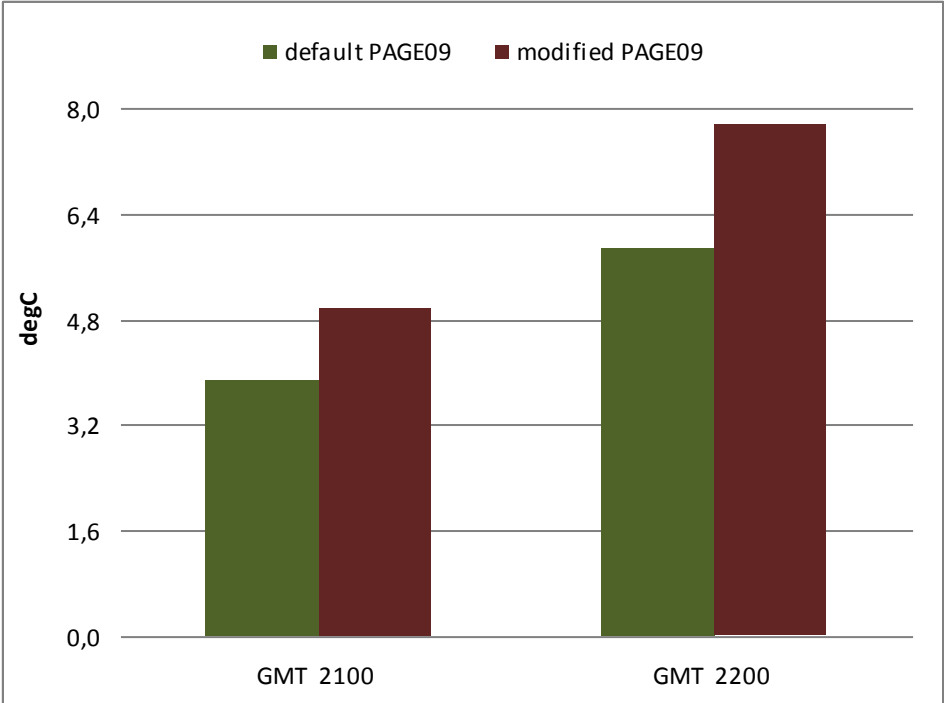


Note: EU – European Union; US – United States; OT – Other OECD; EE – Former Soviet Union and rest of Europe; CA – China and Other Asia; IA – India and South-East Asia; AF – Africa and Middle East; LA – Latin America

Concerning the global temperature, in 2100 (2200) we found a 1 °C (2°C) increase with respect to the default model estimates (Figure 6). This means that the estimated global mean

temperature rise with respect to pre-industrial levels would be 4.87 °C in 2100 and 7.75 °C in 2200.

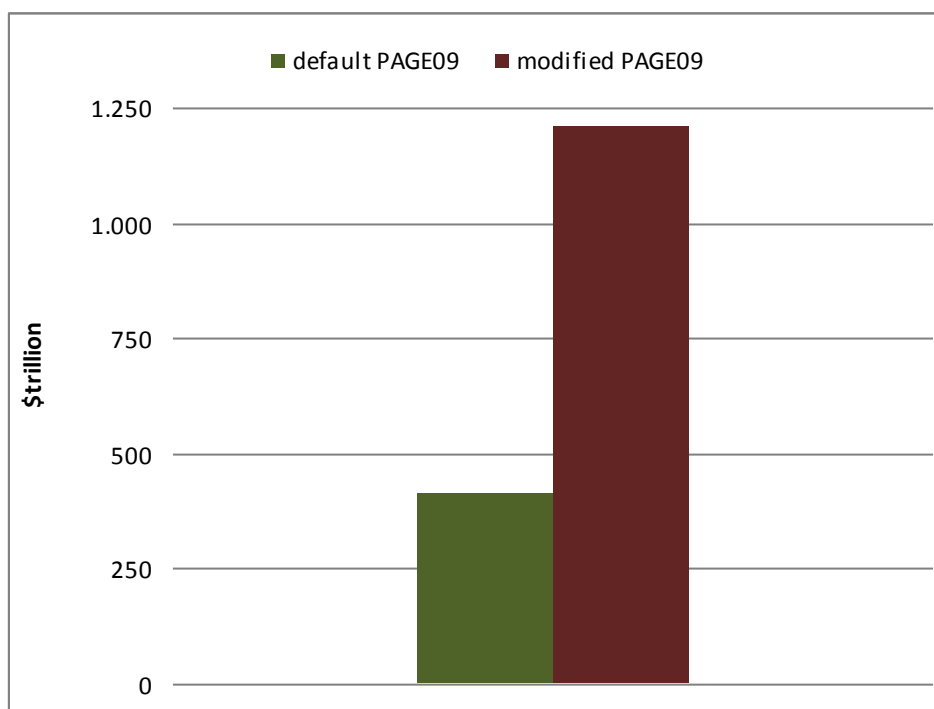
Figure 6 – Global mean temperature



As noted, the SCCO2 is a marginal cost calculated as difference in total damages in two scenarios where the only difference is a marginal drop in CO₂ emission. This is clearly distinct from the level of total costs. Figure 7 represents the total damages for the default and modified models.¹² There is a substantial increase in the total mean damages, which are almost three times higher (+192%) in the modified version of PAGE09. Note that this increase is proportionally comparable to the rise in the SCCO2.

¹² PAGE09 imposes an upper limit on the total damages, which is referred to as the statistical value of civilisation (US\$ 53,333 trillion on average), though in these model runs, this limit was never triggered.

Figure 7 – Total damages (mean net present value in 2009 prices)



8. Conclusions

Integrated assessment models are designed to be used to investigate the consequences of uncertain parameters concerning climate change. If a researcher believes that a different assumption to the standard is appropriate, the models can be adapted to take account of this. In this paper, we have taken a serious concern about the probability distribution of the sensitivity parameter and investigated the consequences if that change is made in isolation.

Weitzman suggested that the climate sensitivity parameter may be substantially larger than commonly assumed. We introduced this by altering the upper tail of the two distributions that determine the climate sensitivity parameter. It is not surprising that the mean SCCO₂ rises, as the estimated average temperature rises are necessarily larger, and consequently the damages are larger. Nevertheless, the magnitude of the increase is of interest. Making this change raises the mean value of SCCO₂ almost threefold – from 104\$/tCO₂ to 290\$/tCO₂. If this representation of the climate sensitivity parameter is more accurate, it suggests a serious underestimate of the mean estimate of SCCO₂.

A great strength of IAMs is that they do not merely offer a single mean value, but a whole distribution of outcomes that take account of the uncertainty that surrounds so much of the climate debate. For example, the value of the 95th percentile is 1,369\$/tCO₂, suggesting that

there is a five percent chance that the “true” marginal social cost of a tonne of carbon dioxide is at least this high (a huge rise from the 95th percentile value of 238\$/tCO₂ in the standard model).

An interesting direction for future research would be to tackle other areas highlighted by Weitzman to the extent that they can be entered into an IAM. In particular, the shape of the damage function could be investigated. This could be done in conjunction with the changes this paper suggests concerning the sensitivity parameter. Adjusting the damage function to take into account the uncertainty of the damage that might occur at very high temperatures would be a useful next step in the use of IAMs.

Appendix A: General probability distribution density function

RiskGeneral(*minimum,maximum,{X1,X2,...,Xn},{p1,p2,...,pn}*) generates a generalized probability distribution based on a density curve created using the specified (*X,p*) pairs. Each pair has a value *X* and a probability weight *p* which specifies the relative height of the probability curve at that *X* value. The weights *p* are normalized by @RISK in determining the actual probabilities used in sampling.

RiskGeneral(0,10,{2,5,7,9},{1,2,3,1}) specifies a general probability density function with four points. The distribution ranges from 0 to 10 with four points — 2,5,7,9 — specified on the curve. The height of the curve at 2 is 1, at 5 is 2, at 7 is 3 and at 9 is 1. The curve intersects the X-axis at 0 and 10.

RiskGeneral(100,200,A1:C1,A2:C2) specifies a general probability distribution with three data points and a range of 100 to 200. The first row of the worksheet — A1 through C1 — holds the *X* value of each data point while row 2 — A2 through C2 — holds the *p* value at each of the three points in the distribution. Note that braces are not required when cell ranges are used as array entries to the function.

Probability weights *p* must be greater than, or equal to, zero. The sum of all weights must be greater than zero. *X* values must be entered in increasing order and must fall within the minimum-maximum range of the distribution. Minimum (min) must be less than Maximum (max).

Both the minimum and the maximum are continuous parameter. $\{x\} = \{x_1, x_2, \dots, x_N\}$ is an array of continuous parameters, being $\min p_i$ $\max. \{p\} = \{p_1, p_2, \dots, p_N\}$ is an array of continuous parameters, being $p_i \geq 0$.

The density and cumulative distribution function are respectively:

$$f(x) = p_i + [(x - x_i) / (x_{i+1} - x_i)] (p_{i+1} - p_i), \text{ for } x_i \leq x \leq x_{i+1}$$

$$F(x) = F(x_i) + (x - x_i) \{p_i + [(p_{i+1} - p_i) (x - x_i) / 2 (x_{i+1} - x_i)]\}, \text{ for } x_i \leq x \leq x_{i+1}.$$

Their domain is the following: $\min \leq x \leq \max$.

The arrays are ordered from left to right. The $\{p\}$ array has been normalized to give the general distribution unit area. The i index runs from 0 to $N+1$, with two extra elements:

$$x_0 \equiv \min, p_0 \equiv 0 \text{ and } x_{N+1} \equiv \max, p_{N+1} \equiv 0.$$

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