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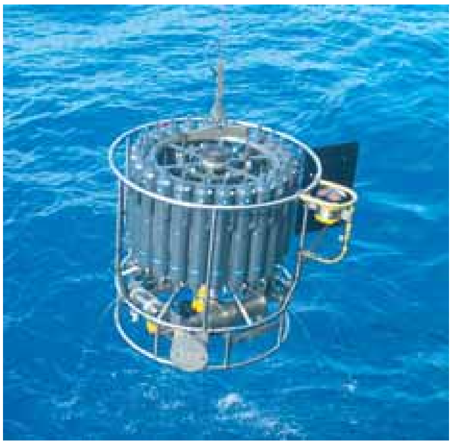
Equity and Climate Change: Applications of FUND

David Anthoff



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Reports on Earth System Science

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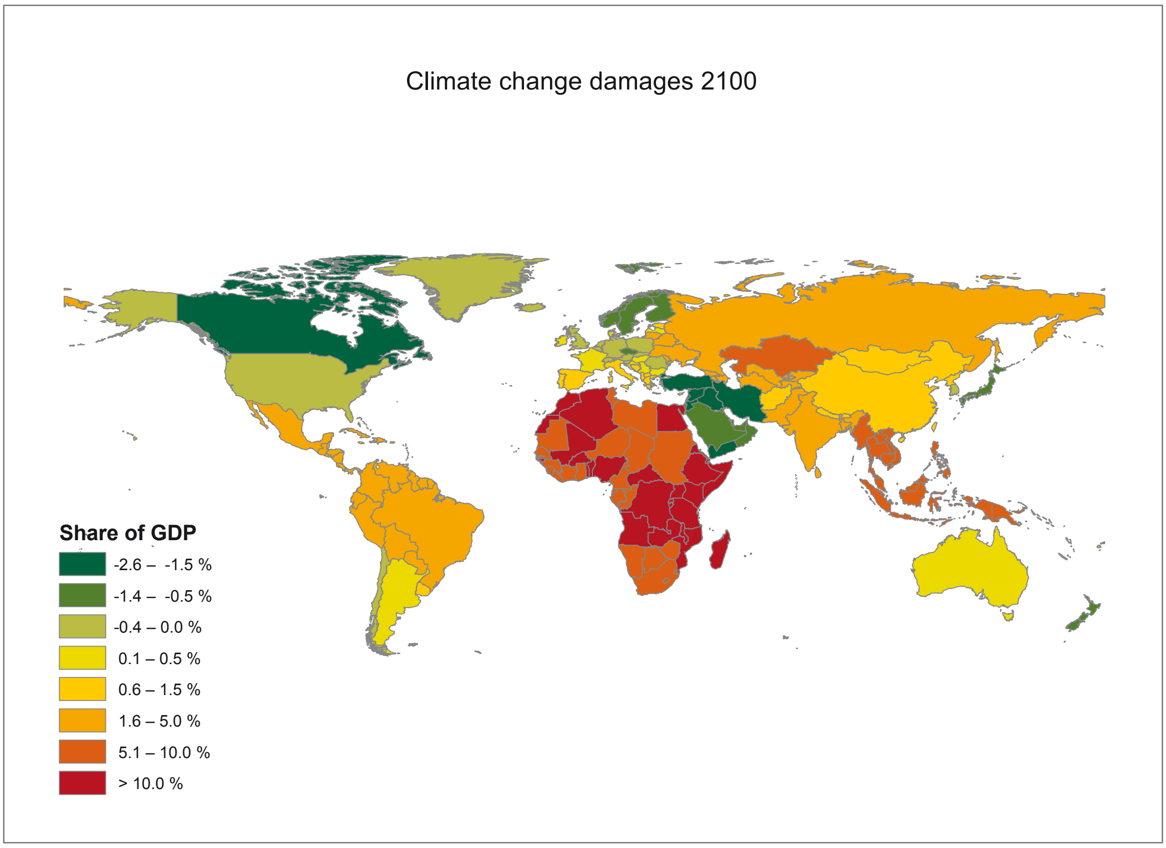

David Anthoff

Hamburg 2009

Preface

The five chapters of this thesis were also submitted individually to journals and presented at conferences.

1. The Impact of Climate Change on the Balanced-Growth-Equivalent: An Application of FUND (with Richard Tol)

This paper is published in *Environmental and Resource Economics*, 2009, **43**(3), 351-367.

It was presented at

- Ph.D. Workshop on International Climate Policy, ZEW, Mannheim, Germany, 1.5.2008
- The Economic and Social Research Institute, Dublin, Ireland, 18.6.2008
- The International Dimensions of Climate Policies, Universität Bern, Bern, Switzerland, 23.1.2009
- 2009 International Energy Workshop, Venice, Italy, 18.6.2009
- 17th Annual Conference of the European Association of Environmental and Resource Economists, Amsterdam, Netherlands, 26.6.2009
- CESifo Venice Summer Institute 2009 - Workshop on the Economics and Politics of Climate Change, Venice, Italy, 6.7.2009
- Jahrestagung des Verein für Socialpolitik, Magdeburg, Germany, 11.9.2009

2. Global Sea-Level Rise and Equity Weighting (with Robert Nicholls and Richard Tol)

This paper is currently under peer review.

It was presented at

- Integrated Coastal Zone Management and Valuation of Socio-Economic Impacts, ENCORA Thematic Network Conference, Fondazione Eni Enrico Mattei, Venice, Italy, 12.3.2007

It was also the basis of the commissioned background paper on sea-level rise for the *Stern Review*.

3. Risk Aversion, Time Preference, and the Social Cost of Carbon (with Richard Tol and Gary Yohe)

This paper is published in *Environmental Research Letters*, 2009, **4**, 024002.

4. On International Equity Weights and National Decision Making on Climate Change (with Richard Tol)

This paper is currently under peer review.

It was presented at

- The Economic and Social Research Institute, Dublin, Ireland, 11.1.2008
- Kiel Institute for the World Economy, Kiel, Germany, 21.1.2008
- Fondazione Eni Enrico Mattei, Venice, Italy, 22.5.2008
- SURED 2008 (Monte Verità Conference on Sustainable Resource Use and Economic Dynamics), Ascona, Switzerland, 4.6.2008
- 16th Annual Conference of the European Association of Environmental and Resource Economists, Gothenburg, Sweden, 27.6.2008
- CESifo Venice Summer Institute 2008 - Workshop on Europe and Global Environmental Issues, Venice, Italy, 14.7.2008

5. Optimal Dynamic Carbon Taxation

This paper is currently under peer review.

It was presented at

- Smith School of Enterprise and the Environment, University of Oxford, Oxford, United Kingdom, 29.10.2008
- The Economic and Social Research Institute, Dublin, Ireland, 10.12.2008
- University of Warwick, United Kingdom, 13.3.2009
- 17th Annual Conference of the European Association of Environmental and Resource Economists, Amsterdam, Netherlands, 26.6.2009
- CESifo Area Conference on Energy & Climate Economics, Munich, Germany, 16.10.2009

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I thank Jana Lippelt for creating the map of climate change damages reproduced on the title page.

Finally, but most importantly, I want to thank my family and friends for their support throughout the years of this thesis. Constanze’s love, help and encouragements carried me through the last years. My family and friends provided the much needed change from academic work.

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General Introduction

Climate change was for a long time the domain of natural science research. While a small group of economists was working on the issue early on as well (Nordhaus, 1991; Cline, 1992; Fankhauser, 1995; Tol, 1995; Pearce *et al.*, 1996), the focus of policy makers and the controversies surrounding climate change research focused on the basic physical science question for a long time. Through a series of reports from the Intergovernmental Panel on Climate Change (Houghton *et al.*, 1990; Houghton *et al.*, 1995; Houghton *et al.*, 2001; Solomon *et al.*, 2007), many of these controversies have been settled. The basic scientific questions of whether humans cause climate change and whether climate change will intensify in the future due to human greenhouse gas emission were answered affirmatively in those reports, and these results are widely accepted today.

Such agreement is mostly missing though on the question how a response to climate change should look like. Should one try to slow global warming by putting resources into mitigating greenhouse gas emissions? Or should one put resources into adapting to the expected impacts of climate change? Reductions of emissions are a global public good, which immediately brings up the question how it can be provided and who should provide how much of it. Climate change is characterized by an extremely slow causal connection: Emissions today will mostly affect people that are not yet alive and any costs to mitigate emission reductions today will be borne by people that will most likely not be alive anymore when the benefits of those emission reductions occur, which leads to difficult questions of how the interests of different generations are to be weighed against each other. Finally, one of the key characteristics of climate change policy is that one has to come up now with policies that are meant to solve problems whose precise magnitude is inherently uncertain, simply because they are based on predictions of what is going to happen many decades from now. How should such potentially large catastrophic, but nevertheless highly unlikely, events be considered when designing climate change policy?

All of the above are questions that are outside the traditional physical sciences whose results started the initial urge to act against climate change. The need for other disciplines, and economics in particular, to work on climate change research was recognized in expert circles for a long while, but found its most prominent public expression in the publication of the *Stern Review* in 2006 (Stern, 2007). In this thesis I try to contribute to the economic research on climate change, by both applying existing economic theory to specific issues thought to be of importance in relation to climate change, as well as in clarifying on what theoretical basis one might tackle specific questions that are posed by climate change.

In the remainder of this introduction I will give a brief outline of the chapters of this thesis and locate their role in the economic climate change research agenda.

1. Overview

A useful first starting point for a discussion of the economics of climate change is an estimate of the total damage to be expected from climate change impacts. The *Stern Review* (Stern, 2007) published one such impact estimate, but used a different metric than all other previous economic impact studies, making it difficult to compare the results from the *Stern Review* with the existing literature. The *Stern Review* expressed impacts as changes in balanced growth equivalents (BGE), whereas previous studies had used either net present total impact estimates or marginal damage cost estimates. In chapter 1 we first propose rigorous definitions of the BGE for multiple regions and under uncertainty, which was missing from the *Stern Review* itself. We show that the change in the BGE is independent of the assumed scenario of per capita income. For comparable welfare economic assumptions as the *Stern Review*, we calculate lower changes in BGE between a business as usual scenario and one without climate impacts with the model *FUND* than the *Stern Review* found with the model *PAGE*. We find that mitigation policies give even lower changes in BGE and argue that those policy choices should be the focus of the research effort rather than total damage estimates. According to our results, the current carbon tax should be below $55/tC. Sensitivity analyses show that the *Stern Review* chose parameters that imply high impact estimates. However, for regionally disaggregated welfare functions, we find changes in BGE that are significantly higher than the results from the *Stern Review*, both for total damage and for policy analysis. With regional disaggregation and high risk aversion, we observe fat tails and with that very high welfare losses.

Most studies of the total impact of climate change are based on an enumerative approach, where primary impact estimates are calculated for different sectors of the economy and then added up later to derive a total impact estimate. In chapter 2 we contribute to the estimation of one particular impact sector, namely impacts from rising sea-levels. Using the *FUND* model, we conduct an impact assessment over the 21st century for rises in sea-level of up to 2m/century and a range of national socio-economic scenarios. The model balances the costs of retreat with the costs of protection, including the effects of coastal squeeze. While the costs of sea-level rise increase due to greater damage and protection costs, the model suggests that an optimum response in a benefit-cost sense remains widespread protection of developed coastal areas. The socio-economic scenarios are also important in terms of influencing these costs. In terms of the four components of costs considered in *FUND*, protection seems to dominate, with substantial costs from wetland loss under some scenarios. The regional distribution of costs shows that a few regions experience most of the costs, especially East Asia, North America, Europe and South Asia. Importantly, this analysis suggests that protection is much more likely and rational than is widely assumed, even with a large rise in sea level. However, there are some important limitations to the analysis, which collectively suggest that protection may not be as widespread as suggested in the *FUND* analysis. Equity weighting allows the damages to be modified to reflect the wealth of those impacted by sea-level rise. Taking these distributional issues into account increases damage estimates by a factor of three, reflecting that the costs fall disproportionately on poorer developing countries.

Chapter 3 presents a systematic sensitivity analysis of the social cost of carbon with respect to two crucial parameters: the pure rate of time preference and the curvature parameter of the utility function, which plays the triple role of risk aversion, inequality aversion and elasticity of intertemporal substitution parameter in the standard preference function mostly used in climate change economics. We show that the social cost of carbon lies anywhere in between 0 and $120,000/tC. However, if we restrict these two parameters to match observed behavior, an expected social cost of carbon of $60/tC results. If we correct this estimate for income differences across the world, the social cost of carbon rises to over $200/tC.

Estimates of the marginal damage costs of carbon dioxide emissions require the aggregation of monetized impacts of climate change over people with different incomes and in different jurisdictions. Implicitly or explicitly, such estimates assume a social welfare function and hence a particular attitude towards equity and justice. In chapter 4 we show that previous approaches to equity weighing are inappropriate from a national decision maker's point of view, because domestic impacts are not valued at domestic values. We propose four alternatives (sovereignty, altruism, good neighbour, and compensation) with differing views on concern for and liability towards foreigners. The four alternatives imply radically different estimates of the social cost of carbon and hence the optimal intensity of climate policy.

A necessary condition of an efficient global climate change mitigation policy is to equate marginal abatement costs across world regions, so that the cheapest available abatement options are used. The welfare economic justification for such an approach rests on lump sum transfers between regions to compensate for any unwanted distributional consequences of such a policy. In chapter 5 I contrast this efficient solution with a second best situation in which lump sum transfers between regions are impossible. I derive that in the latter case optimal taxes are different for regions with different per capita consumption in a dynamic setting. I estimate the optimal tax rates with the integrated assessment model *FUND* and find that optimal mitigation is less stringent when equity is explicitly considered for widely used parameter choices of a utilitarian social welfare function.

I The Impact of Climate Change on the Balanced-Growth-Equivalent: An Application of *FUND*

1. Introduction

The *Stern Review on The Economics of Climate Change* (Stern, 2007) has caused substantial discussion, not least about the validity of the headline conclusion that climate change would cause a welfare loss equivalent to a permanent income loss of 5 to 20%. The initial responses of many economists (Arrow, 2007; Dasgupta, 2007; Mendelsohn, 2006; Nordhaus, 2007a; Nordhaus, 2007b; Pielke Jr, 2007; Tol, 2006c; Tol and Yohe, forthcoming; Weitzman, 2007; Yohe *et al.*, 2007) focused on a variety of shortcomings of the research and the choice of the rates of pure time preference and risk aversion, but later reactions (Yohe and Tol, 2007; Weitzman, 2008) emphasized that the *Stern Review* has also brought renewed attention to the conceptual and moral difficulties of any economic appraisal of projects to limit climate change and its impacts.

This paper contributes in four ways to the ongoing debate about the conclusions of the *Stern Review*. First, this paper uses a different integrated assessment model and is thus a sensitivity analysis of the conclusions of the *Stern Review*. Second, we extend the analysis conducted by the *Stern Review* with a regionally disaggregated welfare module. Third, we not only calculate the difference between scenarios with and without climate impacts, but evaluate specific policies in terms of changes in balanced growth equivalents. Fourth, we propose a rigorous definition of the balanced growth equivalent, which was lacking from the *Stern Review*.

The *Stern Review* diverged from the usual approaches of calculating the welfare impact of climate change employed in the literature (Pearce *et al.*, 1996; Smith *et al.*, 2001) in a number of ways. For one, it presented the results of its modelling exercise as changes in balanced growth equivalents (cf. Mirrlees and Stern, 1972). Previous studies of climate change had presented economic damages as total impacts for a benchmark scenario (typically, the effect of a doubling of atmospheric carbon dioxide on today's population and economy).[1] The introduction of a new measure is certainly a refreshing move, but it makes comparison with previous results difficult. One could attempt to infer what the results from the *Stern Review* are in the metrics used in previous studies. In this paper we choose the other direction: We use the welfare measure of the *Stern Review* but use the *FUND* model instead of *PAGE*. As such, this paper analyses how the results from the *Stern Review* depend on the specific assumptions made in the *PAGE* model. We also run the model with more combinations of input parameters than the *Stern Review* did, in particular we investigate sensitivity to all IPCC SRES scenarios and more discounting schemes.

Mirrlees' and Stern's (1972) definition of the balanced growth equivalent is for a single decision maker and a constant population. The *Stern Review's* calculation of welfare measures is based on globally averaged per capita consumption and a growing population.[2] The *Stern Review* suggests that a more appropriate aggregation would take

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[1] The marginal impacts according to the *Stern Review* can be compared to previous studies. Tol (2008) does exactly that and finds that the *Stern Review* is an outlier.

[2] The text in the *Stern Review* is not clear on this point and Stern (2008, p. 18) claims that the welfare function used for the Stern Review is a function of regional per capita consumption, but subsequent private communication (Simon Dietz) with the *Stern Review* team and a look at the source code that was used for the *Stern Review* and provided to us in the meantime confirmed that the *Stern Review* operated with global and not regional per capita consumption. Similar ambiguity is illustrated by the exchange on

up regional data when deriving the welfare measure. Due to time constraints, the *Stern Review* seems not to have carried out those calculations. Here, we do use regional impacts, income, and population data to estimate changes in the balanced growth equivalent due to climate change.

Finally, the *Stern Review* presented its results as differences between scenarios with no impacts from climate change at all and scenarios with climate change impacts. This cannot be regarded as an evaluation of policy options: There is no feasible policy option available today to avoid all climate change impacts in the future. A more meaningful result is obtained by looking at changes in welfare from feasible policy options. We here restrict the attention to one climate policy, described in section 4.3.

Section 2 reviews the original definition of the balanced growth equivalent and shows our extension with non-constant populations, regional disaggregation, and uncertainty. While our derivations are relatively straightforward, they have not been presented before. The equations shown should avoid future ambiguities about the definition of the BGE and its extensions. Section 3 outlines the *FUND* model. Section 4 presents the numerical results. Section 5 concludes.

2. Balanced growth equivalent

2.1. Basic concept

Mirrlees and Stern (1972) introduced the concept of a *balanced growth equivalent* (BGE) as a commodity measure of welfare. The thought was that when looking at policy proposals one could calculate the change in BGE for a particular policy and use that as a rough first estimate of whether further investigation of that policy would be warranted or whether the impact of that policy would be too small in the first place to

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abatement costs between Anderson (2007), Dietz *et al*. (2007), and Tol and Yohe (2006; 2007a). See also Weyant (2008).

warrant further research. The authors themselves suggest that there might be many broad economic policy options unexplored that would cause an increase of at least 1% in BGE and propose that those should attain more research time.[3] The BGE as a welfare measure has largely been ignored in the economics literature: only 9 papers refer to Mirrlees and Stern (1972) according to the *Web of Science*, and none of these papers develops the BGE further or applies it. Stern (2007) appears to be the first application.

The following will briefly review the original concept with the notation used for this paper. Since we will later use a numerical model to run simulations, we use discrete time for the model, unlike the original specification of BGE. One key exercise of this paper is to compare the effects of various policy options with respect to climate change in terms of welfare changes. Policy choices are represented by ω. A specific policy choice ω could for example designate one specific carbon tax schedule. ω can stand for any policy out of all possible policy options, the numerical analysis later in the paper will restrict itself to a subset of policy options.

Let welfare for a specific policy ω be

$$W(\omega) = \sum_{t=0}^{T} U\left(C_{\omega,t}\right) P_t \left(1+\rho\right)^{-t} \tag{1.1}$$

where $C_{\omega,t}$ is *per capita* consumption at time t as it results from choosing policy ω, P is population, ρ is the utility discount rate, U is the utility function and T is the time up to which the analysis is carried out.

The BGE for policy ω is then defined by solving[4]

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[3] Note that the *Stern Review* and this paper use a different baseline than was originally suggested in Mirrlees and Stern (1972). They looked at improvements from the status quo, i.e. how a policy would improve the business as usual scenario. The Stern Review and this paper evaluate changes from a hypothetical world without climate change, where smaller changes (i.e. smaller damages) are better.

[4] Note that equation (7) in chapter 6 in the *Stern Review* purports to define the BGE as used by Stern (2007, p. 185) and thus would play the same role as our equation (1.2). Unfortunately, equation (7) in the

$$\sum_{t=0}^{T} U\left[\gamma(\omega)(1+\alpha)^{t}\right] P_t (1+\rho)^{-t} = W(\omega) \tag{1.2}$$

for $\gamma(\omega)$, with α being a constant growth rate (that later drops out when changes in γ are calculated). Note that $\gamma(\omega)$ is the initial level of per capita consumption that would give the same welfare as $W(\omega)$ if it grew at constant rate α.

For a standard constant-relative-risk-aversion utility function

$$U(C) = \begin{cases} C^{1-\eta}(1-\eta)^{-1} & \text{for } \eta \neq 1 \\ \ln C & \text{for } \eta = 1 \end{cases} \tag{1.3}$$

with η being the marginal elasticity of consumption, we have an explicit solution for γ

$$\gamma(\omega) = \begin{cases} \left[(1-\eta)W(\omega)\right]^{\frac{1}{1-\eta}} \left[\sum_{t=0}^{T} \frac{(1+\alpha)^{t(1-\eta)} P_t}{(1+\rho)^{t}}\right]^{-\frac{1}{1-\eta}} & \text{for } \eta \neq 1 \\ \exp\left(\frac{W(\omega) - \ln(1+\alpha)\sum_{t=0}^{T} t P_t (1+\rho)^{-t}}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) & \text{for } \eta = 1 \end{cases} \tag{1.4}$$

Defining the relative change in BGE for two policies ω and ω' as $\Delta\gamma$, we get

$$\Delta\gamma := \frac{\gamma(\omega') - \gamma(\omega)}{\gamma(\omega)} = \begin{cases} \left(\frac{W(\omega')}{W(\omega)}\right)^{\frac{1}{1-\eta}} - 1 & \text{for} \, \eta \neq 1 \\ \exp\left(\frac{W(\omega') - W(\omega)}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) - 1 & \text{for } \eta = 1 \end{cases} \tag{1.5}$$

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review contains a number of errors: As printed, the function is not defined for $\eta = 1$, a balanced growth path is given by $C_{BGE}(1+g)^{t}$ and not the term $C_{BGE} + gt$ that is printed in the *Stern Review*, and finally this wrong term for consumption at time t is wrongly converted into utility by only putting C_{BGE} into the utility function and then adding gt to utility. Private communication with members of the *Stern Review* team (Simon Dietz, Nick Stern) and later comparison with the source code (also provided privately) used for the *Stern Review* assured us that these errors were only present in the text and that the equations used for the numerical results in the Stern Review did not contain these mistakes. Public availability of the source code and an errata (which we could not find) of the Stern Review could clear questions up for other readers of the *Stern Review*.

Note that $\Delta\gamma$ is independent of α, so that the change in BGE does not depend on the growth rate assumed in the calculation of a specific BGE – as long as the growth rates are the same for the two policy choices. The change in BGE thus expresses the difference between two scenarios as a constant change in relative consumption. It is an annuity, but an annuity that is based on the equivalence of net present welfare.

Note that population is (assumed to be) independent of the policy choice. If population is endogenous to the policy decision, one cannot use a welfare function like Equation (1.1). See Blackorby and Donaldson (1984) and Blackorby *et al.* (1995).

2.2. Uncertainty

We now treat $W(\omega,s)$ as a random variable where $p(s)$ is the probability of state of the world s. Expected welfare then is

$$\mathrm{E}W(\omega)=\sum_{p} p(\omega,s)\sum_{t=0}^{T} U\left(C_{\omega,s,t}\right)P_t(1+\rho)^{-t} \tag{1.6}$$

The certainty- and balanced growth equivalent (CBGE) is obtained be replacing $W(\omega)$ in (1.2) with expected welfare $\mathrm{E}W(\omega)$ as defined in (1.6). The CBGE can then be solved as:

$$\gamma_C(\omega)=\begin{cases}\left[(1-\eta)\mathrm{E}W(\omega)\right]^{\frac{1}{1-\eta}}\left[\sum_{t=0}^{T}\frac{(1+\alpha)^{t(1-\eta)}P_t}{(1+\rho)^t}\right]^{-\frac{1}{1-\eta}} & \text{for } \eta\neq 1\\ \exp\left(\frac{\mathrm{E}W(\omega)-\ln(1+\alpha)\sum_{t=0}^{T}tP_t(1+\rho)^{-t}}{\sum_{t=0}^{T}P_t(1+\rho)^{-t}}\right) & \text{for } \eta=1\end{cases} \tag{1.7}$$

The CBGE is the initial level of per capita consumption, which, if it grows without any uncertainty at some constant rate α, gives the same level of welfare as the expected welfare for some policy ω as defined in (1.6). It is a combination of the certainty equivalence ideas put forward by Rothschild and Stiglitz (1970) with the balanced growth equivalent of Mirrlees and Stern (1972).

The change in the CBGE equals:

$$\Delta\gamma_C := \begin{cases} \left(\dfrac{\mathrm{E}W(\omega')}{\mathrm{E}W(\omega)}\right)^{\frac{1}{1-\eta}} - 1 & \text{for } \eta \neq 1 \\ \exp\left(\dfrac{\mathrm{E}W(\omega') - \mathrm{E}W(\omega)}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) - 1 & \text{for } \eta = 1 \end{cases} \tag{1.8}$$

As before, the growth scenario α cancels.

2.3. Multiple regions

In the final step, we introduce multiple regions. Assuming that the global welfare function is utilitarian, we have

$$W_E(\omega) = \sum_r \sum_{t=0}^{T} U\left(C_{\omega,t,r}\right) P_{t,r} (1+\rho)^{-t} \tag{1.9}$$

for a deterministic analysis and

$$\mathrm{E}W_E(\omega) = \sum_p p(\omega,s) \sum_r \sum_{t=0}^{T} U\left(C_{\omega,s,t,r}\right) P_{t,r} (1+\rho)^{-t} \tag{1.10}$$

for an analysis with uncertainty. Per capita consumption C and population P are now fed into the welfare function for each region r individually.

Replacing $W(\omega)$ in (1.2) with the deterministic welfare function that is disaggregated by regions $W_E(\omega)$ gives the equity- and balanced growth equivalent (EBGE) for a specific policy choice. This solves as:

$$\gamma_E(\omega)=\begin{cases}\left[(1-\eta)W_E(\omega)\right]^{\frac{1}{1-\eta}}\left[\sum_{t=0}^{T}\frac{(1+\alpha)^{t(1-\eta)}P_t}{(1+\rho)^t}\right]^{-\frac{1}{1-\eta}} & \text{for } \eta\neq 1\\ \exp\left(\frac{W_E(\omega)-\ln(1+\alpha)\sum_{t=0}^{T}tP_t(1+\rho)^{-t}}{\sum_{t=0}^{T}P_t(1+\rho)^{-t}}\right) & \text{for } \eta=1\end{cases} \tag{1.11}$$

This combines the BGE concept with a measure of inequality very much like Atkinson’s (1970). The EBGE is the equally distributed (over the regions under consideration) initial per capita consumption, growing at a constant rate α that gives the same level of welfare as obtained for a specific policy choice ω from the welfare function defined in (1.9). Note that (1.11) has a different treatment for income difference between regions and between generations (cf. Tol, 2002c).

The certainty, equity- and balanced growth equivalent (CEBGE) follows by replacing $W(\omega)$ in (1.2) with the expected welfare from the regional disaggregated welfare function as defined in (1.10) for some policy choice ω. This solves as:

$$\gamma_{CE}(\omega)=\begin{cases}\left[(1-\eta)\mathrm{E}W_E(\omega)\right]^{\frac{1}{1-\eta}}\left[\sum_{t=0}^{T}\frac{(1+\alpha)^{t(1-\eta)}P_t}{(1+\rho)^t}\right]^{-\frac{1}{1-\eta}} & \text{for } \eta\neq 1\\ \exp\left(\frac{\mathrm{E}W_E(\omega)-\ln(1+\alpha)\sum_{t=0}^{T}tP_t(1+\rho)^{-t}}{\sum_{t=0}^{T}P_t(1+\rho)^{-t}}\right) & \text{for } \eta=1\end{cases} \tag{1.12}$$

which is the equally distributed (over the regions under consideration) initial per capita consumption growing without uncertainty at a constant rate α, that gives the same welfare level as the expected welfare of a certain policy choice ω as obtained by using (1.10).

From this it follows that the change in the EBGE between two policy options is

$$\Delta\gamma_E := \begin{cases} \left(\dfrac{W_E(\omega')}{W_E(\omega)}\right)^{\frac{1}{1-\eta}} - 1 & \text{for } \eta \neq 1 \\ \exp\left(\dfrac{W_E(\omega') - W_E(\omega)}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) - 1 & \text{for } \eta = 1 \end{cases} \tag{1.13}$$

And the change in the CEBGE between two policy options is

$$\Delta\gamma_{CE} := \begin{cases} \left(\dfrac{\mathrm{E}W_E(\omega')}{\mathrm{E}W_E(\omega)}\right)^{\frac{1}{1-\eta}} - 1 & \text{for } \eta \neq 1 \\ \exp\left(\dfrac{\mathrm{E}W_E(\omega') - \mathrm{E}W_E(\omega)}{\sum_{t=0}^{T} P_t (1+\rho)^{-t}}\right) - 1 & \text{for } \eta = 1 \end{cases} \tag{1.14}$$

Note that in Equation (1.14), the parameter η has a triple role. It is a measure of the curvature of the utility function – more specifically, the consumption elasticity of marginal utility – but it functions as the intertemporal substitution elasticity of consumption, the rate of risk aversion, and the rate of inequity aversion. Below, we refer to η as the rate of risk aversion.

Tol and Yohe (2007b) show a similar derivation, but use the term *certainty- and equity-equivalent annuity* because Equation (1.14) distributes the impact equally over time, as well as over states of the world and over regions.

As stated in the introduction, we think that the *Stern Review* intended to report $\Delta\gamma_{CE}$ as defined in Equation (1.14), but they seem to report $\Delta\gamma_C$ (1.8) instead.

3. The Model

FUND (the Climate Framework for Uncertainty, Negotiation and Distribution) is an integrated assessment model linking projections of populations, economic activity and emissions to a simple carbon cycle and climate model, and to a model predicting and monetizing welfare impacts. Climate change welfare impacts are monetarized in 1995 dollars and are modelled over 16 regions. Modelled welfare impacts include agriculture, forestry, sea level rise, cardiovascular and respiratory disorders influenced by cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems (Link and Tol, 2004). The source code, data, and a technical description of the model can be found at http://www.fund-model.org.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. Version 3.2, used in this paper, runs from 1950 to 2300 in time steps of one year. The primary reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, the welfare impacts of climate change are assumed to depend in part on the impacts during the previous year, reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical impacts and monetized welfare impacts of climate change tend to be misrepresented in the first few decades of the model runs. The 22nd and 23rd centuries are included to provide a proper long-term perspective.

The period of 1950-1990 is used for the calibration of the model, which is based on the *IMAGE* 100-year database (Batjes and Goldewijk, 1994). The period 1990-2000 is based on observations (http://earthtrends.wri.org). The 2000-2010 period is interpolated from the immediate past. The climate scenarios for the period 2010-2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett *et al.*, 1992). The period 2100-2300 is extrapolated.

The scenarios are defined by varied rates of population growth, economic growth, autonomous energy efficiency improvements, and decarbonization of energy use (autonomous carbon efficiency improvements), as well as by emissions of carbon dioxide from land use change, methane emissions, and nitrous oxide emissions.

Emission reduction of carbon dioxide, methane and nitrous oxide is specified as in Tol (2006b). Simple cost curves are used for the economic impact of abatement, with limited scope for endogenous technological progress and interregional spillovers (Tol, 2005b).

The scenarios of economic growth are perturbed by the effects of climatic change.[5] Climate-induced migration between the regions of the world causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The tangible welfare impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. As a result, climate change reduces long-term economic growth, although consumption is particularly affected in the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies.

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[5] Note that in the standard version of FUND population growth is also perturbed by climate change impacts. That particular feature was switched off in the runs for this paper because endogenous population changes cannot be evaluated with the kind of welfare function investigated, see discussion above.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the effect of carbon dioxide emission reductions on the economy and on emissions, and the effect of the damages on the economy caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt *et al*. (1992).

The radiative forcing of carbon dioxide, methane, nitrous oxide and sulphur aerosols is determined based on Shine *et al*. (1990). The global mean temperature, T, is governed by a geometric build-up to its equilibrium (determined by the radiative forcing, RF), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. Regional temperature is derived by multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn *et al.*, 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996).

The climate welfare impact module, based on Tol (2002a; b) includes the following categories: agriculture, forestry, hurricanes, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages are triggered by either the rate of temperature change (benchmarked at 0.04°C/yr) or the level of temperature change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol, 2002b).

In the model individuals can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all welfare impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income.[6] The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set to be three times the per capita income (Tol, 1995a; 1996), the value of immigration is 40 per cent of the per capita income in the host region (Cline, 1992). Losses of dryland and wetlands due to sea level rise are modelled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 (cf. Fankhauser, 1994). The wetland value is assumed to have a logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other welfare impact categories, such as agriculture, forestry, hurricanes, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their ‘natural’ units (cf. Tol, 2002a). Modelled effects of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive

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[6] Note that this implies that the monetary value of health risk is effectively discounted with the pure rate of time preference rather than with the consumption rate of discount (Horowitz, 2002). It also implies that, after equity weighing, the value of a statistical life is equal across the world (Fankhauser *et al.*, 1997).

or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol, 2002b).

The welfare impacts of climate change on coastal zones, forestry, hurricanes, unmanaged ecosystems, water resources, diarrhoea, malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (cf. Tol, 2002b).

Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth) and heat-related disorders (with urbanization), or more valuable, such as ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) (cf. Tol, 2002b).

In the Monte Carlo analyses, essentially all parameters are varied. The probability density functions are mostly based on expert guesses, but where possible "objective" estimates were used. Parameters are assumed to vary independently of one another, except when there are calibration or accounting constraints. Details of the Monte Carlo analysis can be found on *FUND*'s website at http://www.fund-model.org.

4. Results

4.1. Scenarios

Stern (2007) present the impacts of climate change as the change in BGE between a baseline scenario with no climate change impacts and various scenarios with climate impacts. This is a measure of the overall damage of climate change. We present similar results but add more sensitivity analysis. In particular, we present results for alternative assumptions on discounting and risk aversion, and include four alternative socio-economic scenarios.

We refer to these runs as total damage estimates. Contrary to what Stern (2007) assert, these estimates of the total impact of climate change differ from the estimated benefits of climate policy. Avoiding all climate change is impossible, and emission abatement slows economic growth. We therefore present a second set of results where we evaluate specific carbon taxation policies and calculate the change in BGE (or any of the more complicated concepts) from a hypothetical scenario with neither climate change impacts nor any policy costs to a scenario with both policy costs of carbon taxation and impacts of climate change.

For any combination of socio economic scenario, pure rate of time preference, rate of risk aversion, uncertainty treatment and social welfare function, we calculated the BGE for two policy choices: One business as usual policy with no greenhouse gas taxation and the BGE for a particular policy choice. The latter is characterised as follows: Following a widely used practise, we impose a globally harmonized carbon tax on all regions. For the first time period we search for a carbon tax rate that equals the social cost of carbon emissions, which in turn depends on the choice and parameterisation of the social welfare function. We then increase this carbon tax with the world average discount rate in every time period[7]. We then present results as a change in the BGE from a run without any climate change impacts or policy costs to the BGE of one of the two policy choices.

In the following sections we point out our key findings both for the costless mitigation runs and the policy runs.

4.2. Total damage

Figure 1 shows the loss of going from a scenario without climate change impacts to a business as usual policy (i.e. a scenario with no climate change mitigation but full impacts) in terms of change of CBGE for various pure rates of time preference, risk aversion and socio-economic scenario choices. Figure 1 shows the mean change in BGE over all socio-economic scenarios, with the minimum and maximum shown on the error bars. The numbers in this figure form the model sensitivity analysis to the results of the *Stern Review*.

In general, the numbers calculated by *FUND* tend to suggest lower total damages than the figures from the *Stern Review*, given apparently comparable welfare economic treatment.[8] One difference is that *FUND* has a time horizon of 2300, while *PAGE* stops at 2200. In the *Stern Review* impacts were assumed to be constant as a fraction of income for the time period 2200 to infinity and fully accounted for in the welfare function, whereas we assume no impacts after 2300. Note that the very questionable assumption of constant damages until infinity after the year 2200 is not a feature of the *PAGE* model, but was only implemented for the results of the *Stern Review*, as far as we

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[7] Note that this ignores a number of complicated issues. First, the rate of increase of the optimal carbon tax would be less than the discount rate due to the decay of carbon in the atmosphere. In our experience the difference in results between the two approaches is marginal and would not have justified the significant computational complications associated with it. Second, there is an ongoing debate in the literature whether a harmonized carbon tax is optimal (cf. Chichilnisky and Heal, 1994; Anthoff, 2009), but we ignore these issues in this paper.

[8] Note that *PAGE* tends to report *lower* marginal impacts than *FUND* (Tol, 2008).

can tell. Probably the main driver for this effect is one crucial difference in modeling impacts in the model *PAGE* as used for the *Stern Review* and *FUND*: *PAGE* puts more emphasis on the negative impacts of climate change, i.e. it will rarely produce a net global benefit from an increase in temperature for any time step.[9] *FUND* on the other hand has various sectors in which modest temperature increases in some regions can lead to net benefits, so that in particular in the earlier time periods impacts of climate change are positive for some regions.[10] Besides, *PAGE* includes an arbitrary catastrophe caused by climate change, while *FUND* only includes identified impacts – which does not imply that *FUND* cannot produce very large impacts (Tol, 2003) or analyze supposedly catastrophic scenarios (Link and Tol, 2004). Furthermore, *PAGE* assumes that vulnerability to climate change is constant, while *FUND* has that regions grow less vulnerable as they grow richer. Sterner and Persson (2008) and Tol and Yohe (2007b) show that this is an important assumption.

At the same time, our results mimic some key features of the *Stern Review* results: higher time preference rates and higher risk aversion always lead to lower impacts estimates. For time discounting, this is rather well established in the literature (e.g. Guo *et al.*, 2006; Newell and Pizer, 2003). That higher η values lead to lower damages is less straight forward, as it controls two effects at the same time. First, the effective discount rate is increased, which certainly leads to lower damage estimates. Second, more weight is given to unlikely but bad outcomes, i.e. the decision maker is assumed to be more risk averse, which should lead to higher damage estimates. Figure 1 shows that the first effect strongly dominates the second in the kind of uncertainty analysis

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[9] Note that *PAGE* does produce positive market impacts for some regions.

[10] Initially positive economic impacts of climate change are not unique to *FUND*, and are not a new finding. See Smith *et al*. (2001). For detailed discussions of *FUND's* estimated impacts and in particular their time profile as well as their regional distribution, see Tol (2002b) and Tol *et al.* (2003).

employed for this paper, i.e. that the increase in the discount rate offsets the increase in risk aversion.

The *Stern Review* itself pointed out that a global welfare function cannot take into account how damages are distributed with respect to high/low income regions, and that a regional disaggregated welfare function would be a more appropriate choice. Figure 2 shows results using a social welfare function that is disaggregated into 16 world regions, again with the mean (and minimum and maximum) of the socio-economic scenarios for total impacts.

There are three key insights: First, using a disaggregated regional social welfare function always increases total damage estimates; second, the role of η is reversed; and third, high η values lead to estimates that are very large.

We find higher damages for a regional disaggregated welfare function for all scenarios. A disaggregated regional welfare function in general gives higher weights to impacts in poor regions than in high income regions. In general (but not in every detail), *FUND* has more negative impacts in poor regions, so this result is not unexpected.

With a regional welfare function, η plays a third role, namely that of inequality aversion, in addition to the parameter of risk aversion and substitution of consumption over time. With this third role added, the response of the total damage estimates to higher values for η is reversed, in particular the inequality and risk aversion aspect dominate the higher discount rate aspect of high η values and therefore total damage estimates increase with higher values for η. This directly points to one central problem with the kind of welfare function commonly employed in climate change analysis (and this paper), namely the over use of η to control three issues at the same time (cf. Beckerman and Hepburn, 2007). A number of the critics of the *Stern Review* (e.g.

Dasgupta, 2007) have argued that while a low pure rate of time preference might be acceptable, one should pick a higher value for η, so that the overall discount rate is more in line with market interest rates. In the context of a global welfare function as used by Stern (2007) this suggestion makes sense, but with a regional welfare function the effect on the estimated damage may be unexpected.

Finally, we produce very large damage estimates for high η values with a regional welfare function. This is a direct manifestation of Weitzman's (2008) fat tail argument: Comparing the regional probabilistic results with deterministic runs, and a detailed analysis of the drivers of those extreme values shows that some regions approach very low consumption (subsistence) levels in some scenarios in our Monte Carlo analysis – and this implies that welfare in these regions, years and runs becomes large and negative, and potentially unboundedly so. With a global welfare function those extreme results in a few regions are averaged out, but with a regional welfare function these fat tails in single regions drive the analysis.

4.3. Mitigation policy

While an analysis of the total expected damage of climate change is of interest, a more policy relevant question is what improvement a realistic policy that would have both mitigation costs and avoided damage benefits accounted for could achieve.

Table 1 compares the total damage of a scenario with no emission mitigation with the total damage of our mitigation policy scenario (in which case the total damage includes the now reduced impacts from climate change as well as the mitigation costs) for SRES scenario A2 for a probabilistic analysis. The A2 scenario is the scenario of choice in the *Stern Review*. For a global welfare function as used by the *Stern Review*, the best possible improvement is always significantly lower than the total damage estimate.

Except for runs with high η values, this conclusion also holds for a regional welfare function. The runs with $\eta = 2$ have to be interpreted with care, since the manifestation of fat-tails showing up there might make the framework used to determine our policy response less appropriate.

A global welfare function underestimates by a large margin the improvements that can be obtained by an actual mitigation policy. Table 2 compares the carbon tax levels in the year 2000 for the A2 scenario. Note the discrepancy in the results. While our total impact estimate is 3% for η=1 and ρ=0.1% compared to Stern's 5%, our social cost of carbon is $41/tC compared to Stern's $314/tC. This is probably explained by the highly non-linear impact function in the (adjusted) *PAGE* model. While the initial tax is higher for a regional welfare function, the change in the BGE for a regional welfare function is much larger for the mitigation policy than the change in the tax level. The prime reason for this is that the introduction of a regional welfare function not only gives more weight to damages in low income regions, but mitigation costs in poor regions also get a higher weight, thereby balancing the effect of the regional welfare function somewhat.

Table 3 highlights the importance of distributional issues and uncertainty in climate change. Table 3 shows our estimate of the total impacts of climate change using a global welfare function ignoring uncertainty and compares this to the regional welfare function. In the global welfare function, global average impacts are computed before being converted to utility. In the regional welfare function, regional average impacts are converted to utility and then averaged for the world. Irrespective of the rates of pure time preference or risk aversion, the regional welfare function implies impacts that are substantially higher. This is well-known in the literature (Azar and Sterner, 1996; Fankhauser *et al.*, 1997; Azar, 1999; Anthoff *et al.*, 2009). It appears that the *Stern*

Review overlooked this. With uncertainty, the difference between a global and a regional welfare function is even stronger.

Qualitatively, the results for the A2 scenario hold for the other scenarios as well. Quantitatively, the results are different, of course, and where the relationship is ambiguous (e.g., between η and $\Delta\gamma$), different scenarios may show different signs. Table 4 shows the total impact of climate change for five alternative socio-economic and emissions scenarios. The A2 scenario is generally in the middle of the range. Hotter (FUND) and poorer (B2) scenarios show higher impacts, while cooler (B1) and richer (A1b) scenarios show lower impacts.

5. Conclusion

This paper defines various balanced growth equivalences, and applies them to compute the impacts of climate change and the benefits of emission reduction with the integrated assessment model *FUND*. We conduct a wider sensitivity analysis than run by the *Stern Review*. We find that the impacts of climate change are sensitive to the pure rate of time preference, the rate of risk aversion, the level of spatial disaggregation, the inclusion of uncertainty, and the socio-economic scenario. Our results span a wider range in both directions compared to the *Stern Review*, thereby questioning the assertion that the high results obtained by the *Stern Review* are robust. We find that the guess of the *Stern Review* that a regional welfare function might increase overall damage estimates by a quarter (Stern, 2007, p. 187) is very conservative. In our runs, the introduction of a regional welfare function, in particular in combination with a high risk aversion, has a much larger effect on the results. Finally, we show that the *Stern Review* was wrong to equate the impact of climate change and the benefits of emission reduction – their "optimal" climate policy does not maximise welfare in the mathematical sense of the word. Qualitatively, this was known. Quantitatively, we show that this is a big mistake.

The results also show areas that need more research work. This includes improved socio-economic and climate scenarios, and better and more complete estimates of the impacts of climate change. In particular, disentangling intertemporal substitution from risk aversion and inequality aversion is a high priority (e.g., Carlsson *et al.*, 2005). With only one parameter to control three important effects, as commonly used in climate policy analysis, model- and scenario-specific ambiguities emerge. The fat tails that showed up in some of our results with high risk aversion and a regional welfare function are another area for further research.

6. Acknowledgements

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7. Figures

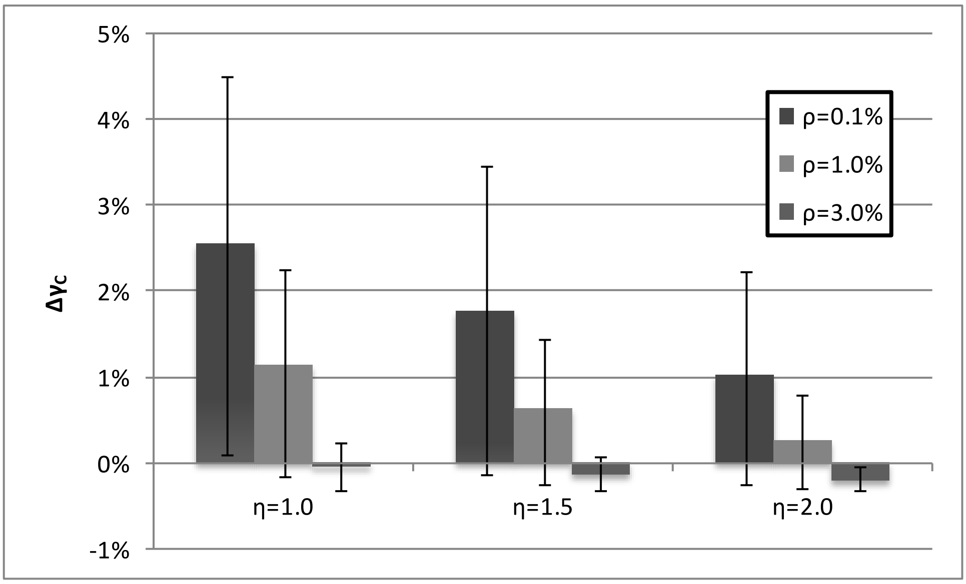

Figure 1: Total damage as a change in BGE with a global welfare function

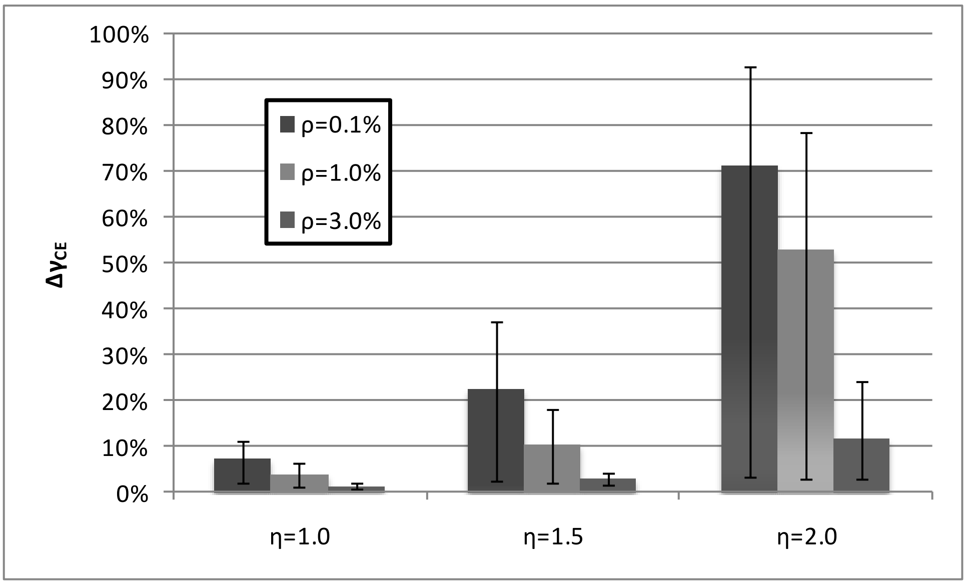

Figure 2: Total damage with a regional welfare function

8. Tables

	η=1.0	**η=1.5**	**η=2.0**
Global welfare function			
ρ=0.1%	1.33% (3.27%)	0.85% (2.40%)	0.40% (1.49%)
ρ=1.0%	0.40% (1.55%)	0.19% (0.92%)	0.08% (0.46%)
ρ=3.0%	0.01% (0.03%)	0.02% (-0.07%)	0.01% (-0.14%)
Regional welfare function			
ρ=0.1%	4.27% (9.24%)	27.86% (32.60%)	91.07% (91.67%)
ρ=1.0%	1.52% (5.12%)	9.74% (13.95%)	70.58% (72.11%)
ρ=3.0%	0.08% (1.56%)	0.61% (3.29%)	10.25% (13.73%)

Table 1: Change in CBGE and CEBGE from a scenario without climate impacts to a mitigation policy scenario (to a business as usual scenario in brackets) for SRES scenario A2

	η=1.0	**η=1.5**	**η=2.0**
Global welfare function			
ρ=0.1%	40.63	23.75	11.88
ρ=1.0%	15.63	6.88	3.13
ρ=3.0%	0.63	0.63	0.63
Regional welfare function			
ρ=0.1%	51.25	54.38	50.63
ρ=1.0%	21.25	25.63	31.25
ρ=3.0%	2.50	6.88	7.50

Table 2: Carbon tax ($/tC in 1995 USD) in the year 2000 for SRES A2 scenario under a probabilistic analysis for the mitigation policy

	η=1.0	**η=1.5**	**η=2.0**
Global welfare function			
ρ=0.1%	1.53%	0.59%	-0.15%
ρ=1.0%	0.07%	-0.46%	-0.76%
ρ=3.0%	-0.92%	-0.95%	-0.95%
Regional welfare function			
ρ=0.1%	3.05%	2.67%	2.48%
ρ=1.0%	1.06%	1.20%	1.72%
ρ=3.0%	-0.51%	0.40%	1.42%

Table 3: Change in BGE and EBGE for total damage estimates for a business as usual scenario for SRES scenario A2 without uncertainty

	η=1.0			**η=1.5**			**η=2.0**		
	ρ =0.1%	**ρ=1.0%**	**ρ=3.0%**	**ρ=0.1%**	**ρ=1.0%**	**ρ=3.0%**	**ρ=0.1%**	**ρ=1.0%**	**ρ=3.0%**
Global welfare function									
FUND	4.50%	2.25%	0.23%	3.45%	1.45%	0.06%	2.24%	0.80%	-0.05%
A1b	1.49%	0.49%	-0.20%	0.56%	0.02%	-0.28%	-0.01%	-0.21%	-0.32%
A2	3.27%	1.55%	0.03%	2.40%	0.92%	-0.07%	1.49%	0.46%	-0.14%
B1	0.09%	-0.16%	-0.32%	-0.13%	-0.26%	-0.33%	-0.25%	-0.30%	-0.33%
B2	3.42%	1.57%	-0.01%	2.59%	0.97%	-0.11%	1.66%	0.49%	-0.19%
Regional welfare function									
FUND	11.30%	6.45%	1.89%	37.26%	18.28%	4.14%	92.74%	78.66%	24.20%
A1b	4.83%	2.54%	0.94%	14.87%	5.38%	1.97%	80.28%	44.69%	5.72%
A2	9.24%	5.12%	1.56%	32.60%	13.95%	3.29%	91.67%	72.11%	13.73%
B1	1.92%	1.22%	0.70%	2.39%	1.98%	1.77%	3.42%	3.04%	2.99%
B2	8.35%	4.46%	1.40%	25.60%	11.02%	3.03%	88.74%	65.82%	12.00%

Table 4: Total damages for probabilistic runs by socio-economic scenario

II Global Sea-Level Rise and Equity Weighting

1. Introduction

Sea-level rise due to human-induced climate change has caused concern for coastal areas since the issue emerged more than 20 years ago. Rapid sea-level rise (>1-m/century) raises most concern as it is commonly felt that this would overwhelm the capacity of coastal societies to respond and lead to large losses and a widespread forced coastal retreat (e.g., Overpeck *et al.*, 2006). While the IPCC AR4 (IPCC, 2007) suggests that a rise of >1-m/century is highly unlikely during the 21st Century, others argue that this remains an important issue for scientific analysis (Rahmstorf, 2007; Rahmstorf *et al.*, 2007). Less appreciated is the so-called 'commitment to sea-level rise' whereby even if the climate is stabilized immediately, sea levels continue to rise for many centuries due to the long timescales of the oceans and the large ice sheets (Nicholls *et al.*, 2006a; Nicholls and Lowe, 2006).

To date few studies have considered large rises in sea level rise – the few analyses tend to focus on exposure (i.e. potential impacts) only (Nicholls *et al.*, 2006a). This paper also includes a coastal protection response. It builds on the earlier global analysis of Nicholls *et al.* (2006c) and provides evidence on the consequences of large rises in sea level over the 21st Century using the coastal module of an integrated assessment model (*FUND*: The Climate Framework for Uncertainty, Negotiation and Distribution) for scenarios of sea-level rise in the range of 0.5 to 2 meters (which are consistent with the extremes analysis of Arnell *et al.* (2005)). The model calculates the welfare loss due to rising sea levels for a number of socio-economic scenarios, assumes some basic adaptation of humans to sea-level rise (a simple choice between protect and retreat) and aggregates damages for a number of assumed damage types.

The results are presented using standard discounting methodology and using equity weights. The use of equity weights in the context of climate change was first suggest by Pearce *et al.* (1996) and since then a number of studies have applied equity weights on a regional scale in the context of climate change (Azar and Sterner, 1996; Tol *et al.*, 1996; Azar, 1999; Tol, 1999; Pearce, 2003; Anthoff *et al.*, 2009). This paper is the first to present damage estimates that use equity weights on a national basis. Equity weights correspond to the intuition that ‘a dollar to a poor person is not the same as a dollar to a rich person’. More formally, the marginal utility of consumption is declining in consumption: a rich person will obtain less utility from an extra dollar available for consumption compared to a poor person. Equity-weighted damage estimates take into account that the same monetary damage to someone who is poor causes greater welfare loss than if that damage had happened to someone who is rich. Using national data instead of regional data for such an exercise is important in order to avoid smoothing of income inequalities by using larger regions to calculate average per capita incomes. Use of equity weights is particular appropriate in the context of sea-level rise, given the huge difference in income of those effected and the difficulties to assess the true welfare loss in such a situation without using a concept like equity weighting.

2. Model

The Coastal Module of *FUND* 2.8n is used to calculate damages[11] caused by various scenarios of sea-level rise over the next century (see Figure 3). This section will give a brief outline of the model components relevant to the calculation of sea-level rise damages. More details of the *FUND* coastal module can be found in Tol (2007) and Nicholls, Tol *et al.* (2006b).

The model is driven by exogenous scenarios of population and GDP growth on a per country scale. Five distinct socio-economic scenarios are evaluated for this study: the four well-known SRES scenarios A1, A2, B1 and B2 downscaled from the original source (Nakicenovic and Swart, 2000) and a control scenario of constant population and GDP at 1995 levels over the 21st century (termed C1995)[12].

Sea-level rise is specified as a global exogenous scenario. Three distinct scenarios are examined: a rise of 0.5-m, 1.0-m and 2.0-m above today's (2005) sea levels in the year 2100. These correspond to rates of 0.5m per 95 years, 1.0m per 95 years and 2.0m per 95 years, respectively. For the sake of simplicity, sea-level rise for the time steps between 2005 and 2100 is a linear interpolation.

Rising sea levels are assumed to have four damage cost components: (1) the value of dryland lost, (2) the value of wetland lost, (3) the cost of protection (with dikes) against rising sea levels and (4) the costs of displaced people that are forced to leave their original place of settlement due to dryland loss (Figure 3). *FUND* determines the optimum amount of protection (in benefit-cost terms) based on the socio-economic

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[11] In this paper, all the costs of sea-level rise are considered damages, including protection costs.

[12] 1995 was chosen as the base year for the control scenario purely on technical modeling grounds. FUND internally uses that year as its base year. Since the objective for the control scenario is not to produce a prediction what would happen without economic growth from now on (which in itself would be a silly endeavor), but rather to get an idea of what role economic growth plays, and since socio-economic parameters relevant to FUND have changed little in the time between 1995 to 2005 compared to what they change over the model period, this choice seems warranted.

situation, the expected damage of sea-level rise if no protection existed, and the necessary protection costs. Unprotected dryland is assumed to be lost, while wetland loss is also influenced by the amount of protection: more protection leads to greater wetland loss via coastal squeeze. Wetland loss due to coastal squeeze is counted as a cost of protection. The number of people displaced is a linear function of dryland loss.

The area of dryland loss is assumed to be a linear function of sea-level rise and protection level. The value of lost dryland is assumed to be linear in income density ($/km^2).

Wetland value is assumed to be logistic in per capita income, with a correction for wetland scarcity, and a cap:

$$V_{t,i} = \alpha \frac{y_{t,i} / 30{,}000}{1 + y_{t,i} / 30{,}000} \min\left(2, 1 - \sigma + \sigma \frac{L_{\max,i}}{L_{\max,i} - L_{t,i}} \right) \qquad (2.1)$$

where $V_{t,i}$ is wetland value at time t in country i; y is per capita income; L is the wetland lost to date; $L_{\max}$ is a parameter, given the maximum amount of wetland that can be lost to sea-level rise; α is a parameter such that the average value for the OECD is $5 million per square kilometre; and $\sigma = 0.05$ is a parameter.

The number of people forced to migrate from a country due to sea-level rise is a function of the average population density in the country and the area of dry land lost. The cost of people displaced is three times average per capita income.

Following the method of Nicholls *et al.* (2006b), average annual protection costs are assumed to be a bilinear function of the rate of sea-level rise as well as the proportion of the coast that is protected. This is a first step to overcoming the linear assumptions of the *FUND* model. The costs increase by an order of magnitude if sea-level rise is faster than 1 cm per year (i.e., protection costs are much higher for the 1-m and 2-m rise scenarios than the 0.5-m scenarios). The level of protection is based on a cost-benefit analysis that compares the costs of protection (the actual construction of the protection and the value of the wetland lost due to the protection) with the benefits, i.e. the avoided dry land loss.

The level of protection is based on a cost-benefit analysis. The level of protection is modeled as the share of the coastline which is protected. The cost-benefit equation is

$$L_{t,i} = \max\left\{0, 1 - \frac{1}{2}\left(\frac{PC_{t,i} + WL_{t,i}}{DL_{t,i}}\right)\right\} \tag{2.2}$$

where L is the fraction of the coastline to be protected. PC is the net present value of the protection cost if the whole coast is protected, WL is the net present value of wetland lost if the whole coast would be protected and DL is the net present value of dryland lost if no protection would take place.

PC is calculated assuming annual protection costs are constant, which is justified for the following three reasons: Firstly, the coastal protection decision makers anticipate a linear sea level rise. Secondly, coastal protection entails large infrastructural works, which which have a life of decades. Thirdly, the considered costs are direct investments only, and technologies for coastal protection are mature. Throughout the analysis, a pure rate of time preference, ρ, of 1% per year is used. The actual discount rate lies thus 1% above the growth rate of per capita income of the economy, g. The net present costs of protection PC are

$$PC_{t,i} = \sum_{s=t}^{\infty}\left(\frac{1}{1+\rho+g_{t,i}}\right)^{s-t} PC_i^a = \frac{1+\rho+g_{t,i}}{\rho+g_{t,i}} PC_i^a \tag{2.3}$$

where PC^a is the average annual costs of protection, which is constant.

WL is the net present value of the wetlands lost due to full coastal protection. Land values are assumed to rise at the same pace as per capita income growth. The amount of wetland lost per year is assumed to be constant. The net present costs of wetland loss WL follow from

$$WL_{t,i} = \sum_{s=t}^{\infty} \left(\frac{1+g_{t,i}}{1+\rho+g_{t,i}} \right)^{s-t} W_{t,i} = \frac{1+\rho+g_{t,i}}{\rho} W_{t,i} \tag{2.4}$$

where $WL_{t,i}$ denotes the value of wetland loss in the year and country the decision is made (see above).

DL denotes the net present value of the dryland lost if no protection takes place. Land values are assumed to rise at the same pace as per capita income growth. The amount of dryland lost per year is assumed to be constant. The net present costs of dryland loss DL are

$$DL_{t,i} = \sum_{s=t}^{\infty} \left(\frac{1+g_{t,i}}{1+\rho+g_{t,i}} \right)^{s-t} D_{t,i} = \frac{1+\rho+g_{t,i}}{\rho} D_{t,i} \tag{2.5}$$

where $DL_{t,i}$ is the value of dryland loss in the year and country the decision is made (see above).

For a more complete discussion of sea-level rise in the context of climate change, see Nicholls and Tol (2006) and Nicholls *et al.*(2006c).

The damage costs presented in this paper are the total damage costs for the period 2005-2100. Two different welfare functions are used to aggregate damages across time and space, depending on whether equity weights are employed or not. Without equity weights, monetary damages for every country are calculated, then discounted per country using a social discount rate with a pure rate of time preference of 1% and then those totals for every country are summed as follows:

$$D = \sum_{i}^{N} \sum_{t=0}^{T} D_{t,i} \left(1 + \rho + \varepsilon g_{t,i}\right)^{-t} \tag{2.6}$$

where D is total damage from sea-level rise, $D_{t,i}$ is damage in country i at time t, $g_{t,i}$ is the average per capita growth rate of consumption in country i from the start of the time period to time t, N is the number of countries and T is the end of the time period under consideration. ε is a parameter for inequality aversion (set to 1 for this paper) and ρ is the pure rate of time preference (set to 1% for this paper).

Equity weighting follows the reasoning outlined in Anthoff *et al.* (2009). When equity weights are employed, the equation for the aggregation of damages is derived explicitly from a utilitarian social-welfare function as follows:

$$W = W\left(C_{1,1}, \ldots, C_{N,T}\right) = \sum_{i}^{N} \sum_{t=0}^{T} U\left(C_{t,i}\right) P_{t,i} \left(1 + \rho\right)^{-t} \tag{2.7}$$

Where W is welfare, $C_{t,i}$ is average per capita income in country i at time t, $P_{t,i}$ is population and $U\left(.\right)$ is the utility function. For this paper the usual logarithmic utility function $U\left(c\right) = \ln c$ is employed. Such a utility function reflects the intuition that a dollar is worth more to a poor person than to a rich person, i.e. it has a declining marginal utility of consumption.

As a linear approximation, damages from sea-level rise are multiplied with the marginal welfare change of consumption of the country they occur to before they are summed:

$$\sum_{i}^{N} \sum_{t=0}^{T} D_{t,i} \frac{\partial W}{\partial C_{t,i}} \approx \sum_{i}^{N} \sum_{t=0}^{T} D_{t,i} \frac{1}{C_{t,i}} \left(1 + \rho\right)^{-t} \tag{2.8}$$

This gives the welfare loss from sea-level rise in welfare units. In order to convert back to monetary units, one has to multiply the results with the marginal. We follow Fankhauser *et al.* (1997) and normalise with world average per capita income. Conceptually this is just a linear transformation of the welfare function, i.e. the optimal solution of the welfare function is not altered by such an operation. The damage calculated such is

$$D_{ew} = \frac{1}{U'\left(\bar{C}_0\right)} \sum_{i}^{N} \sum_{t=0}^{T} D_{t,i} \frac{1}{C_{t,i}} (1+\rho)^{-t} = \sum_{i}^{N} \frac{\bar{C}_0}{C_{0,i}} \sum_{t=0}^{T} D_{t,i} \frac{C_{0,i}}{C_{t,i}} (1+\rho)^{-t} \tag{2.9}$$

where D_{ew} is the equity-weighted damage and $\bar{C}_0$ is world average per capita income at time 0, in our case in the year 2005. Equation (2.9) can be approximated as

$$D_{ew} = \sum_{i}^{N} \frac{\bar{C}_0}{C_{0,i}} \sum_{t=0}^{T} D_{t,i} \left(1+g_{t,i}+\rho\right)^{-t} \tag{2.10}$$

where $g_{t,i}$ is the average growth rate of per capita income between year 0 and year t. The right most term is thus the neoclassical discount rate of money. The term $\bar{C}_0 / C_{0,i}$ is the equity weight for every country. It can be seen that countries with higher average per capita income than the world average will receive a lower weight and countries with lower per capita income a higher weight, following the logic of equity weighting.

3. Results

Results from the model runs are analyzed along the following dimensions: (1) global damage costs by scenario; (2) the damage cost components; (3) regional impacts; (4) impacts without protection; and (5) equity-weighted results.

3.1. Global damage costs by socio-economic and sea-level rise scenarios

While the choice of socio-economic scenario has an influence on the global damage costs from sea-level rise for the time period analysed for this study, the damage costs vary more over the choice of sea-level rise scenario (Figure 4).

The damage costs for a 1m rise are between 4.8 and 5.2 times as high as the damage costs for the 0.5m sea-level rise, depending on the scenario (except for the 1995 control scenario, where the increase in costs is only 4 times). The increase in costs from 1m to 2m is only 2.0 times the damage cost of the 1m sea-level rise scenario. The assumed bilinear protection costs between the scenario with 0.5m rise and 1m rise explains these different increases in damage costs with respect to sea-level rise. While the increase in damage costs from the 1m to 2m sea-level rise scenario is almost linear (i.e., a factor of two) over all socio-economic scenarios, the choice of socio-economic scenario has a more significant role to play in the step between the 0.5m and 1m sea-level rise scenario. In all cases (except the 1995 control scenario) the increase of the total damage is lower than the assumed tenfold increase in protection costs. The overall difference between the SRES scenarios is very small.

While the damages from sea-level rise are substantial, they are small compared to the total economy, provided that coastal protection is built. This also holds for the 2m scenario. Note that the global total of Figure 4 hides considerable differences between countries. This issue is discussed in more detail below.

In order to understand the reasons for the differences between the scenarios, a closer look at the four damage cost components is needed.

3.2. Disaggregating damage costs by socio-economic and sea-level rise scenarios

Figure 5 shows the damage cost components as calculated by *FUND* and their share of the total damage cost for the 0.5m sea-level rise scenario under the assumption that dikes are built, i.e. that people attempt to protect against rising sea levels following current practise against coastal flooding in much of the world (e.g., East Asia and Europe). The results changes dramatically when it is assumed that people do not protect, a scenario that is analysed in a later section.

Ignoring the control scenario for a moment, three conclusions can be drawn. First, damage costs from dryland loss and migration are a fraction of the costs of protection in every scenario (dryland costs being about one fifth and migration being one tenth of protection costs). Protection costs on the other hand are the most important component for every scenario. This underlines the significance of protection (and adaptation in general). Second, protection costs are less affected by the choice of socio-economic scenario than dryland loss and migration costs. The biggest difference between scenarios for dryland loss and migration costs is a factor of 1.8, for protection costs it is 1.5. Damage costs from wetland loss are even less sensitive to the choice of scenario, with a maximum difference of factor 1.3. Wetland costs are the second most significant damage component in all scenarios. Third, for every cost component except wetland loss, the highest cost scenario is A2, followed by B2, B1 and A1. For wetland costs, the order is reversed, because wetland cost differences between scenarios are mainly driven by the differences in valuation between socio-economic scenarios: higher per capita income place a higher value on wetland loss and therefore produce higher wetland costs. With the other damage costs, higher per capita income mainly leads to more protection, which explains why the effect of higher per capita income is positive in those cases.

Figure 6 presents the disaggregation into damage components for the 1m sea-level rise scenario. Wetland costs are the only ones that react roughly linearly to the doubling of sea-level rise, they are around two times as high as for the 0.5m sea-level rise in all scenarios. Protection costs increase between 4.2 to 6.6 times compared to the lower sea-level rise scenario, while dryland loss and migration costs increase by an order of magnitude (factors between 10.7 and 11.4) compared to the lower sea-level rise scenario. Due to the increase in adaptation costs (i.e. the bilinear nature of protection costs), adaptation is significantly more costly in the 1m sea-level rise scenario and the cost-benefit analysis finds that the optimal length of coast to protect is lower than in the 0.5m scenario (e.g. it is about 40% lower averaged over time for the A1 scenario, 46% lower for A2, 42% lower for B1 and 45% lower for B2), which leads to a situation where total damage is more evenly divided between the four damage cost components.

While the step from 0.5m to 1m sea-level rise changed the distribution of costs between the four components significantly, the step to the 2m scenario has no such surprises. As can be seen in Figure 7, all costs roughly double compared to the 1m scenario. This is not surprising, since the model does not have a change in cost assumptions build into this step.

3.3. Regional Distribution of Damage Costs

Sea-level rise damages are not evenly distributed over the world. Figure 8 compares the two scenarios that show the largest difference in total damage cost due to sea-level rise across all regions. While the distribution of damage costs is not the same for the two scenarios, the same countries bear the majority of damage costs in both scenarios. This should not be a surprise as relative exposure to sea-level rise is the main variable that drives relative damages and for example, East Asia and South Asia have large, densely-populated coastal lowlands irrespective of the scenario considered.

The three regions that are widely thought to be the most vulnerable to sea-level rise, i.e. the Pacific, Indian Ocean and Caribbean islands bear only a tiny share of the total global damage. At the same time these damage costs for the small island states are enormous in relation to the size of their economy (Nicholls and Tol, 2006). Together with deltaic areas, they will find it hardest to raise the finances necessary to implement protection.

3.4. Protection Analysis

The level of protection, that is the length of coastline that is protected using dikes, is normally determined endogenously by a cost-benefit analysis in *FUND*. Another set of runs where no protection against sea-level rise is allowed were also conducted (and, for the first time, reported in a *FUND* analysis). Comparing these two sets of runs with and without protection is insightful for three reasons. First, it shows the huge benefits of protection to sea-level rise in terms of the damages avoided. Second, there might be countries that do not have the means to protect their coastline up to the optimal level that would follow from the cost-benefit analysis. This is especially relevant for large rises in sea level as considered in this analysis (Nicholls *et al.*, 2006b). Third, all too often, sea level rise impacts are presented without coastal protection. This allows for a comparison between such studies and *FUND*.

Figure 9 clearly shows the importance of protection, in particular for the 0.5m sea-level rise scenario. Total damages are between 3.4 and 3.7 times higher when no protection is build for that scenario, depending on the socio-economic scenario. For 1m and 2m sea-level rise the damages in the no-protection scenario are only around 1.4 times as high compared to a protection scenario. Since protection costs are assumed to be ten times higher than in the 0.5m case, this is hardly surprising. A look at the control Scenario C1995 is particularly interesting in this case. In that scenario, population and economic indicators are held constant at 1995 levels, while sea-level rise is assumed to take place.

Especially in the two scenarios with high protection costs (1m and 2m) the importance of the significant economic development assumed in all the SRES scenarios can be seen: In both cases, effective protection is hardly possible under the assumption of today’s socio-economic situation. The lesson to be learned from this is twofold: (1) protection can significantly lower total damages, but (2) only when economic growth enables this sometimes costly investment in protection.

Some of the results for no protection scenarios are peculiar at first sight. For example, the Maldives are estimated to be completely inundated in 2085 for the 1-m rise scenario, which raises the value of its dryland for the time step 2080-4 to very large values. After 2085, the value is zero. This cannot be regarded as a satisfactory valuation from an economic point of view: Such non-marginal damages are outside of the realm of economic valuation. The Maldives disappear much earlier (2050) for the 2m sea-level rise scenarios without protection, so that the costs of the 2m scenario fall below that of the 1m between 2050 and 2085.

Figure 10 displays the benefit gained from protection for specific countries. It shows that protection is a lot more important for some countries than for others.

3.5. Equity weighting

Figure 11 compares damages from sea level that are equity weighted with estimates that are not weighted – or rather, that are weighted with the particular assumption that a dollar to a poor woman equals a dollar to a rich woman. Damages are between 2.9 and 3.2 times higher when equity weights are employed. The equity-weighted results give an idea of how large the welfare loss due to sea-level rise is, when the distribution of income of those damaged is taken into consideration. Equity-weighing makes the smallest difference in the B1 scenario, which assumes rapid convergence of per capita income, and the largest difference in the A2 scenario for which income convergence is slower. However, the effect of equity weighing is much smaller than the difference in 2100 income distributions would suggest. This is because, in the first part of the scenario, the income distribution is determined by the 2000 income distribution, which is equal between the scenarios.

Figure 12 disaggregates the results for some example countries. Two forces drive the results. Damages in high income countries, like the United States, are scaled down by a significant proportion, in this case the damage estimates for the United States without equity weights are six times higher than with equity weights. For low income countries, the result of applying equity weights is just the opposite: Bangladesh's damage estimates for example are 12 times higher with equity weighting compared to unweighted monetary results. The application of equity weights therefore is not uniform on the whole world: They will increase damage estimates for countries that have a per capita income below world average and decrease damages for countries with per capita income above world average. Given that more impacts accrue in low income places, the overall effect of applying equity weights is to increase global damage estimates.

4. Discussion/Conclusions

This analysis with *FUND* suggests that if sea-level rise was up to 2-m per century, while the costs of sea-level rise increase due to greater damage and protection costs, an optimum response in a benefit-cost sense remains widespread protection of developed coastal areas, as identified in earlier analyses (Nicholls and Tol, 2006; Nicholls *et al.*, 2006b). This analysis also shows that the benefits of protection increase significantly with time due to the economic growth assumed in the SRES socio-economic scenarios. Due to the different assumptions about population and gross domestic product, the socio-economic scenarios are also important drivers of these costs. In terms of the four components of costs considered in *FUND*, protection dominates, with substantial costs from wetland loss under some scenarios. The regional distribution of costs shows a few regions experience most of the costs, especially South Asia, South America, North America, Europe, East Asia and Central America. Under a scenario of no protection, the costs of sea-level rise increase greatly due to land loss and population displacement: this scenario shows the significant benefits of the protection response in reducing the overall costs of sea-level rise.

While the *FUND* analysis suggests widespread protection, earlier analysis shows that the actual adaptation response to sea-level rise is more complex than the benefit-cost approach used in *FUND* (Tol and Fankhauser, 1998; Nicholls and Tol, 2006). Building on these views, there are several factors to consider. Firstly, the aggregated scale of analysis in *FUND* may overestimate the extent of protection as shown by more detailed multi-scale analyses of parts of the UK and Germany (Turner *et al.*, 1995; Sterr, 2007). It is also worth noting that retreat is now being considered more seriously, especially in parts of Europe (DEFRA, 2004; EUROSION, 2004; DEFRA, 2006; Rupp-Armstrong and Nicholls, 2007), driven by multiple goals including maintaining coastal wetlands. However, this is unlikely to change the qualitative conclusion that protection can be justified in more developed locations, even given a large rise in sea level. Secondly, the SRES socio-economic scenarios are quite optimistic about future economic growth: lower growth may lead to lower damages in monetary terms, but it will also reduce the capacity to protect as shown in these analyses. Strong growth underpins the investment necessary to protect. Thirdly, the benefit-cost approach implies perfect knowledge and a proactive approach to the protection, while historical experience shows most protection has been a reaction to actual or near disaster. Therefore, high rates of sea-level rise may lead to more frequent coastal disasters, even if the ultimate response is better protection.

Fourthly, even though it is economically rational to protect, there are questions of who pays and who benefits, and in some cases such as islands and deltas the diversion of investment from other uses could overwhelm the capacity of these societies to protect (cf. Fankhauser and Tol, 2005). As the benefit-costs ratios improves with time, it appears that near-term decisions on protection may have important consequences for the long-term direction of the adaptation response to sea-level rise. Fifthly, building on the fourth point, *FUND* assumes that the pattern of coastal development persists and attracts future development. However, major disasters such as New Orleans and Hurricane Katrina in 2005 could trigger coastal abandonment, and hence have a profound influence on society's future choices concerning coastal protection as the pattern of coastal occupancy might change radically. A cycle of decline in some coastal areas is not inconceivable, especially in future worlds where capital is highly mobile and collective action is weaker. As the issue of sea-level rise is so widely known, disinvestment from coastal areas may even be triggered without disasters: for example, small islands may be highly vulnerable if investors are cautious (cf. Barnett and Adger, 2003; Gibbons and Nicholls, 2006).

For these above reasons, protection may not be as widespread as suggested in this analysis, especially for the largest scenario of 2m/century. However, the *FUND* analysis shows that protection is more likely and rational than is widely assumed, even with a large rise in sea level. The common assumption of a widespread retreat from the shore is not inevitable and coastal societies will have more choice in their response to this issue than is often assumed.

While the no protection scenarios have damages that transcend the marginal valuation framework of economics and therefore have to be examined with care, it is also clear from this analysis that – under the assumption that protection is built – such non-marginal losses of land do not occur and calculation of damage costs is possible.

The equity-weighted results highlight how important it is to not only look at the absolute magnitude of damage but also who will be affected. The welfare loss of even small damages to poor societies can be enormous. There is no consensus within the economic literature that equity-weighted damages ought to be used when policy instruments like Pigouvian taxes are designed, and hence the results presented here should not be used without further investigation for policy design. But there is little question that as a measure of actual welfare loss happening, equity-weighted results are much more accurate than pure monetary damage estimates. The question of what to do about the discrepancy in severity of impacts to poor and rich people is an ethical one, but in calculating damage estimates these differences should be made explicit to not under- or overstate the true welfare loss that climate change might cause, as we have done with the equity-weighted results in this paper.

5. Acknowledgements

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6. Figures

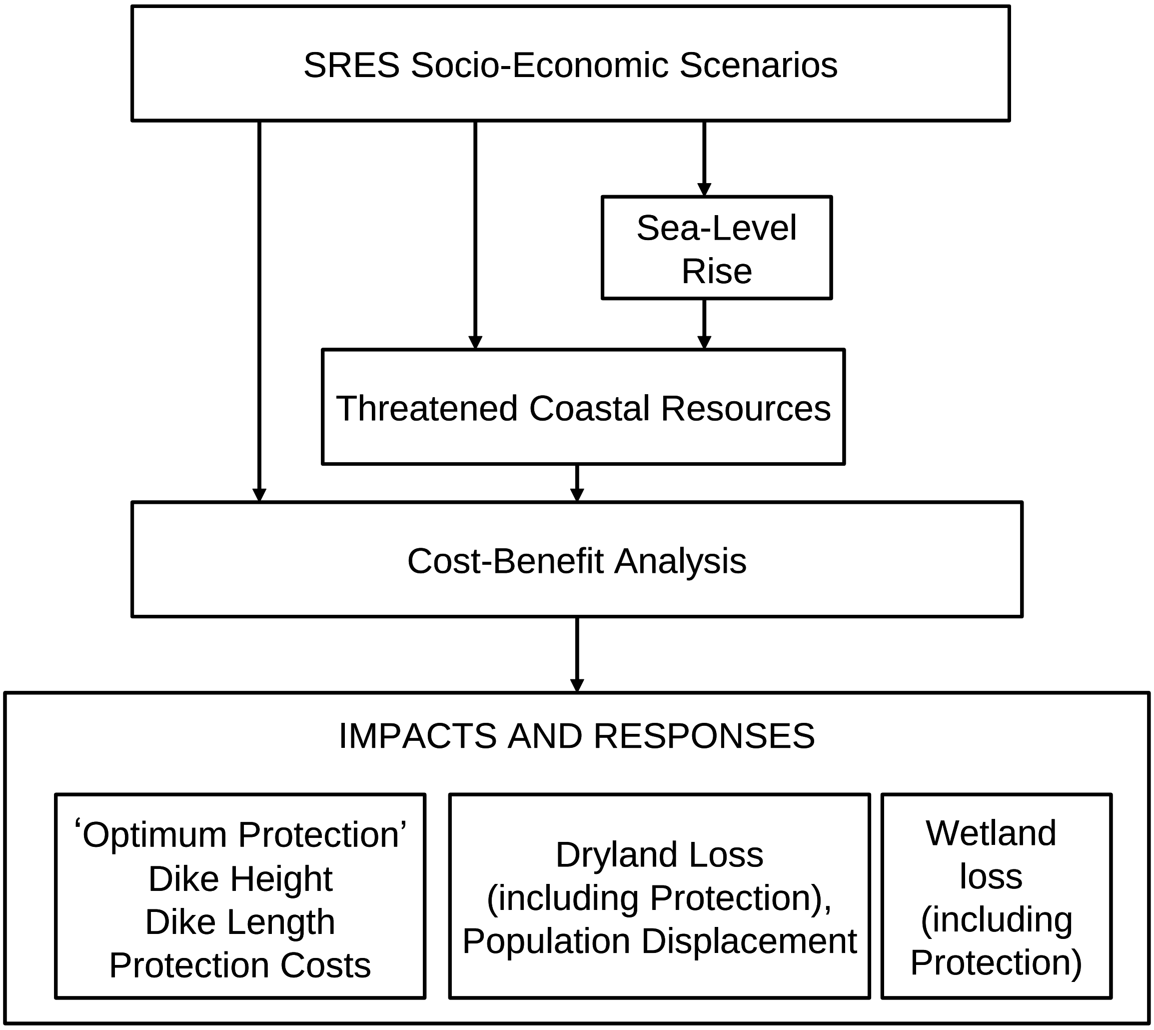

Figure 3: Flow chart summarising the operation of the *FUND* module for coastal areas

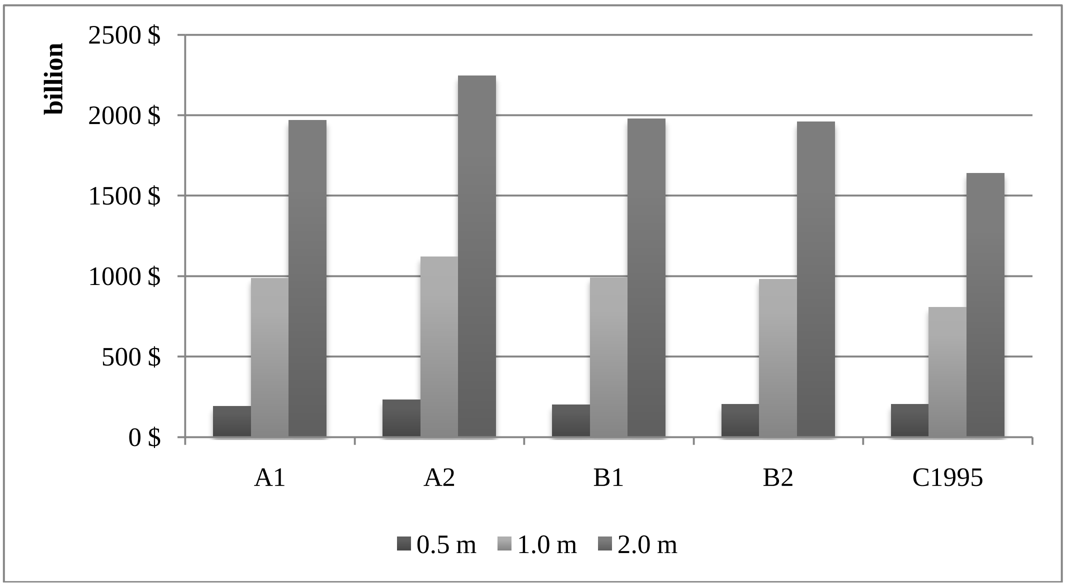

Figure 4: Total damage costs due to sea-level rise for 0.5m, 1m and 2m sea-level rise in 2100 and for the five socio-economic scenarios with protection

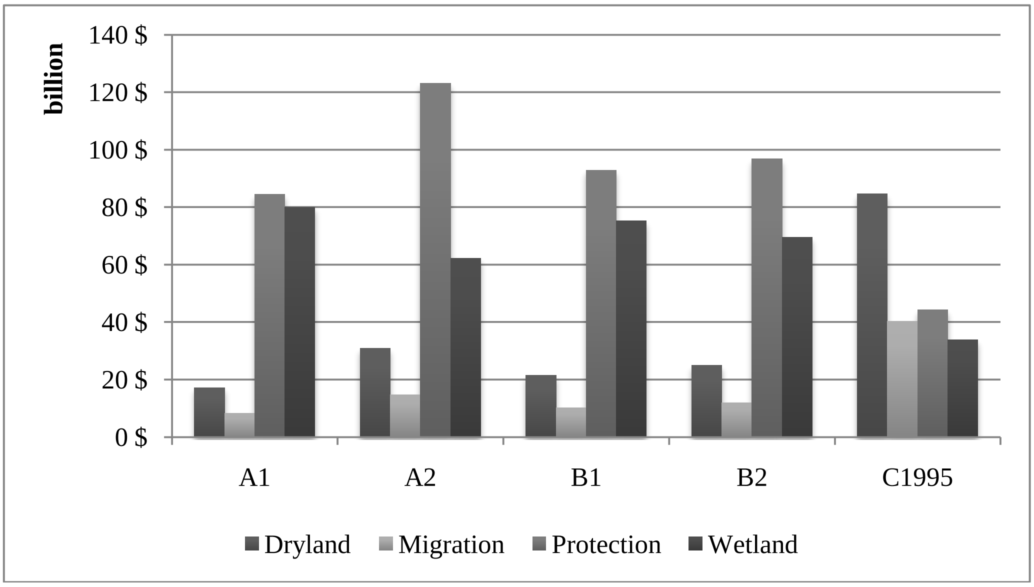

Figure 5: Damage costs of sea-level rise over the four damage cost components for 0.5m sea-level rise in 2100 with protection

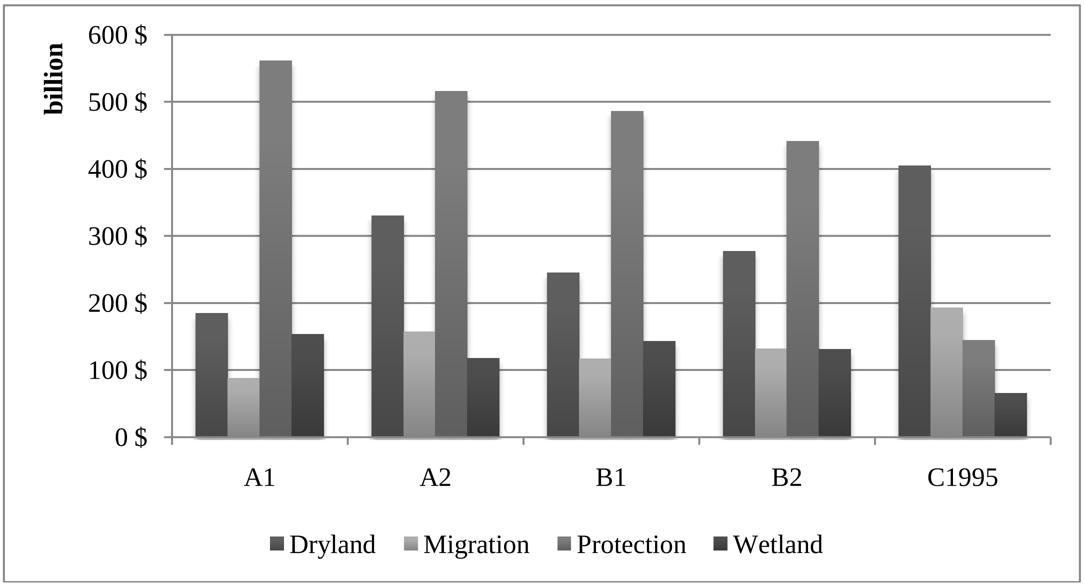

Figure 6: Damage costs of sea-level rise over the four damage cost components for 1m sea-level rise in 2100 with protection

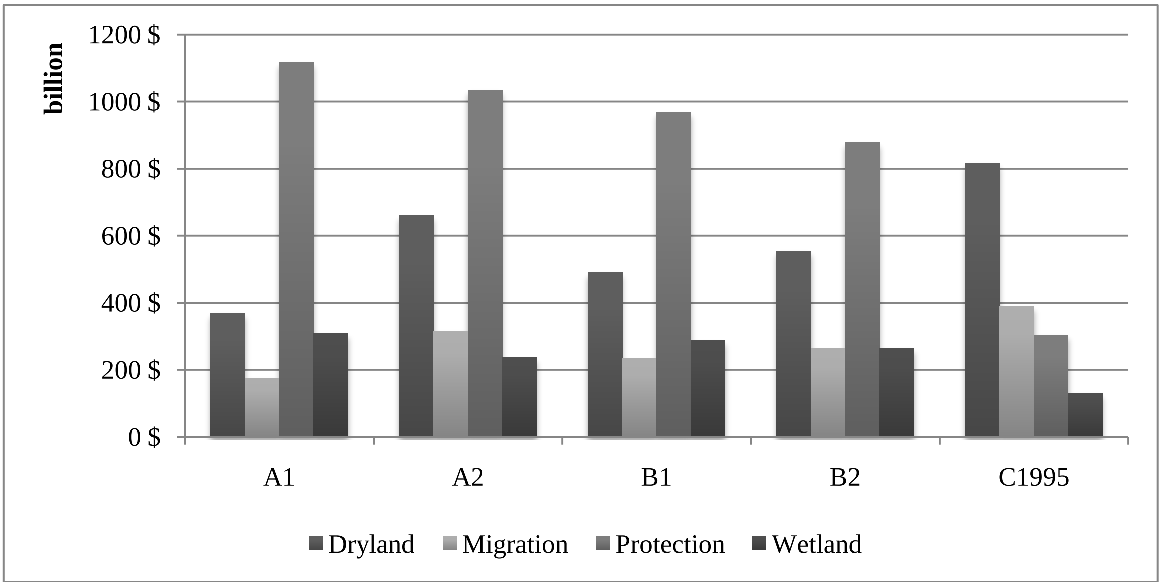

Figure 7: Damage costs of sea-level rise over the four damage cost components for 2m sea-level rise in 2100 with protection

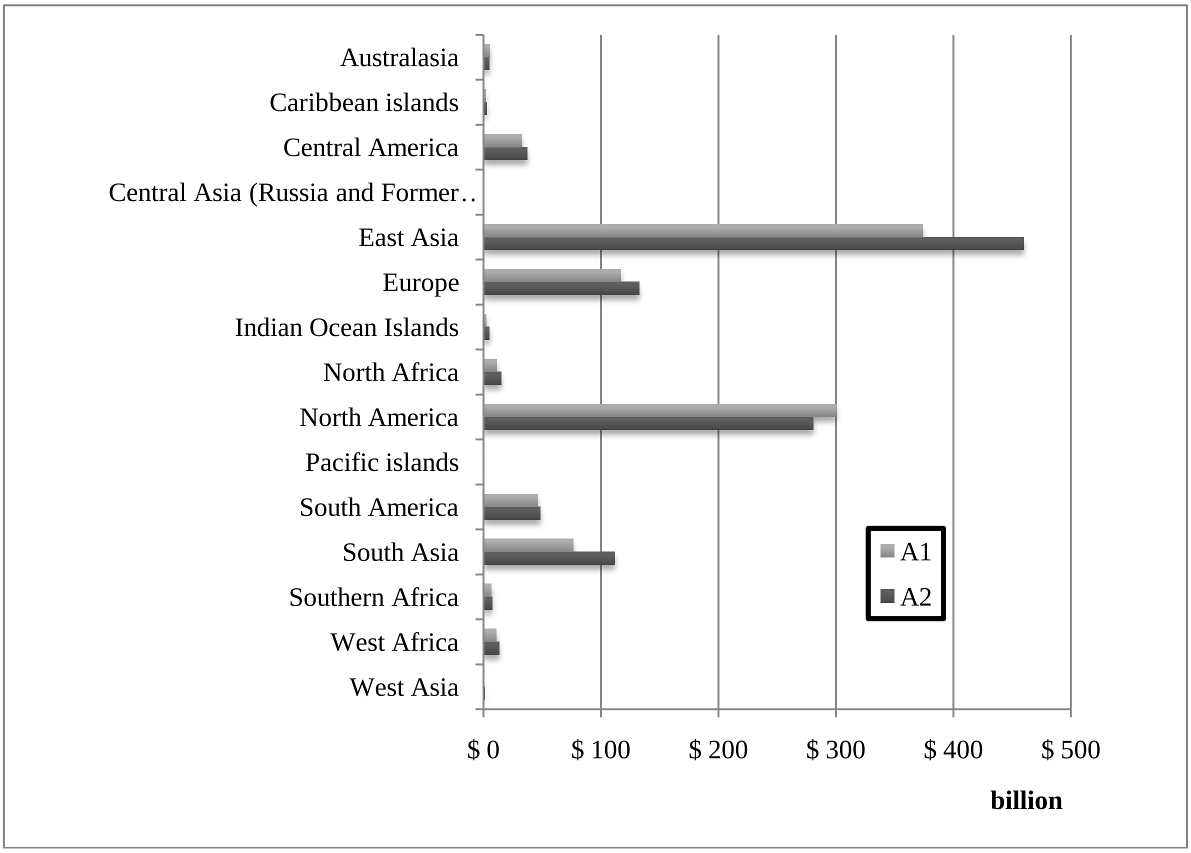

Figure 8: Damage costs of sea-level rise by region for 1m sea-level rise in 2100 for scenario A1 (highest costs) and A2 (lowest costs) with protection

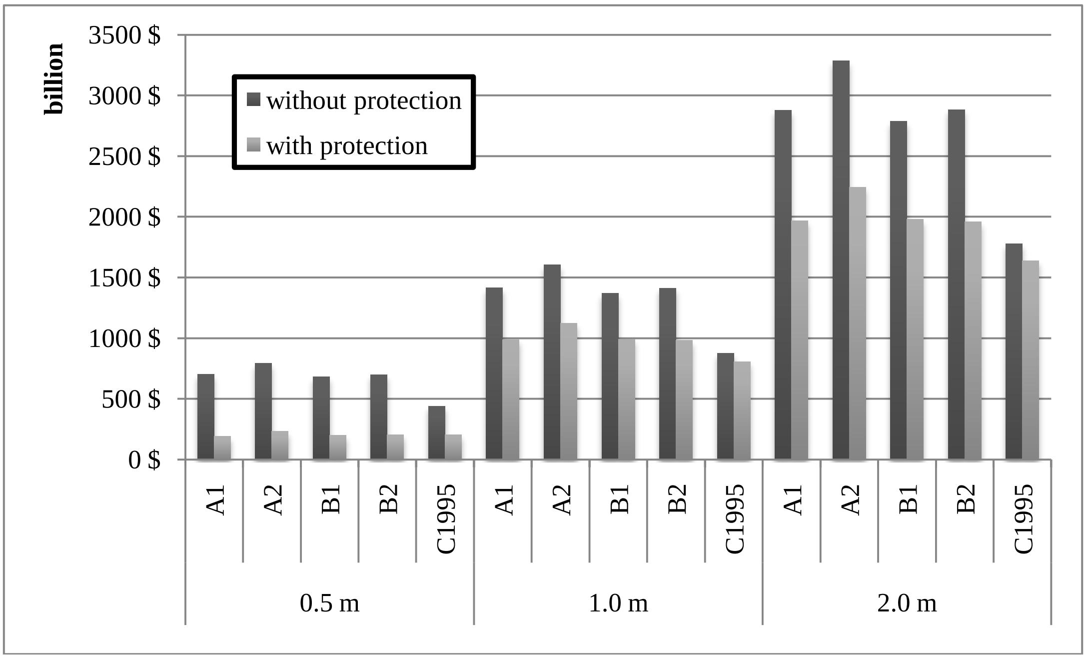

Figure 9: Damage costs due to sea-level rise with and without protection

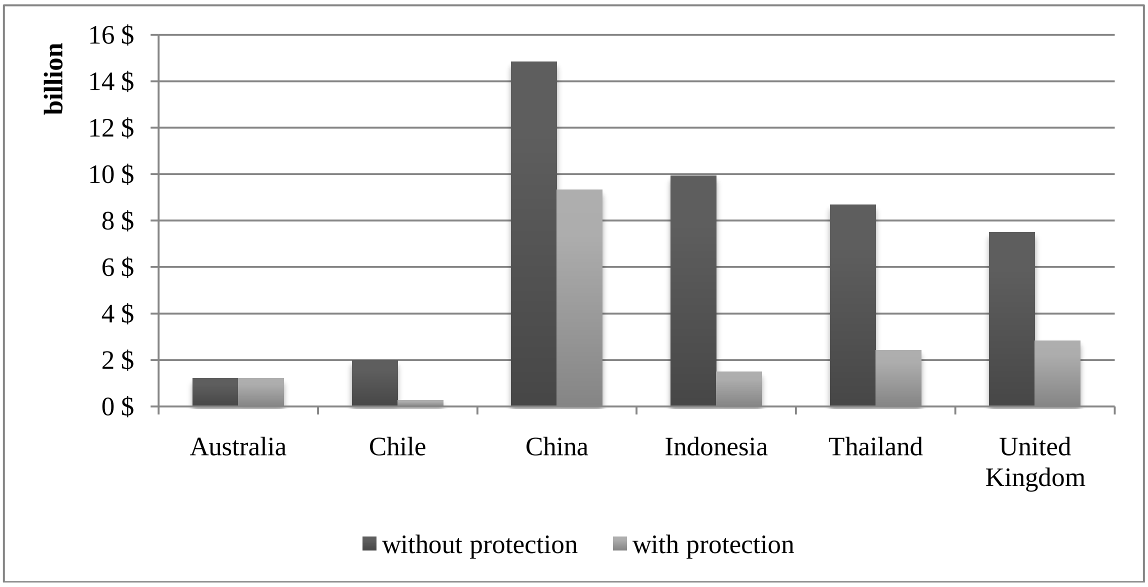

Figure 10: Damage costs of sea-level rise for 0.5m sea-level rise in 2100 for scenario A1 with and without protection

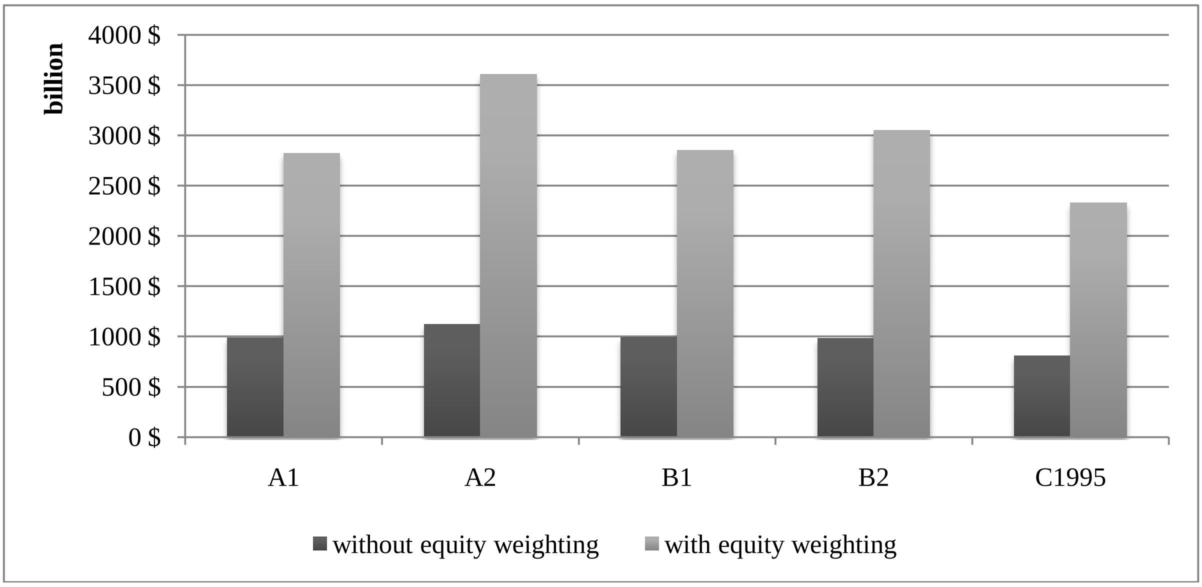

Figure 11: Equity-weighted damage costs of sea-level rise for 1m sea-level rise in 2100 with protection

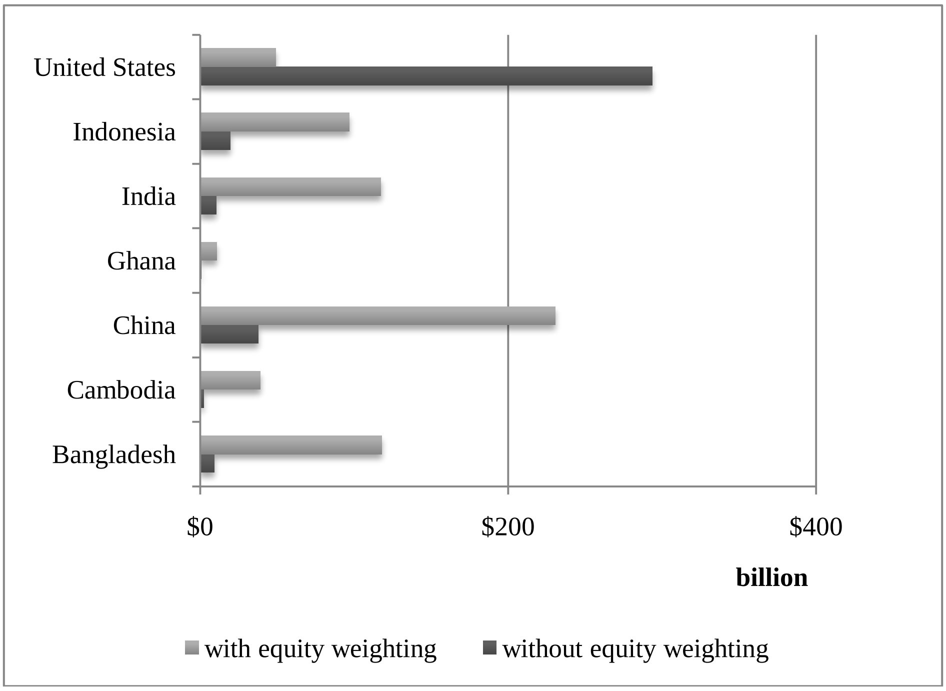

Figure 12: Damage costs of sea-level rise for 1m sea-level rise in 2100 with protection for scenario B1

III Risk Aversion, Time Preference, and the Social Cost of Carbon

1. Introduction

The social cost of carbon (the SCC) estimates the discounted value of the damage associated with climate change impacts that would be avoided by reducing carbon emissions by one tonne. It is a useful measure for assessing the benefits of climate policy at any point in time. It is generally thought to increase over time, and textbook economics would recommend that carbon emissions be taxed by a price set equal to the SCC. The *Stern Review* (Stern, 2007; Stern and C.Taylor, 2007; Stern, 2008) reported a SCC in excess of $300/tC in the absence of any climate policy – an estimate that lies well above the upper bound of $50/tC that was found in an extensive literature survey and meta-analysis (Tol, 2005c). Many analysts have attributed this high estimate to the very low rate of pure time preference adopted by the *Stern* author team (Arrow, 2007; Jensen and Webster, 2007; Nordhaus, 2007a; Mendelsohn, 2008; Weyant, 2008).

Others (Dasgupta, 2007; Weitzman, 2007) have argued that the *Stern Review* also included unusual assumptions about risk aversion. We respond to this observation by exploring the relative sensitivity of the SCC to both the pure rate of time preference *and* the rate of risk aversion. Our results support the hypothesis that the assumed rate of risk aversion is at least as important as the assumed rate of time preference in determining the social cost of carbon even though our analysis reveals an enormous range of estimates. Some are negative (that is, showing social benefits), but our positive estimates span *six* orders of magnitude on the positive side depending on both the pure rate of time preference and a standard measure of risk aversion.

Philosophers would likely confront this range by choosing a particular estimate based on what they deemed to be appropriate reflections of both parameters (Broome, 1992; Lumer, 2002; Ott, 2003; Beckerman and Hepburn, 2007). This approach was adopted in the *Stern Review*, but here we take a different tact. Instead of imposing our own normative values on the selection of a single SCC estimate, we look at the behaviours of democratically elected governments to infer distributions of the rates of risk aversion and pure time preference that are actually used in practice. We use the resulting probability density to constrain the estimates of the SCC and compute its expected value. Perhaps surprisingly, the *expected* social cost of carbon turns out to be reasonably close to the value reported in the *Stern Review*.

2. Time preference and risk aversion

To be sure, climate change is a long-term problem. This is why the pure rate of time preference is so important. Greenhouse gas emission reduction over the near-term would mitigate future damages, but they would do little to alter the present climate and/or the present rate of change in climate impacts. The costs of emission abatement must therefore be justified by the benefits of avoided impacts in the future. It follows that any statement about the desirability of climate policy necessarily contains a value judgement about the importance of future gains relative to present sacrifices. The discount rate employed in benefit and cost calculations over time can be thought of as the opportunity cost of investment, but it can also be seen as the relative value of consumption over time. The two are equivalent if the economy is in a dynamic equilibrium; and this equivalence means that time preference is not alone in playing a critical role in determining any SCC estimate.

To explain why, we note that people discount future consumption for two reasons. Firstly, they expect to become richer in the future, and so they care less about an additional dollar then than they do about an additional dollar today. Secondly, they are impatient. We also recall the so-called Ramsey discount rate r that was designed to sustain optimal saving over time (Ramsey, 1928). It consists of three components:

$$r = \rho + \eta g \tag{3.1}$$

where ρ is the rate of pure time preference, g is the growth rate of per capita consumption, and η is the elasticity of marginal utility of consumption.

Both motives of personal discounting can be detected in the Ramsey rule for dynamic optimality by considering the rate at which people would be willing to sacrifice a dollar of current consumption for additional consumption in the future (see the appendix for brief details). The pure rate of time preference is defined implicitly by the marginal rate of substitution between present and future consumption *under the condition that consumption levels in both periods are equal* (so that $g = 0$). In words, the definition of the pure rate of time preference calibrates inter-temporal trading so that individuals who anticipate constant levels of consumption from one period to the next would be willing to sacrifice one dollar of present consumption if he or she would be compensated with $\$(1+\rho)$ of *extra consumption* in the next period. Higher values of ρ therefore reflect higher degrees of impatience because higher compensation would be required to compensate exactly for the loss of $1 in current consumption.

Consumption levels need not be constant over time, and the second term in (3.1) works the implication of this fact into this trading calculus. While g measures the growth rate of material consumption, ηg reflects the growth rate of happiness measured in terms of underlying personal utility. If consumption were to climb by $g \cdot 100\%$ from one period to the next, then each future dollar would be worth $g \cdot \eta \cdot 100\%$ less (assuming no impatience so $\rho \equiv 0$). It follows that our individual would consider sacrificing one dollar in current consumption only if he or she could be compensated by an amount equal to $\$(1+g\eta)$ in the future.

In contemplating welfare-based equivalence of consumption over time, it is now clear that this trading-based accommodation of growing consumption works in exactly the same way as the pure rate of time preference in defining the rate at which the future needs to be discounted. Put another way, if one considered empirical estimates for both ρ and η that range from zero to three,[13] then both parameters should play equally important roles in determining the appropriate discount rate. Perhaps because "impatience" is intuitively clear while the role of the "elasticity of marginal utility with respect to consumption" is not, the debate over how the SCC could be so high has focused undue attention over ρ almost to the exclusion of η.

This need not be the case; indeed, the utility-based association with the Ramsey discounting rule shows that this should not be the case. Climate change is not only a long-term problem; it is also a very uncertain problem and a problem that differentially affects people with widely different incomes. The rate of pure time preference ρ speaks only to the first characteristic of the climate policy problem – the time scale issue. The elasticity of marginal utility with respect to consumption, the parameter η, speaks to all three characteristics. It is, first of all, a measure of the curvature of the utility function, which maps material consumption to happiness. It indicates precisely the degree to

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[13] Strictly, ρ ranges between 0 and 3 per cent per year, while η, as a ratio of percentage changes, is unitless.

which an additional dollar brings less joy as income increases. Moreover, the parameter η can also be interpreted as a measure of how one evaluates a gain of a dollar for rich person relative to a gain of a dollar for a poor person. This is why η is occasionally referred to as the parameter of inequity aversion. In its simplest form, equity-weighted impacts are based on the following equation

$$D_w = \sum_c \left(\frac{y_w}{y_c} \right)^\eta D_c \tag{3.2}$$

where D_w is the globally aggregate impact, D_c is the monetary impact of climate change in country c, y_w is globally average per capita income, and y_c is per capita income in country c. If $\eta = 0$, the global impact is the unweighted sum of national impacts but if $\eta > 0$, the impact of climate change on poor countries (relative to the world average) receive a greater weight than impacts on rich countries.

At the same time, curvature in the utility function can be viewed as a reflection of risk aversion. In this role, η explains why risk-averse people buy insurance; they are willing to pay a premium that is proportional in first order approximation to the parameter η to eliminate variability in outcomes because doing so increases their expected utility.[14] Note that η also affects the value one attaches to the impacts of climate change, but we abstract from this in our discussion.

3. Estimating the social cost of carbon

Armed with these insights from the first principles of microeconomic theory, we used the integrated assessment model *FUND* to test the hypothesis that η could actually turn

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[14] The risk premium is, by definition, the difference between the expected outcome of a risky situation and the "certainty equivalent" outcome – the guaranteed outcome that would sustain a level of utility equal to expected utility across the full range of possible outcomes. For a risk averse individual, the certainty equivalent is always less than the mean because losses relative to the mean reduce utility more than equal gains above the mean.

out to be more important in determining the SCC than ρ. In many ways, *FUND* is a standard integrated assessment model (Tol, 1997; 1999; Guo *et al.*, 2006; Tol, 2006b). It has simple representations of the demography, economy, energy, emissions, and emission reduction policies for 16 regions. It has simple representations of the cycles of greenhouse gases, radiative forcing, climate, and sea level rise. In other ways, though, *FUND* is unique. It is alone in the detail of its representation of the impacts of climate change. Impacts on agriculture, forestry, water use, energy use, the coastal zone, hurricanes, ecosystems, and health are all modelled separately – both in "physical" units and their monetary value (Tol, 2002a; b). Moreover, *FUND* allows vulnerability to climate change impacts to be an explicit function of the level and rate of regional development (Tol, 2005a; Tol *et al.*, 2007). See the SOM for more details on the model.

We estimated the SCC cost of carbon by computing the total, monetised impact of climate change along a business as usual path and along a path with slightly higher emissions between 2005 and 2014.[15] Differences in impacts were calculated, discounted back to the current year, and normalised by the difference in emissions.[16] The SCC is thereby expressed in dollars per tonne of carbon at a point in time – the standard measure of how much future damage would be avoided if today's emissions were reduced by one tonne. More details on *FUND* are provided in the SOM.[17]

We estimated the SCC for a range of values for ρ and η, but we report our results in stages to highlight the triple role of η. We first consider results for cases in which η affected only the discount rate. That is, we pretended that uncertainty about climate change had been resolved and that income differences between countries were

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[15] The social cost of carbon of emissions in future or past periods is beyond the scope of this paper.

[16] We abstained from levelizing the incremental impacts within the period 2005-14 because the numerical effect of this correction is minimal while it is hard to explain.

[17] Full documentation of the *FUND* model, including the assumptions in the Monte Carlo analysis, is available at http://www.fund-model.org.

irrelevant. The second set of results put uncertainty back into the problem; the reported expected values of the SCC are the product of a Monte Carlo analysis of all the uncertain parameters in the *FUND* model. A third batch of results were drawn from the original world of perfect climate certainty, but social cost estimates applied equity weighting to the regional impacts of climate change. Finally, we report expected social cost estimates for cases in which both uncertainty and equity-weighing play a role – the cases where η plays its theoretically appropriate triple role.[18]

Based on first principles, we expected that the SCC would react as follows to parameter changes. The higher the pure rate of time preference, ρ, the less one cares about the future. Damages from climate change, as they occur over time, are therefore less of problem and the SCC should fall. Similarly, the higher risk aversion, η, the higher the discount rate in a scenario of growing per capita income and so the SCC should again fall. However, higher aversion to risk means that one is more concerned about uncertainty and particularly concerned about negative surprises; as a result, the SCC should rise with higher values of η. Furthermore, the higher aversion to risk also corresponds to greater concern about income distribution; if one assumes that climate change disproportionally affects the poor, then the SCC should again rise. Based on first principles, therefore, we can predict the effect of changes in time preference ρ, but the effect of risk aversion η is ambiguous.

4. Results

Figure 13 shows the SCC cost of carbon for the four cases, varying both ρ and η while Figure 14 portrays various cross-sections. If we ignore concerns about equity and

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[18] Note that we assume that the scenarios of population, economy, energy and emissions are independent of ρ and η. Implicitly, we thus assume that changes in ρ and η are exactly offset by changes in the scenario of technological change.

uncertainty (Panel A), the SCC roughly decreases with the discount rate. For $\rho = \eta = 0$, SCC = \$1,939/tC; it falls to SCC = \$10/tC for $\rho = \eta = 1$ and to SCC = -\$5/tC for $\rho = \eta = 2$. The sign changes because climate change is initially beneficial to the world economy. For $\rho = \eta = 3$, however, SCC climbs back to -\$4/tC because the discount rate is so high that it even discounts initial benefits significantly.

The profiles change when uncertainty is taken into account. Panel B shows that a maximum is still observed where $\rho = \eta = 0$ and the expected social cost of carbon, denoted E(SCC) equals \$2,036/tC. This is a local maximum, though. E(SCC) falls monotonically as ρ increases. E(SCC) also falls initially as η (and thus the discount rate) increases, but it starts rising as a greater η values puts more emphasis on the tail of the distribution. For $\rho = 0$ and $\eta = 3$, E(SCC) = \$152,155/tC. E(SCC) is negative only for $\rho \geq 2.7\%$ and $1.10 \leq \eta \leq 2.25$.

Panel C shows that the results are different again with equity weighing (Azar and Sterner, 1996; Fankhauser *et al.*, 1997) and no uncertainty. For $\rho = \eta = 0$, SCC = \$1,939/tC; since $\eta = 0$ implies equal weights, this is the global maximum. A local maximum appears at SCC = \$122/tC when $\rho = 0$ and $\eta = 3$. Since this maximum is smaller than the expected social cost reported above for the second set of values for $\rho = 0$, $\eta = 3$, we see that uncertainty is a bigger concern for climate policy than equity, at least in terms of an aggregate measure like the SCC. A global minimum is observed when $\rho = \eta = 3$ and SCC = -\$50/tC. It emerges because CO_2 fertilization brings short-term benefits even to poor countries that will be hurt by climate change in the longer term. For these parameters, long-term losses are heavily discounted and short-term benefits in developing countries are emphasized. See the appendix for the case without CO_2 fertilization.

Estimates of expected social cost are similar when equity weighting is added to the complication of uncertainty. Panel D has a local a maximum at $\rho = \eta = 0$ as before where E(SCC) = $2,036/tC, but the global maximum is E(SCC) = $120,977/tC at $\rho = 0$, $\eta = 3$. E(SCC) is lowest for a high ρ and a medium η ; E(SCC) = $9/tC, for example, at $\rho = 3.0\%$, $\eta = 0.90$. Note that the E(SCC) is strictly positive for this, the theoretically correct scenario.

For reference, Lord Stern of Brentford chose $\rho = 0.1\%$, $\eta = 1$; in our calibration through *FUND,* the result was E(SCC) = $721/tC. Since the *Stern Review* essentially ignored equity weighing, though, E(SCC) = $333/tC is a more comparable statistic. The *Stern Review* estimate E(SCC) = $314/tC, which is remarkable close. However, note that the *Review* used the *PAGE* (Hope, 2008) model – which truncates the tails of distributions of input parameters that *FUND* fully recognizes[19], but keeps vulnerability to climate change as in 1995 while *FUND* has vulnerability declining with development – the two main differences between the two models roughly offset one another.

5. Choosing a social cost of carbon

We used two different approaches to inform our representations of combinations ρ and η that reflect actual practice across decision-makers. In the first, we worked with results from Evans and Sezer (2004; 2005), who estimated $\eta = 1.49$, with a standard deviation of 0.19 for 22 rich and democratic countries from income redistribution data (Stern, 1977). They also independently estimated $\rho = 1.08 \pm 0.20$ %/year using data on mortality rates. Assuming normality, these results support the probability density function on ρ and η displayed in Panel A of Figure 15. The first row of Table 5

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[19] Note that we discard the top and bottom .1% of Monte Carlo results because these outliers have an undue impact on the mean.

records estimates of the expected value of the SCC derived from this distribution for the four cases described above (see the appendix for details). Ignoring concerns about equity and uncertainty, E(SCC) = -\$1/tC. Considering either equity or uncertainty alone increases the estimate to \$13/tC or \$62/tC, respectively. Uncertainty is again seen to play a larger role in determining the social cost of carbon than equity. Considering both equity and uncertainty produces the fourth estimate: E(SCC) = \$210/tC. Equity and uncertainty reinforce one another.

Our second approach relied data on per capita consumption growth rates, inflation rates, and nominal interest rates for 27 OECD countries from 1970 to 2006. We interpreted observations of the real interest rate (r in (3.1) and the difference between the nominal rate and the rate of inflation) and the growth rate g as drawings from a bi-variate normal distribution. The Ramsey equation implies that realisations for r and g together support a linear combination for ρ and η. As a result, the bi-variate distribution for r and g implies a degenerate bi-variate distribution for ρ and η. Panel B of Figure 15 displays this distribution. The mean for η is 1.18, with a standard deviation of 0.80, but the distribution is right skewed with a mode of $\eta = 0.55$. The mean of ρ is 1.4%, with a standard deviation of 0.9%; the distribution is again right-skewed, this time with a mode of $\rho = 0.9\%$. The characteristics of this distribution are not inconsistent with the underlying distributions reported by Evans and Sezer, but it does clearly differ in shape. The second row of Table 5 shows the sensitivity of E(SCC) estimates to the difference. Ignoring uncertainty and equity, E(SCC) = \$41/tC; it is much higher than the estimate reported in the first row from the Evans and Sezer distribution because lower values of ρ and η are deemed more likely. As before, considering either equity or uncertainty increases the E(SCC), this time to \$59/tC and

$117/tC, respectively. The effects of equity and uncertainty are now less pronounced because extreme values of ρ and η receive lower probability mass than before. Finally, as before, uncertainty dominates equity. However, in this case, equity moderates uncertainty; considering both simultaneously produces an estimate for E(SCC) of $228/tC. Again, equity and uncertainty reinforce one another.

The third row of Table 5 shows E(SCC) estimates for a combined probability density function of ρ and η produced by multiplying the two PDFs in Figure 15 and rescaling them to integrate to unity. The estimates lie in between the previous results, but closer to the initial results derived from the Evans and Sezer PDF. The qualitative pattern is the same, though. Uncertainty dominates, and is reinforced by equity. Combining all of this information, our final estimate is E(SCC) = $206/tC.

6. Conclusion

Lord Stern (Stern, 2007) has expressed a preference for debating philosophically about the appropriate discount rate for the benefits of mitigation. We bow out of that debate by exploring the ramifications of actual decision makers and actual developed economies. We find that aversion to risk is as important in determining SCC estimates as time preference. More specifically, we offer high estimates for the SCC given operational combinations of risk aversion and time preference even with a model that incorporates relatively conservative damage estimates (including benefits early) and autonomous adaptation driven by regional economic development.

7. Appendix

7.1. *A utility-based rationale for Equation* (3.1)

To uncover the utility-based interpretation of the Ramsey (1928) optimal saving rule, consider a two period environment wherein inter-temporal discounted utility is given by

$$U\left(C_1, C_2\right) = U\left(C_1\right) + \frac{U\left(C_2\right)}{1+\rho} \tag{3.3}$$

with C_t indicating consumption in period t ($t = 1, 2$). Totally differentiating this relationship defines an inter-temporal marginal rate substitution (i.e., the rate at which an individual would trade current consumption for future consumption while maintaining the same level of discounted utility):

$$\left.\frac{\partial C_2}{\partial C_1}\right|_{U=U^*} = \frac{U'\left(C_1\right)}{U'\left(C_2\right)/1+\rho} \approx \frac{U'\left(C_1\right)(1+\rho)}{U'\left(C_1\right)(1-\eta g)} = \frac{(1+\rho)}{(1-\eta g)} \approx 1+\rho+\eta g \tag{3.4}$$

The interpretation in the text – that the Ramsey rule can be interpreted as representing the sum of an impatience effect and the effect of diminishing marginal utility with increasing consumption – follows.

7.2. *FUND details*

This paper uses version 3.0 of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*). Version 3.0 of *FUND* corresponds to version 1.6, described and applied by Tol (1999; 2001; 2002c), except for the impact module, which is described by Tol (2002a; b) and updated by Link and Tol (2006). A full list of papers, the source code and the technical documentation with all equations and all parameter values for the model can be found on line at http://www.fund-model.org.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United

States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. The model runs from 1950 to 2300 in time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, the impacts of climate change are assumed to depend on the impact of the previous year, this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be misrepresented in the first few decades of the model runs. The 22nd and 23rd centuries are included to assess the long-term implications of climate change. Previous versions of the model stopped at 2200.

The period of 1950-2000 is used for the calibration of the model, which is based on the *IMAGE* 100-year database (Batjes and Goldewijk, 1994). The scenario for the period 2010-2100 is based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett *et al.*, 1992). The 2000-2010 period is interpolated from the immediate past (http://earthtrends.wri.org), and the period 2100-2300 extrapolated.

The scenarios are defined by the rates of population growth, economic growth, autonomous energy efficiency improvements as well as the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide.

The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (http://earthtrends.wri.org). It is extrapolated based on the statistical relationship between urbanization and per-capita income, which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The tangible impacts are dead-weight losses to the economy (cf. Fankhauser and Tol, 2005). Consumption and investment are reduced without changing the savings rate.[20] As a result, climate change reduces long-term economic growth, although consumption is particularly affected in the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies, an option not considered in this paper.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane, nitrous oxide and sulphur hexafluoride, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and

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[20] The savings rate is exogenous in this paper, given that we do not present results from an intertemporal optimization exercise. See Fankhauser and Tol (2005) for an in depth discussion of climate change impacts and economic growth models.

Hasselmann (1987). Its parameters are taken from Hammitt *et al*. (1992). The model also contains sulphur emissions (Tol, 2006b).

The radiative forcing of carbon dioxide, methane, nitrous oxide, sulphur hexafluoride and sulphur aerosols is determined based on Ramaswamy *et al*. (2001). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by the radiative forcing RF), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. Regional temperature follows from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn *et al.*, 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996).

The climate impact module, based on Tol (2002a; b) includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol, 2002b).

People can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set to be 3 times the per capita income (Tol, 1995b), the value of immigration is 40 per cent of the per capita income in the host region (Cline, 1992). Losses of dryland and wetlands due to sea level rise are modelled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 (cf. Fankhauser, 1994). The wetland value is assumed to have logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their ‘natural’ units (cf. Tol, 2002a). Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol, 2002b).

The impacts of climate change on coastal zones, forestry, unmanaged ecosystems, water resources, diarrhoea malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (cf. Tol, 2002b).

Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) (cf. Tol, 2002b). The income elasticities in Tol (2002b) are estimated with cross- sectional data.

The social cost of carbon (*SCC*) is estimated by running the model twice, perturbed and unperturbed. In the perturbed run, an additional one million metric tonnes of carbon are emitted in each year between 2005 and 2015. The difference in impacts is computed and discounted back to the year 2005, using the discount rate as specified in Equation (3.4). The difference is then divided by 10 mln tC to obtain an incremental cost estimate. That is,

$$SCC_r = \sum_{t=2005}^{2300} \frac{I_{t,r}\left(\sum_{s=1950}^{t-1} E_s + \delta_s\right) - I_{t,r}\left(\sum_{s=1950}^{t-1} E_s\right)}{\prod_{s=2005}^{t} 1+\rho+\eta g_{s,r}} \Bigg/ \sum_{t=2005}^{2015} \delta_t \tag{3.5}$$

where

- SCC_r is the regional social cost of carbon (in 1995 US dollar per tonne of carbon);
- r denotes region;
- t and s denote time (in years);

- I are monetised impacts (in 1995 US dollar per year);
- E are emissions (in metric tonnes of carbon);
- δ are additional emissions (in metric tonnes of carbon);
- ρ is the pure rate of time preference (in fraction per year);
- η is the elasticity of marginal utility with respect to consumption; and
- g is the growth rate of per capita consumption (in fraction per year).

We first compute the SCC per region, and then aggregate, as follows

$$SCC = \sum_{r=1}^{16} \left(\frac{Y_{2005,world}}{Y_{2005,r}} \right)^{\varepsilon} SCC_r \tag{3.6}$$

where

- SCC is the global social cost of carbon (in 1995 US dollar per tonne of carbon);
- SCC_r is the regional social cost of carbon (in 1995 US dollar per tonne of carbon);
- r denotes region;
- Y_{world} is the global average per capita consumption (in 1995 US dollar per person per year);
- Y_r is the regional average per capita consumption (in 1995 US dollar per person per year); and
- ε is the rate of inequity aversion; $\varepsilon = 0$ in the case without equity weighing; $\varepsilon = \eta$ in the case with equity weighing.

In the case of uncertainty, we compute the expected value of the SCC, as follows:

$$\mathrm{E}(SCC)=\frac{1}{MC}\sum_{i=1}^{MC}SCC(\theta_i) \tag{3.7}$$

where

- $\mathrm{E}\left(SCC\right)$ is the expected value of the social cost of carbon (in US dollar per tonne of carbon);
- i indexes the Monte Carlo run;
- MC is the number of Monte Carlo runs; $MC=1000$; and
- θ is the vector of uncertain input parameters, fully specified on http://www.fund-model.org/

7.3. The rate of risk aversion, the pure rate of time preference, and the discount rate

We compute the SCC and the $\mathrm{E}\left(SCC\right)$ for a range of the pure rate of time preference (ρ) and the rate of risk aversion (η), and we also compute a weighted average using three alternative bivariate PDFs for ρ and η, as follows:

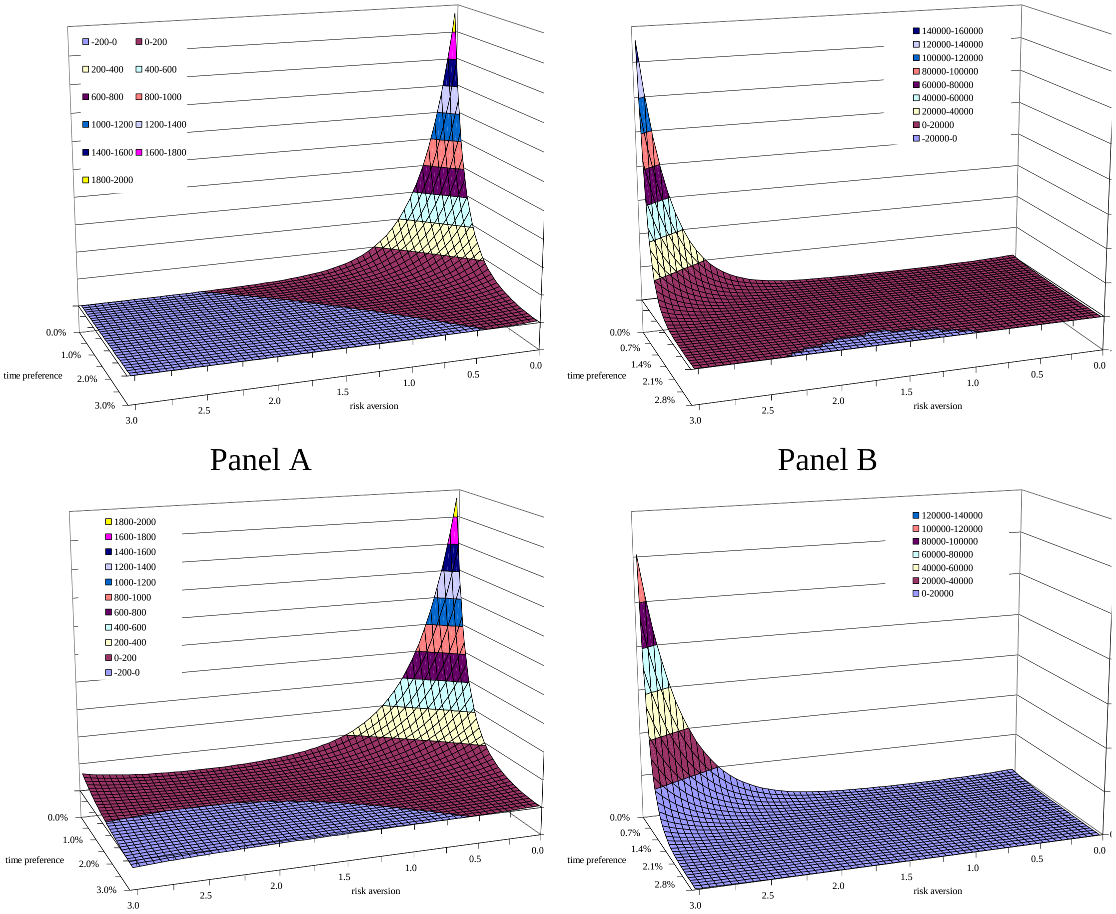
$$SCC^{*}=\int_{\mathrm{H}}\int_{\mathrm{P}}SCC(\rho,\eta)f(\rho,\eta)\mathrm{d}\rho\mathrm{d}\eta \tag{3.8}$$

The first bi-variate PDF of ρ and η assumes that these parameters are normally distributed with $\mu_\rho=1.08\%$, $\mu_\eta=1.49$, $\sigma_\rho=0.20\%$, $\sigma_\eta=0.19$ and $\sigma_{\rho\eta}=0$. See Table 6. The second bi-variate PDF is degenerate. It corresponds to a bi-variate normal PDF of r and g with $\mu_r=3.45\%$, $\mu_g=2.70$, $\sigma_r=2.56\%$, $\sigma_g=1.61$ and $\sigma_{rg}=0$ (see Table 7) and $r=\rho+\eta g$. The third bi-variate PDF is the convolution of the first two.

7.4. The impact of CO_2 fertilization on the social cost of carbon

In the main text, we find that social cost of carbon is positive for a high value of η if equity weighing is included and uncertainty is not. We assert that this is because of CO_2 fertilization of agriculture, which has large benefits in developing countries in the short term. High values of η emphasize these benefits. In order to test this assertion, we reran the model with the CO2 fertilization switched off. Figure 16 compares the results. With CO_2 fertilization, the SCC falls with rising η. Without CO2 fertilization, the SCC first falls (as the discount rate increases) but then starts rising (as the rising discount rate is more than compensated by the increasing equity weights).

8. Figures



Panel A

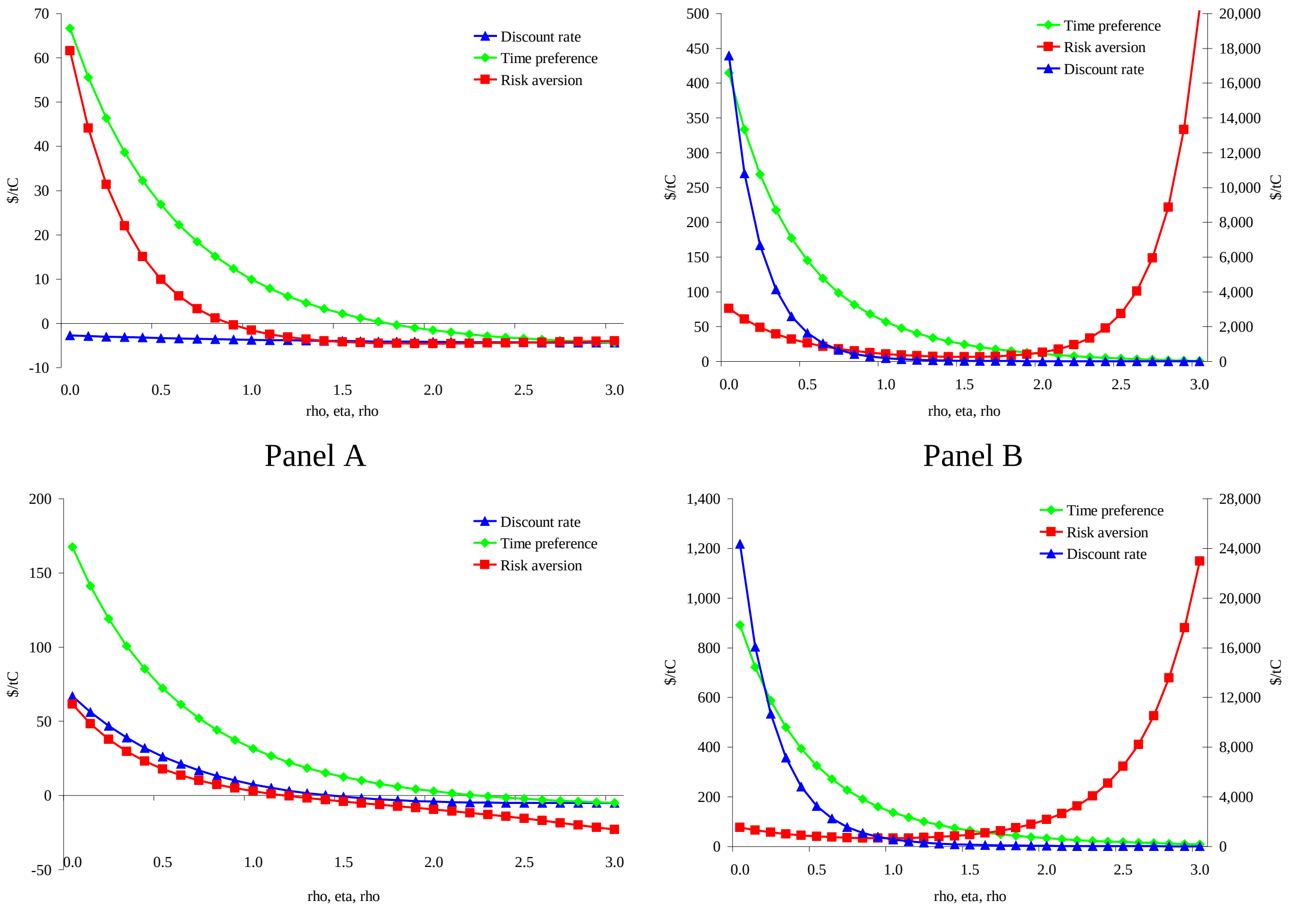
Panel B

Panel C

Panel D

Figure 13: The marginal damage cost of carbon emissions as a function of the rate of time preference and the rate of risk aversion.

Panel A (top left) shows the sensitivity of SCC estimates without equity weighting and without uncertainty; low pure rates of time preference and risk aversion produce high SCC estimates because they work exclusively through the discount rate. Panel B (top right) shows the sensitivity of SCC estimates to uncertainty without equity weighting; low rates of time preference produce higher estimates, but uncertainty dominates especially for high levels of risk aversion where the associated risk premium climbs enormously. Panel C (bottom left) shows the sensitivity of SCC estimates to equity weighting derived from the “inequity aversion) interpretation of η and without uncertainty; higher aversions to inequity reduce the SCC for any time preference because the positive gains in developing countries from CO_2 fertilization dominate “downstream” losses that are, by virtue of the higher values for η, discounted more severely. Panel D (bottom right) shows the sensitivity of SCC estimates to equity weighting with uncertainty fully represented; the moderating effect of higher values for η is dominated by the effect of uncertainty.



Panel A

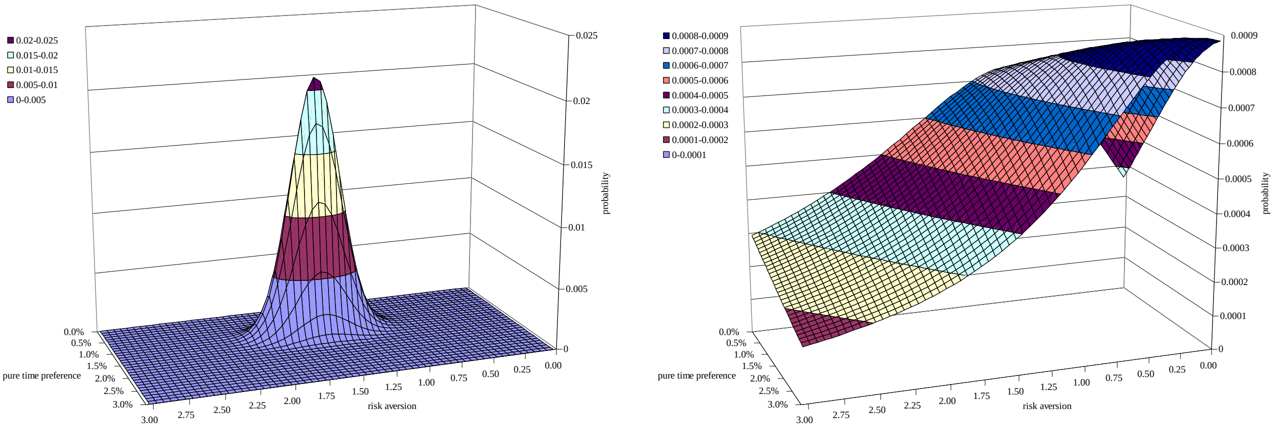
Panel B

Panel C

Panel D

Figure 14: The SCC as a function of the rate of time preference (green diamonds for a rate of risk aversion of 1.0), the rate of risk aversion (red squares for a rate of time preference of 2.0), and of the rate to time preference (blue triangles for a rate of risk aversion adjusted to maintain the discount rate at 5.0 assuming that consumption grows at 2.0% per year – right axis)

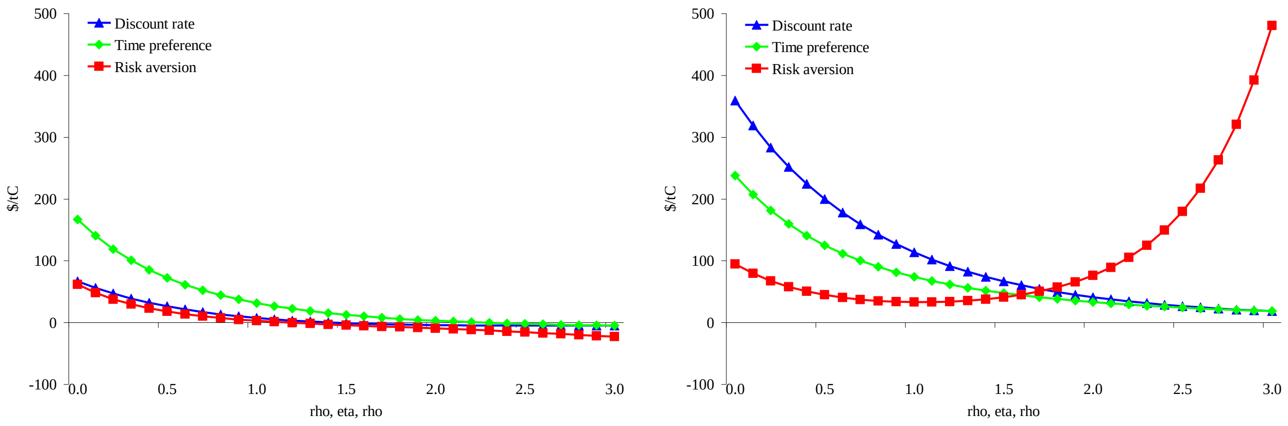
Panel A (top left) shows contours without equity weighting and without uncertainty. Negative values for SCC are possible for high rates of risk aversion and/or time preference (and guaranteed for a 5% discount rate); this is an indication of the conservative damage estimates embodied in *FUND*. Panel B (top right) displays contours with η working as a risk aversion parameter given complete manifestation of uncertainty but ignoring its role as equity weighting parameter at any point in time; the U-shaped contour associated with risk aversion is particularly instructive – the discounting effect of high values is dominated by the risk-premium effect of increased aversion to risk. Panel C (bottom left) shows contours with η working to produce equity weights without uncertainty; the early agricultural benefits of CO_2 fertilization in developing countries produces negative estimates for SCC for high discount rates born of high rates of risk aversion and/or time preference. Panel D (bottom right) allows η to work both as a source of equity weighting and as a measure of risk aversion given climate and socio-economic uncertainty; the U-shaped contours of the uncertainty only case from Panel B return.



Panel A Panel B

Figure 15: Probability density functions of risk aversion and time preference

Panel A displays the distribution reported by Evans and Sezer. Panel B was derived from the Ramsey rule using OECD data.



Panel A Panel B

Figure 16: The SCC as a function of the rate of time preference (green diamonds for a rate of risk aversion of 1.0), the rate of risk aversion (red squares for a rate of time preference of 2.0), and of the rate to time preference (blue triangles for a rate of risk aversion adjusted to maintain the discount rate at 5.0 assuming that consumption grows at 2.0% per year)

Both panels show contours with equity weights but without uncertainty. Panel A includes the immediate, positive effects of CO2 fertilization on agriculture across the world, whereas Panel B assumes no CO2 fertilization. Panel A equals Figure 14, Panel C (rescaled).

9. Tables

Uncertainty Included?	**No**	**No**	**Yes**	**Yes**
Equity weighting Included?	**No**	**Yes**	**Yes**	**No**
Rate of pure time preference and rate of risk aversion from Evans and Sezer	-0.7	12.6	210.1	61.6
Inference from interest rate and consumption growth rates from OECD countries	40.6	58.7	227.8	117.4
Both	-0.4	13.2	205.5	60.7

Table 5: Estimates of the Expected Social Cost of Carbon ($/tC)

	ρ	g	η^a	η^b
Australia*	1.5	1.9	1.4	1.7
Austria	1.0	2.7	1.6	1.6
Belgium	1.0	2.3	1.5	1.6
Czech Rep	1.1	1.4	1.4	1.4
Denmark	1.1	1.0	1.2	1.3
Finland	1.0	2.2	1.6	1.6
France	0.9	1.8	1.3	1.3
Germany	1.0	2.2	1.6	1.5
Greece	1.0	2.5	1.7	1.5
Hungary	1.3	1.6	1.2	1.4
Ireland	0.8	3.0	1.6	2.0
Italy	1.0	2.5	1.5	1.4
Japan*	1.5	2.5	1.4	1.4
Luxembourg	0.9	2.5	1.8	1.8
The Netherlands	0.9	1.8	1.5	1.6
Poland	1.0	4.6	1.1	1.1
Portugal	1.0	2.7	1.6	1.7
Slovakia	1.1	3.7	1.6	1.5
Spain	1.0	2.3	1.6	1.6
Sweden	1.1	1.2	1.1	1.4
UK	1.0	2.0	1.5	1.5
USA*	1.5	2.2	1.3	1.4
Mean	1.08	2.30	1.46	1.51
St dev	0.20	0.79	0.19	0.19

Table 6: Data on the rates of pure time preference and risk aversion

[a] Risk aversion evaluated at the average wage.
[b] Average risk aversion evaluated at a range of wages.
Sources: (Evans and Sezer, 2005) and (Evans and Sezer, 2004)*.

	Per capita growth[a]		**Real interest**[b]		**Corr**	**N**	**Year**	
	mean	**St dev**	**Mean**	**St dev**			**first**	**last**
Australia	2.42	0.88	3.25	3.63	0.28	30	1971	2005
Austria	1.99	0.99	3.54	1.22	0.19	16	1990	2006
Belgium	2.44	1.47	3.85	2.42	-0.29	33	1970	2005
Canada	2.48	1.41	3.56	2.58	0.08	32	1970	2005
Czech Rep	4.45	1.68	2.45	1.06	-0.08	5	2001	2005
Denmark	1.90	1.30	4.16	1.91	0.09	18	1988	2006
Finland	3.58	1.33	4.60	1.96	0.32	14	1988	2005
France	2.17	1.37	3.58	2.10	-0.21	34	1970	2005
Germany	2.46	1.28	3.86	1.25	-0.01	32	1970	2006
Greece	3.86	0.51	1.86	1.32	-0.20	9	1998	2006
Iceland	4.03	1.57	5.65	1.60	0.09	9	1995	2005
Ireland	4.80	2.68	3.25	3.40	0.21	28	1976	2005
Italy	1.57	0.98	3.90	2.03	0.31	12	1993	2006
Japan	1.98	1.25	2.60	0.87	0.03	13	1989	2005
Korea	4.39	1.36	2.30	1.11	-0.24	5	2001	2005
Luxembourg	3.69	2.23	2.83	1.78	0.03	11	1995	2005
Netherlands	2.46	1.09	3.51	2.20	-0.23	32	1970	2006
New Zealand	2.46	1.59	2.67	3.88	-0.20	26	1970	2005
Norway	2.39	1.33	4.86	1.65	0.20	20	1985	2005
Poland	4.17	1.84	4.47	1.11	-0.51	5	2001	2005
Portugal	2.35	1.65	3.07	2.12	0.73	11	1994	2005
Slovak Rep	5.55	1.67	-0.15	2.94	-0.23	5	2001	2005
Spain	2.63	1.33	3.84	2.46	0.32	25	1981	2006
Sweden	2.61	1.25	5.00	1.79	-0.10	16	1987	2005
Switzerland	1.87	1.13	1.50	1.66	-0.04	27	1970	2005
UK	2.82	1.20	3.22	3.72	-0.02	30	1970	2005
USA	2.76	1.27	3.28	2.39	0.18	30	1970	2005
Total	2.70	1.61	3.45	2.56	0.01	528	1970	2006

Table 7: Data on the growth rate of per capita income and the real rate of interest

[a] Gross domestic product (expenditure approach) per capita in constant prices.
[b] Long-term interest rate minus the percentage change in the consumer price index (all items).
Source: OECD.Stat Monthly Economic Indicators (http://stats.oecd.org)

IV On International Equity Weights and National Decision Making on Climate Change

1. Introduction

Equity weights, in one form or other, are now frequently used to aggregate the monetized impacts of climate change that would befall different countries (Azar and Sterner, 1996; Fankhauser *et al.*, 1997; Azar, 1999; Tol, 1999; Pearce, 2003; Anthoff *et al.*, 2009). Equity weights reflect that a dollar to a poor person is not the same as a dollar to a rich person. That is, one cannot add up monetized welfare losses across disparate incomes. Instead, one should add up welfare losses and then monetize. Equity weighting does just that, albeit with a linear approximation.

The aggregation of welfare losses to different countries assumes a supranational perspective. Indeed, the formal derivation of equity weights presumes a global social planner. As an academic exercise, this is fine. However, equity-weighted worldwide marginal damage cost estimates for carbon dioxide are also used by the European Commission and the UK Government in their cost-benefit analysis of domestic policies (Clarkson and Deyes, 2002; Commission of the European Communities, 2005).

This is peculiar. Within countries, equity weights are shunned. Instead, the welfare loss of some average person is used.[21] This is because the democratic principle of "one person, one vote" sits awkwardly with the notion that some people are worthier than others. Between countries, matters are different, as the world is made up of sovereign nations.

One can, of course, argue that as a matter of principle one should act on the basis of how the world ought to be, not how the world is. If one then further believes that democracy is good, then one would probably argue for using the global average welfare loss to guide climate policy. Combined with the assumption that willingness to pay for climate change impacts varies linearly with per capita income, certain equity weights are indeed equivalent to global average values (see below). These are many ifs.

The UK Government and the European Commission, however, answer to the people of the UK and (ultimately) the EU, respectively, not to the people of the world. Using equity weights for impacts of climate change, impacts in Africa, say, are valued higher than the average African would; while impacts in Europe are valued lower than the average European would. At the same time, in Europe, health impacts, say, due to climate change are valued less than health impacts due to air pollution, say. This is most peculiar. Pretending to be the world government, the UK Government and the European Commission short-change the people they actually represent. And, the application of monetization and cost-benefit techniques introduces inconsistencies.

This of course is the consequence of using equity weights only for specific policy areas, i.e. climate change, which is wrong from a theoretical point of view. Equity weights are an all-or-nothing thing: Once a decision-maker opts to use equity weights, she has to

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[21] Note that, although every citizen is in principle considered equally worthy regardless of their income, poorer areas are often dirtier (Brown, 1995).

use equity weights for all her decision-making procedures, otherwise inconsistencies between various policy arenas will arise. If the UK opted to use equity weights for all its cost-benefit analysis, no such problems would arise. While in theory it is clear how equity weights should be used by a national decision maker without introducing inconsistencies in its decision making process, these guidelines are not followed in practise. Equity weights are used in the context of climate change by the UK government and the EU, but not for other policy areas. The resulting inconsistencies are grave and cannot be justified by any known theoretical argument.

Instead, in the absence of international cooperation, a national government committed to climate policy and cost-benefit analysis has five options. First, a country could ignore impacts outside its territory. Second, a country could care about foreign impacts to the extent that its citizens care about foreigners. These two options are numerically close; and they reflect tough *realpolitik*. Third, a country could argue that it has the duty to protect foreigners to the same extent as it does its own citizens. This is common practice for health and safety: Foreign visitors and resident enjoy the same level of protection as do citizens. Here, foreign impacts would be valued the same as domestic impacts. Fourth, a country could argue that it has the duty to be a good neighbour[22] and prevent damage to others and, failing that, feel guilty about the welfare loss it caused abroad. Fifth, a country could offer compensation for the damages it caused abroad, because it feels morally obliged to do so; or because it is told to by a court. Compensation presumably equals the damage done, and foreign impacts would be assessed with foreign values. We argue below that option 3 and 4 are identical under certain conditions. This paper therefore presents four alternative estimates of the marginal damage costs estimates for various world regions – and we compare these four

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[22] Climate change is a global phenomenon, so all are neighbours.

alternatives to two estimates that are commonly used. We show that the different estimates differ not only in the values assigned to impacts abroad, but also in the discount rate used.

The central metric in the paper is the social cost of carbon. The social cost of carbon if often thought of as the net present value of the additional damage done by an infinitesimally small increase in emissions, and thus equals the Pigou tax along an efficient emissions trajectory. However, the social cost of carbon can also be thought of as society's willingness to pay (at the margin) for greenhouse gas emission reduction. We use the latter interpretation in the current paper, and show how the social cost of carbon varies with different positions on damage done to others. As a corollary, our social cost of carbon differs between countries – even if countries agree on the ethical principles that underlie the social cost of carbon. Our social cost of carbon then also obviously differs from the Pigou tax, and it is in fact lower in many cases.

Section 2 formalizes the above discussion and reviews the relevant literature. Section 3 presents the numerical model used for estimating marginal damage costs. Section 4 shows the results. Section 5 discusses and concludes.

2. Equity weighting

2.1. Previous work

Fankhauser *et al.* (1997) defined equity-weighted impacts as

$$D_W = \sum_{i=1}^{N} \left(\frac{W_{U_i} U_{C_i}}{W_M} \right) D_i \tag{4.1}$$

Where D_i is the damage in country i, $i = 1, 2, ..., N$; U is the utility function of country i, and U_C is its first partial derivative of utility to average per capita consumption C;

W is the global welfare function, and W_U is its first partial derivative to utility; W_M is a normalization constant to go back from welfare to money – W_M is the first partial derivative to average per capita consumption, evaluated at the optimal point; D_W is the global damage. Equation (4.1) holds for any welfare and utility function, but in their numerical results Fankhauser *et al*. (1997) only consider constant rate of risk aversion (CRRA) utility functions and generalised utilitarian (e.g. Atkinson, 1970) welfare functions.

The normalization constant has an element of arbitrariness. In this case, the anchor point is a world that is fair (according to the welfare function), and the damage is spread in an equitable manner. If the anchor point were an unfair world because of reasons other than climate change, the valuation of climate change would reflect such inequities – and we may end up using greenhouse gas emission reduction to rectify other wrongs than climate change. In this sense, the chosen normalisation reflects first-best policy.

If we use a utilitarian global welfare function $W = \sum_{i=1}^{N} U_i$ and a CRRA utility function, Equation (4.1) becomes

$$D_W = \sum_{i=1}^{N} \left(\frac{C_W}{C_i} \right)^{\varepsilon} D_i \tag{4.2}$$

where C_W is the world average per capita consumption, and ε is the elasticity of marginal utility with respect to income. In our model ε is a parameter of inter- and intratemporal inequality aversion.[23] Clearly, countries with an income above (below) the world average receive a low (high) weight, and this is more pronounced as the utility

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[23] In probabilistic models ε is also the parameter of risk aversion, but we restrict our analysis in this paper to a deterministic case. For a discussion of this triple role of ε in the climate change economics debate see Beckerman and Hepburn (2007).

function is more curved. Indeed, with a linear utility function ($\varepsilon = 0$), equity weights would equal unity.[24]

Equations (4.1) and (4.2) were used in previous work (Fankhauser *et al.*, 1997). We now reconstruct (4.1) and (4.2) for a national decision maker.

2.2. Welfare functions

Let's assume that an individual utility function is specified as:

$$u\left(C\right) = \frac{C^{1-\varepsilon}}{1-\varepsilon} \tag{4.3}$$

This is a conventional CRRA utility function.

We further assume that the national policy maker optimises a welfare function that is defined over the utility of individuals. In particular, we look at welfare functions that take the sum of individual utilities. This utilitarian assumption is disputable, but it is beyond the scope of this paper. Instead, we focus on variations of utilitarian welfare and the consequences for the social cost of carbon. Each represents a specific policy position of a national decision maker.

2.2.a. Impacts abroad are ignored

If a national planner is indifferent to what happens abroad, the welfare function is

$$w^s\left(C_{t,i}\right) = \sum_{t=0}^{T}\sum_{i=1}^{N_t} u\left(C_{t,i}\right)(1+\rho)^{-t} \tag{4.4}$$

---

[24] Climate change damages are typically approximated by the direct costs (that is price times quantity) with constant prices. If the "price", or rather unit value, varies with an income elasticity of willingness to pay of η, then we have that

$$D_W = \sum_{c=1}^{C}\left(\frac{C_W}{C_c}\right)^{\varepsilon} D_c = \sum_{c=1}^{C}\left(\frac{C_W}{C_c}\right)^{\varepsilon} V_c I_c = \sum_{c=1}^{C}\left(\frac{C_W}{C_c}\right)^{\varepsilon} V_0 \left(\frac{C_c}{C_W}\right)^{\eta} I_c \overset{\varepsilon=-\eta}{=} \sum_{c=1}^{C} V_0 I_c$$

where I_c is the impact in country c, V_0 is its unit value, and V_W is the world average value. Under these assumptions, all impacts are effectively valued the same – and at the world average. Note that that the rate of inequity aversion and the income elasticity of willingness to pay are the same by chance only – even though both are set equal to unity in many applied papers.

where $C_{t,i}$ is consumption of agent i at time t, T is the end of the time horizon the policy maker is taking into account, N_t is the population size at time t and ρ is the pure rate of time preference.

In practise, policy makers do not have data on an individual basis. We therefore use a welfare function based on average per capita consumption:

$$\bar{w}^s\left(\bar{C}_t\right)=\sum_{t=0}^{T}u\left(\bar{C}_t\right)P_t(1+\rho)^{-t} \tag{4.5}$$

where $\bar{C}_t$ is average per capita consumption at time t in the region of the policy maker and P_t is the population size of the region at time t.[25] We omit the average bars from here on.

The social cost of carbon (SCC), or marginal damage cost of carbon dioxide emissions, is defined as the damage done by a small change in emissions E today ($t=0$). In utils, we take the utility effect of a marginal change in consumption caused by climate change, and add that up:[26]

$$scc^s=\sum_{t=0}^{T}\frac{\partial u(C_t)}{\partial C_t}\frac{\partial C_t}{\partial E_0}P_t(1+\rho)^{-t} \tag{4.6}$$

In money, the corresponding SCC figure is

$$\begin{aligned}SCC^s&=\left(\frac{\partial u(C_0)}{\partial C_0}\right)^{-1}\sum_{t=0}^{T}\frac{\partial u(C_t)}{\partial C_t}\frac{\partial C_t}{\partial E_0}P_t(1+\rho)^{-t}=\sum_{t=0}^{T}\left(\frac{\partial u(C_0)}{\partial C_0}\right)^{-1}\frac{\partial u(C_t)}{\partial C_t}\frac{\partial C_t}{\partial E_0}P_t(1+\rho)^{-t}\approx\\&\approx\sum_{t=0}^{T}\left(\frac{\partial u\left(C_t\right)}{\partial C_t}\right)^{-1}(1+\varepsilon g_t)^{-t}\frac{\partial u\left(C_t\right)}{\partial C_t}\frac{\partial C_t}{\partial E_0}P_t(1+\rho)^{-t}\approx\sum_{t=0}^{T}\frac{\partial C_t}{\partial E_0}P_t(1+\rho+\varepsilon g_t)^{-t}\end{aligned} \tag{4.7}$$

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[25] Note that using average per capita consumption in this way introduces a small upwards bias in total welfare. See Anthoff *et al.* (2009) for a numerical analysis of this issue.

[26] For a discussion of discounting of non-marginal climate change impacts see Dietz (2006).

where g_t is the average annual growth rate of per capita consumption between now and year t.[27]

2.2.b. *Impacts abroad reduce domestic welfare*

If the social planner is altruistic towards people abroad, the welfare function is

$$w^a\left(C_t, C_{t,i}\right) = \left[\sum_{t=0}^{T} u\left(C_t\right) P_t (1+\rho)^{-1}\right] + \left[\sum_{t=0}^{T}\sum_{i=1}^{N} u^*\left(C_{t,i}\right) P_{t,i} (1+\rho)^{-1}\right] \tag{4.8}$$

Here $C_{t,i}$ is average per capita consumption in country i at time t; N is the number of countries; u^* specifies the foreign utility function of the domestic planner; it may be a scaled transformation of u, that is $u^* = \varphi u$ with $0 < \varphi < 1$. That is, the preferences of other agents are identical to one's own, but less important.

The corresponding scc (in utils) follows as

$$scc^a = \left[\sum_{t=0}^{T} \frac{\partial u\left(C_t\right)}{\partial C_t} \frac{\partial C_t}{\partial E_0} P_t (1+\rho)^{-1}\right] + \left[\sum_{t=0}^{T}\sum_{i=1}^{N} \frac{\partial u^*\left(C_{t,i}\right)}{\partial C_{t,i}} \frac{\partial C_{t,i}}{\partial E_0} P_{t,i} (1+\rho)^{-1}\right] \tag{4.9}$$

If u^* is proportional to u, the corresponding regional SCC (in money) is

$$\begin{aligned} SCC^a &= \left(\frac{\partial u(C_0)}{\partial C_0}\right)^{-1} \left[\sum_{t=0}^{T} \frac{\partial u(C_t)}{\partial C_t} \frac{\partial C_t}{\partial E_0} P_t (1+\rho)^{-t} + \varphi \sum_{t=0}^{T}\sum_{i=1}^{N} \frac{\partial u(C_{t,i})}{\partial C_{t,i}} \frac{\partial C_{t,i}}{\partial E_0} P_{t,i} (1+\rho)^{-t}\right] \\ &\approx \sum_{t=0}^{T} \frac{\partial C_t}{\partial E_0} P_t (1+\rho+\varepsilon g_t)^{-t} + \varphi \sum_{i=1}^{N} \left(\frac{\partial u\left(C_0\right)}{\partial C_0}\right)^{-1} \frac{\partial u\left(C_{i,0}\right)}{\partial C_{i,0}} \sum_{t=0}^{T} \frac{\partial C_{t,i}}{\partial E_0} P_{t,i} (1+\rho+\varepsilon g_{t,i})^{-t} \qquad (4.10) \\ &= \sum_{t=0}^{T} \frac{\partial C_t}{\partial E_0} P_t (1+\rho+\varepsilon g_t)^{-t} + \varphi \sum_{i=1}^{N} \left(\frac{C_0}{C_{0,i}}\right)^{\varepsilon} \sum_{t=0}^{T} \frac{\partial C_{t,i}}{\partial E_0} P_{t,i} (1+\rho+\varepsilon g_{t,i})^{-t} \end{aligned}$$

where $g_{t,i}$ is the average annual growth rate of per capita consumption between now and year t in region i.

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[27] Note that we do not assume a constant growth rate; rather g_t is the geometric mean growth rate of the yearly growth rates between time 0 and t predicted by the model.

For $\varphi = 0$, this reduces to (4.7).

2.2.c. Good neighbour

It is well established, both morally and legally, that one should not do damage to others, or compensate them if damage is done nonetheless. Here we assume that compensation is not possible. Compensation is dealt with below.

If the obligation not to do damage is interpreted as a hard constraint, the implications are simple: One should reduce greenhouse gas emissions to zero. Here we instead assume that the domestic policy maker takes welfare losses abroad caused by herself into account.

Note that good neighbourliness is not the same as altruism. An altruistic agent cares about other agents. A good neighbour only cares about her impact on other agents. An altruistic agent cares about the impacts of climate change on others and about income differences in general. A good neighbour cares about the impacts of climate caused by herself only. An altruistic agent would seek to minimise her impacts on others, and would donate money to less fortunate people. A good neighbour would seek to minimise her impacts on others. Altruism may evolve if survival and procreation are enhanced by the well-being of others. These others are probably a small group of close relatives. Good neighbourliness may evolve if survival and procreation would be reduced by the wrath of others. We do not present an evolutionary game, however, but simply assume that good neighbourliness is in the welfare function.

This may be specified as

$$w^n = \sum_{t=0}^{T} u\left(C_t\right) P_t (1+\rho)^{-t} - \sum_{t=0}^{T}\sum_{i=1}^{N} \Delta u_{t,i} P_{t,i} (1+\rho)^{-t} \tag{4.11}$$

where Δu is the damage done abroad by domestic action, expressed as a reduction in welfare abroad.

We again assume that the domestic agent uses the same utility function for other agents as for herself, an assumption that keeps the model simple. Besides, different utility functions for different agents would be hard to justify too. The scc is then

$$scc^n = \sum_{t=0}^{T} \frac{\partial u\left(C_t\right)}{\partial C_t} \frac{\partial C_t}{\partial E_0} P_t (1+\rho)^{-1} + \sum_{t=0}^{T} \sum_{i=1}^{N} \frac{\partial u\left(C_{t,i}\right)}{\partial C_{t,i}} \frac{\partial C_{t,i}}{\partial E_0} P_{t,i} (1+\rho)^{-1} \qquad (4.12)$$

In money, this becomes

$$\begin{aligned} SCC^n &= \left(\frac{\partial u\left(C_0\right)}{\partial C_0} \right)^{-1} scc^n \approx \\ &\sum_{t=0}^{T} \frac{\partial C_t}{\partial E_0} P_t (1+\rho+\varepsilon g_t)^{-t} + \left(\frac{\partial u\left(C_0\right)}{\partial C_0} \right)^{-1} \sum_{i=1}^{N} \frac{\partial u\left(C_{i,0}\right)}{\partial C_{i,0}} \sum_{t=0}^{T} \frac{\partial C_{t,i}}{\partial E_0} P_{t,i} (1+\rho+\varepsilon g_{t,i})^{-t} = \quad (4.13) \\ &\sum_{t=0}^{T} \frac{\partial C_t}{\partial E_0} P_t (1+\rho+\varepsilon g_t)^{-t} + \sum_{i=1}^{N} \left(\frac{C_0}{C_{i,0}} \right)^{\varepsilon} \sum_{t=0}^{T} \frac{\partial C_{t,i}}{\partial E_0} P_{t,i} (1+\rho+\varepsilon g_{t,i})^{-t} \end{aligned}$$

Note that (4.13) equals (4.10) for $\varphi = 1$. However, there is a conceptual difference between altruism and good neighbourliness. The policy implications are different as well. An altruistic agent would donate money to less well-to-do people or, if that is not possible, would use climate policy to right other wrongs. A good neighbour would not donate money and would reduce emissions for climate change only.

Note that although all foreign parties are treated the same in Equation (4.11), Equation (4.13) gives preferential treatment to the poorer parties.

Note further that, if the income elasticity of the willingness to pay for climate change impacts equals the rate of inequality aversion, then Equation (4.13) is equivalent to assuming that impacts abroad are valued at domestic prices (cf. footnote 24). This is an alternative interpretation of good neighbourliness: One treats impacts on others as if they fell on oneself. Recall, however, that this interpretation is valid only under the restrictive and improbable assumption that the income elasticity and inequality aversion are numerically equal.

Equation (4.13) shows how concern for foreign parties would affect the willingness to pay for domestic greenhouse gas emission reduction. Climate change would also affect biodiversity. Equation (4.13) thus also quantifies the concern for other species. However, while polar bears (say) do not care for monetary compensation, foreign people would. The next subsection therefore turns to this question.

2.2.d. Impacts abroad are compensated

One can imagine a situation in which climate change damages are fully internalized, i.e. the emitter of greenhouse gas emissions fully compensates those that suffer damages. In particular, one can imagine a set of international treaties which puts the obligation to pay compensation for damages caused to every nation. We are not particularly concerned in this paper how or whether such a situation could arise. We merely assume that there is some external forcing or reasoning due to which compensation is paid. This is not the same as good-neighbour-with-compensation, as that would have compensation as a decision variable.[28] The important point is that compensation payments are not happening because there is a desire to do so; rather there is an obligation.

In this case, the welfare function is

$$w^c\left(C_t, L_t^*, L_{t,i}\right) = \sum_{t=0}^{T} u\left(C_t + \frac{L_t^* - \sum_{i=1}^{N} L_{t,i}}{P_t}\right) P_t (1+\rho)^{-t} \tag{4.14}$$

---

[28] Note that the solution would lie somewhere in between the good-neighbour-without-compensation case derived above and the full-compensation case derived below.

Where L is the total compensation paid to country i and L^* is the compensation received.

The scc follows as

$$scc^c = \sum_{t=0}^{T} \frac{\partial u(C_t)}{\partial C_t} \left(\frac{\partial C_t}{\partial E_0} - \frac{1}{P_t} \sum_{i=1}^{N} \frac{\partial L_{t,i}}{\partial E_0} \right) P_t (1+\rho)^{-t} \tag{4.15}$$

as $\partial L^* / \partial E = 0$. The corresponding SCC follows as

$$SCC^c = \sum_{t=0}^{T} \left(\frac{\partial C_t}{\partial E_0} - \frac{1}{P_t} \sum_{i=1}^{N} \frac{\partial L_{t,i}}{\partial E_0} \right) P_t (1+\rho+\varepsilon g_t)^{-t} \tag{4.16}$$

Note that the compensation is discounted with the social discount rate based on the *domestic* growth rate. This follows because the welfare loss is a domestic loss through compensation. Intuitively, the damage abroad is paid for by the domestic consumers and should therefore be discounted using their discount rate.

If compensation is paid to exactly offset the damage done, (4.16) becomes[29]

$$SCC^c = \sum_{t=0}^{T} \left[\frac{\partial C_t}{\partial E_0} + \frac{1}{P_t} \sum_{i=1}^{N} \frac{\partial C_{t,i}}{\partial E_0} P_{t,i} \right] P_t (1+\rho+\varepsilon g_t)^{-t} \tag{4.17}$$

There are two differences between (4.14) and (4.17). Firstly, damage abroad has an equity weight in (4.14) but not in (4.17). Secondly, damage abroad is discounted with the discount factor abroad in (4.14), but with the domestic discount rate in (4.17).

2.2.e. Overview

The social cost of carbon is given by

$$SCC = \sum_{t=0}^{T} \frac{\partial C_t}{\partial E_0} P_t (1+\rho+\varepsilon g_t)^{-t} + \varphi \sum_{i=1}^{N} \omega_i \sum_{t=0}^{T} \frac{\partial C_{t,i}}{\partial E_0} P_{t,i} DF_{t,i} \tag{4.18}$$

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[29] Equation (4.17) follows from (4.16) by equating the term for paid compensation with the term of damage caused, i.e. replacing $\partial L_{t,i} / \partial E_0$ with $\partial C_{t,i} / \partial E_0$.

The alternative positions follow from the appropriate choices for φ, the equity weight ω, and the discount factor DF. See Table 8. For completeness, Table 8 also includes the cooperative solution – in which the regions jointly maximise the sum of the sovereign welfare as specified in Equation (4.4) – equity weights for the global decision maker (Equation (4.2)), and a case inspired by symmetry, but for which we could not find an interpretation.

Note that in all cases domestic impacts are valued with domestic values.

3. The model

This paper uses version 2.9 of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*). Version 2.9 of *FUND* corresponds to version 1.6, described and applied by Tol (1999; 2001; 2002c), except for the impact module, which is described by Tol (2002a; b) and updated by Link and Tol (2006). A further difference is that the current version of the model distinguishes 16 instead of 9 regions. The model considers emission reduction of methane and nitrous oxide as well as carbon dioxide, as described by Tol (2006b). Finally, the model now has sulphur hexafluoride (SF_6) and a newly calibrated radiative forcing code. A full list of papers, the source code and the technical documentation with all equations and all parameter values for the model can be found on line at http://www.fund-model.org. Readers familiar with *FUND* can skip to Section 4 without loosing any continuity in our argument.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-

Saharan Africa, and Small Island States. The model runs from 1950 to 2300 in time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, the impacts of climate change are assumed to depend on the impact of the previous year, this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be misrepresented in the first few decades of the model runs. The 22nd and 23rd centuries are included to assess the long-term implications of climate change. Previous versions of the model stopped at 2200.

The period of 1950-2000 is used for the calibration of the model, which is based on the *IMAGE* 100-year database (Batjes and Goldewijk, 1994). The scenario for the period 2010-2100 is based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett *et al.*, 1992). The 2000-2010 period is interpolated from the immediate past (http://earthtrends.wri.org), and the period 2100-2300 extrapolated.

The scenarios are defined by the rates of population growth, economic growth, autonomous energy efficiency improvements as well as the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide.

Welfare comparisons between regions figure prominently in some of the national social cost definitions of Section 2, in the form of ratios of per capita consumption. Therefore, we measure income in purchasing power parity exchange rates (PPP). This also affects the scenario. The original scenario is formulated in terms of market exchange rates (MER). It assumes a narrowing of the income gap between rich and poor. Following Tol (2006a), we assume an income elasticity of –0.28 for the PPP to MER ratio. That is, in the PPP scenario, poor regions are richer at the start, but grow more slowly. This also affects emissions. Following Tol (2006a), we also adjust the scenario for energy efficiency improvements, such that the drop in the growth rate of energy use is halfway between the drop in economic growth rate and zero. That is, emissions grow less fast in the PPP scenario, but faster than a naïve adjustment with the economic growth rate would suggest (cf. Castles and Henderson, 2003). At the same time, the adjusted scenario for energy efficiency does not fully offset the adjusted income scenario either (cf. Gruebler *et al.*, 2004).

The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (http://earthtrends.wri.org). It is extrapolated based on the statistical relationship between urbanization and per-capita income, which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The tangible impacts are dead-weight losses to the economy (cf. Fankhauser and Tol, 2005). Consumption and investment are reduced without changing the savings rate.[30] As a result, climate change reduces long-term economic growth, although consumption is

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[30] The savings rate is exogenous in this paper, given that we do not present results from an intertemporal optimization exercise. See Fankhauser and Tol (2005) for an in depth discussion of climate change impacts and economic growth models.

particularly affected in the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies, an option not considered in this paper.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane, nitrous oxide and sulphur hexafluoride, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt *et al*. (1992). The model also contains sulphur emissions (Tol, 2006b).

The radiative forcing of carbon dioxide, methane, nitrous oxide, sulphur hexafluoride and sulphur aerosols is determined based on Ramaswamy *et al*. (2001). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by the radiative forcing RF), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. Regional temperature follows from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn *et al.*, 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al*. (1996).

The climate impact module, based on Tol (2002a; b) includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol, 2002b).

People can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set to be 3 times the per capita income (Tol, 1995b), the value of immigration is 40 per cent of the per capita income in the host region (Cline, 1992). Losses of dryland and wetlands due to sea level rise are modelled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 (cf. Fankhauser, 1994). The wetland value is assumed to have logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their ‘natural’ units (cf. Tol, 2002a). Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol, 2002b).

The impacts of climate change on coastal zones, forestry, unmanaged ecosystems, water resources, diarrhoea malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (cf. Tol, 2002b).

Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) (cf. Tol, 2002b). The income elasticities in Tol (2002b) are estimated with cross-sections measured in MER incomes. Following Tol (2006a), they were adjusted for PPP.

4. Results

Table 10 shows the marginal damage cost of carbon dioxide for a pure rate of time preference of 1% per year and a inequality aversion of 1. The simple sum of the regional marginal damage costs is $16/tC, well within the range of estimates in previous studies (Tol, 2005c). Split over 16 regions, under sovereignty, the marginal damage costs per region are obviously much lower. China stands out as very vulnerable. This is due to a range of factors, including its large size, aging population, precarious water supply, and economic concentration in the coastal zone.

The equation for compensated marginal damage costs is similar to that in the cooperative case, but the discount rate is different. For regions with slow (fast) growth, the compensated marginal damage costs are higher (lower) than the cooperative costs. Cf. Table 9.

The equity-weighted marginal damage costs are $28/tC, almost double the simple sum as more weight is placed on the higher impacts in the poorer regions. Good-neighbourliness is similar to equity-weighting, but the normalisation is done with the regional rather than the world average income. As a result, good-neighbour marginal damage costs are much higher than equity-weighted damages for rich regions, and lower for poor regions. Cf. Table 9.

The altruistic marginal damage costs are somewhere in between the sovereign costs and the good-neighbour costs. We here use $\varphi = 0.1$.

The relative magnitudes of the marginal damage costs also give some insight into the preferences of regions. In every region, the sovereign damage costs are lowest. That is, free-riding pays. In the OECD, cooperation would lead to lower emission reduction than compensation and good neighbourliness.[31] In the poorest regions, being a good neighbour would imply the lowest emission reduction obligations (apart from sovereignty). In middle income countries, compensation would imply the minimum emission reduction. It is therefore unlikely that regions would be unanimous in agreeing what would be the “right” framework for setting marginal damage costs and hence marginal abatement costs.

Table 11 and Table 12 show the same information, but for pure rates of time preference of 0% and 3%, respectively, in Table 10, the value is 1%. As one would expect, lower (higher) discount rates lead to higher (lower) marginal damage costs estimates. However, the relative positions of sovereign, cooperative, equity-weighted, altruistic, compensated, and good neighbour marginal damage costs is unchanged.

Table 13 and Table 16 repeat this information for a inequality aversion of 0.5 and 2.0, respectively; Table 15 has the intermediate case of 1.5; in Table 10, the value is 1.0. Changing the CCRA has two effects: First, the equity weights change. Second, the discount rate changes. These two effects work in the opposite direction.

Equity weights are unity for sovereign, cooperative, and compensated marginal damage costs. A higher (lower) inequality aversion implies a higher (lower) discount rate and lower (higher) marginal damage costs.

For equity-weighted, altruistic, and good neighbour marginal damage costs, the rate of inequity aversion affects both the discount rate and the equity weight. In Table 14 and Table 17, we abandon Ramsey discounting and keep the discount rate as in the base case. This confirms that a higher (lower) inequity aversion implies higher (lower) equity-weights and higher (lower) marginal damage costs.

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[31] The equity-weighted marginal damage costs are also lower than the compensated and good neighbour ones for the OECD. However, equity-weighted marginal damage costs cannot be compared to unweighted regional marginal abatement costs.

Returning to Table 13 and Table 16, we see that the discount-rate effect tends to dominate the equity-weight effect, except in the richest regions (e.g., good-neighbour marginal costs in Japan and South Korea) where the marginal cost first falls and then rises with a rising rate of inequity aversion.

5. Discussion and conclusion

Climate change is a global problem, but decisions are made by national decision makers. In previous papers, researchers have discussed the appropriate carbon tax for a global decision maker. Here, we discuss the appropriate carbon tax for a national decision maker. We distinguish four different cases. First, the national decision maker does not care about what happens abroad. Second, the national decision maker is altruistic towards foreigners. Third, the national decision maker compensates damages done abroad. Fourth, the national decision makers feels responsible for damages done abroad, but cannot compensate. Carbon taxes are lowest in the first case (sovereignty). They are highest in the fourth case (good neighbour) for the richest regions, and in the third case (compensation) for the poorest regions. Middle income regions may face the highest carbon taxes under international cooperation. This order is robust to the choice of the pure rate of time preference and the inequality aversion, but carbon taxes are higher if the pure rate of time preference is lower, and carbon taxes tend to be higher if the inequality aversion is higher.

Further research in this field would certainly be welcome. The analysis here should be reproduced with other integrated assessment models. A wider range of utility and welfare functions should be explored, and the link between the utility function and the willingness to pay for climate change impacts should be made. The interactions between risk and inequity aversion should be added. The resolution of the model should be refined, and further interactions between actors should be added. And, of course, the implications of our research for greenhouse gas emission reduction, both in a cooperative and a non-cooperative setting, need to be investigated.

The policy implications are twofold. First, a wide range of carbon taxes can be defended. The highest carbon tax differs from the lowest carbon tax by up to a factor 70 for a 1% pure rate of time preference, and up to a factor 470 for a 0% PRTP. This large difference is due to different ethical positions on the kind of responsibility one country should have towards other countries. Climate policy is a moral issue. Moral positions can be debated, and although reasonable people will disagree, politicians should be able to resolve this. Indeed, some would argue that that is what politicians are for. Furthermore, the stated willingness to pay for climate policy can be "inverted" to find the corresponding ethical position. The EU price of CO2 permits is some $82/tC,[32] so European politicians have a pure rate of time preference that is well below 3% and do display concern for non-European impacts.[33] This of course begs the question of consistency. European pensions policy suffers from short-termism, while European agricultural policy hurts other countries.

The second policy implication is as follows. The results presented here show that, without cooperation, different regions should have different carbon taxes. This is not news. See Bradford (2005), Helm (2003), Rehdanz and Tol (2005), and Tol (2005c) for ways to reconcile non-cooperative target-setting with international trade in emission permits. However, this paper also shows that a lack of international cooperation on target-setting does not necessarily lead to low carbon taxes. If countries agree to compensate one another for the damage they do to one another, carbon taxes would be substantial. One may argue that that obligation already exists in principle, but practice is

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[32] €16.08/tCO_2; 0.719 $/€; price and exchange rate of 22 December 2008

[33] Note that different assumptions about future emissions, climate change, and impacts may also explain a higher willingness to pay.

different. Nonetheless, if our results are to be believed, a treaty on international liability would drive climate policy harder than in the cooperative optimum. But also without any international treaty, a sense of concern for foreign lands, be it in its altruistic or its good neighbourly form, would also lead countries to adopt a more stringent climate policy than is in their strict self-interest. In turn, this would reduce the fear of leakage and lost competitiveness in other countries and may lead to increased abatement there as well.

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7. Tables

	Weight of welfare abroad	**Equity weight**	**Discount rate**
Sovereignty	$\varphi = 0$	-	-
Altruism	$0 < \varphi < 1$	$\omega_f = \left(\frac{C_{0,h}}{C_{0,f}} \right)^{\varepsilon}$	$r = 1 + \rho + \varepsilon g_f$
Good neighbour	$\varphi = 1$	$\omega_f = \left(\frac{C_{0,h}}{C_{0,f}} \right)^{\varepsilon}$	$r = 1 + \rho + \varepsilon g_f$
Cooperation	$\varphi = 1$	$\omega_f = 1$	$r = 1 + \rho + \varepsilon g_f$
Equity weighing	$\varphi = 1$	$\omega_f = \left(\frac{C_{0,w}}{C_{0,f}} \right)^{\varepsilon}$	$r = 1 + \rho + \varepsilon g_f$
No sense	$\varphi = 1$	$\omega_f = \left(\frac{C_{0,h}}{C_{0,f}} \right)^{\varepsilon}$	$r = 1 + \rho + \varepsilon g_h$
Compensation	$\varphi = 1$	$\omega_f = 1$	$r = 1 + \rho + \varepsilon g_h$

Table 8: Alternative positions on impacts abroad; see Equation (4.18); h=home, f=foreign, w=world

	Population		**Income**		**Impact**
	(millions)		**(PPP $/cap)**	**(-)**	**(% GDP)**
	2000	**2100**	**2000**	**2100/2000**	**2100**
USA	278	298	37,317	3.7	-0.51
CAN	31	34	25,498	3.8	-0.14
WEU	388	396	30,312	3.9	-0.91
JPK	171	223	42,872	4.4	0.19
ANZ	20	28	21,437	3.8	0.47
EEU	125	126	5,394	6.0	-0.64
FSU	293	292	4,493	5.2	-4.04
MDE	241	553	3,397	7.7	1.05
CAM	137	216	6,783	5.4	-0.12
SAM	346	537	7,920	5.4	-0.41
SAS	1,366	2,630	1,984	5.9	-0.45
SEA	630	1,197	4,588	5.9	-1.49
CHI	1,315	1,712	5,509	8.1	-0.41
NAF	143	401	2,248	6.2	-4.40
SSA	639	1,831	1,198	5.2	-1.99
SIS	43	66	1,545	9.3	0.29
World	6,168	10,541	8,580	3.9	-0.63

Table 9: Regional characteristics

	Sovereign	**Altruism**	**Compensation**	**Good neighbour**
USA	0.91	13.35	33.76	125.27
CAN	0.07	8.62	33.28	85.60
WEU	1.54	11.56	32.35	101.76
JPK	0.30	14.66	27.95	143.92
ANZ	0.06	7.25	33.15	71.97
EEU	0.12	1.92	17.89	18.11
FSU	0.80	2.23	24.32	15.08
MDE	0.38	1.49	9.82	11.40
CAM	0.26	2.51	17.28	22.77
SAM	0.23	2.86	15.11	26.59
SAS	1.07	1.63	17.28	6.66
SEA	1.27	2.68	16.42	15.40
CHI	7.49	8.59	12.70	18.49
NAF	0.43	1.14	13.39	7.55
SSA	0.57	0.92	18.85	4.02
SIS	0.07	0.58	8.54	5.19
Cooperation	15.56			
Equity weights	27.86			

Table 10: The regional marginal damage costs of carbon dioxide (in $/tC), for a pure rate of time preference of 1% per year and a inequality aversion of 1

	Sovereign	Altruism	Compensation	Good neighbour
USA	5.06	86.45	230.66	818.93
CAN	0.39	56.31	227.44	559.58
WEU	9.33	74.91	222.08	665.21
JPK	2.42	96.26	189.33	940.86
ANZ	0.39	47.40	226.58	470.45
EEU	0.83	12.58	117.34	118.37
FSU	4.99	14.35	164.83	98.61
MDE	2.70	9.88	61.17	74.55
CAM	1.83	16.53	109.59	148.86
SAM	1.40	18.64	94.04	173.81
SAS	7.31	10.93	114.78	43.54
SEA	8.08	17.34	105.49	100.69
CHI	50.30	57.36	84.13	120.90
NAF	2.51	7.19	85.88	49.34
SSA	3.49	5.77	121.86	26.29
SIS	0.48	3.82	54.38	33.91
Cooperation	101.49			
Equity weights	182.12			

Table 11: The regional marginal damage costs of carbon dioxide (in $/tC), for a pure rate of time preference of 0% per year and a inequality aversion of 1

	Sovereign	Altruism	Compensation	Good neighbour
USA	0.05	0.57	1.33	5.22
CAN	0.00	0.36	1.31	3.57
WEU	0.08	0.49	1.27	4.24
JPK	0.00	0.60	1.12	6.00
ANZ	0.00	0.30	1.31	3.00
EEU	0.00	0.08	0.75	0.75
FSU	0.04	0.10	0.98	0.63
MDE	0.01	0.06	0.44	0.48
CAM	0.01	0.10	0.75	0.95
SAM	0.01	0.12	0.68	1.11
SAS	0.04	0.06	0.71	0.28
SEA	0.05	0.11	0.70	0.64
CHI	0.31	0.35	0.53	0.77
NAF	0.02	0.05	0.58	0.31
SSA	0.03	0.04	0.80	0.17
SIS	0.00	0.02	0.37	0.22
Cooperation	0.66			
Equity weights	1.16			

Table 12: The regional marginal damage costs of carbon dioxide (in $/tC), for a pure rate of time preference of 3% per year and a inequality aversion of 1

	Sovereign	**Altruism**	**Compensation**	**Good neighbour**
USA	2.13	17.14	84.22	152.17
CAN	0.16	12.72	83.62	125.78
WEU	3.80	17.13	82.48	137.14
JPK	0.87	17.10	76.49	163.10
ANZ	0.14	11.66	83.46	115.33
EEU	0.42	6.17	60.85	57.85
FSU	2.28	7.34	71.29	52.80
MDE	1.86	6.27	44.57	45.91
CAM	0.94	7.33	59.45	64.88
SAM	0.83	7.76	55.35	70.10
SAS	3.77	6.90	59.94	35.09
SEA	4.48	9.37	58.09	53.36
CHI	30.36	33.17	51.30	58.47
NAF	1.60	5.18	52.39	37.35
SSA	1.85	4.39	62.35	27.27
SIS	0.35	3.42	41.72	30.96
Cooperation	55.87			
Equity weights	71.76			

Table 13: The regional marginal damage costs of carbon dioxide (in $/tC), for a pure rate of time preference of 1% per year and a inequality aversion of 0.5

	Sovereign	**Altruism**	**Compensation**	**Good neighbour**
USA	0.91	4.93	33.76	41.08
CAN	0.07	3.46	33.28	33.96
WEU	1.54	5.09	32.35	37.03
JPK	0.30	4.67	27.95	44.03
ANZ	0.06	3.16	33.15	31.14
EEU	0.12	1.67	17.89	15.62
FSU	0.80	2.15	24.32	14.26
MDE	0.38	1.59	9.82	12.40
CAM	0.26	1.98	17.28	17.52
SAM	0.23	2.10	15.11	18.93
SAS	1.07	1.91	17.28	9.47
SEA	1.27	2.58	16.42	14.40
CHI	7.49	8.32	12.70	15.78
NAF	0.43	1.39	13.39	10.08
SSA	0.57	1.25	18.85	7.36
SIS	0.07	0.90	8.54	8.36
Cooperation	15.56			
Equity weights	19.37			

Table 14: The regional marginal damage costs of carbon dioxide (in $/tC), for a pure rate of time preference of 1% per year and a inequality aversion of 0.5; inequality aversion does not affect the money discount rate

	Sovereign	**Altruism**	**Compensation**	**Good neighbour**
USA	0.40	12.70	13.84	123.46
CAN	0.03	7.00	13.55	69.73
WEU	0.64	9.61	12.97	90.38
JPK	0.10	15.29	10.49	152.03
ANZ	0.02	5.40	13.47	53.76
EEU	0.04	0.71	5.46	6.78
FSU	0.29	0.77	8.53	5.16
MDE	0.08	0.41	2.29	3.39
CAM	0.07	1.02	5.25	9.57
SAM	0.07	1.27	4.36	12.07
SAS	0.31	0.43	5.15	1.51
SEA	0.37	0.87	4.84	5.32
CHI	1.91	2.42	3.26	7.00
NAF	0.12	0.29	3.58	1.83
SSA	0.18	0.24	5.93	0.71
SIS	0.01	0.12	1.84	1.04
Cooperation	4.65			
Equity weights	12.95			

Table 15: The regional marginal damage costs of carbon dioxide (in $/tC), for a pure rate of time preference of 1% per year and inequality aversion of 1.5

	Sovereign	**Altruism**	**Compensation**	**Good neighbour**
USA	0.18	14.85	5.80	146.86
CAN	0.01	6.87	5.63	68.57
WEU	0.27	9.93	5.31	96.90
JPK	0.03	19.42	4.03	193.84
ANZ	0.01	4.85	5.59	48.47
EEU	0.01	0.32	1.72	3.07
FSU	0.11	0.31	3.07	2.13
MDE	0.02	0.14	0.56	1.22
CAM	0.02	0.50	1.66	4.85
SAM	0.02	0.68	1.32	6.62
SAS	0.09	0.13	1.58	0.42
SEA	0.11	0.32	1.48	2.22
CHI	0.51	0.78	0.86	3.20
NAF	0.04	0.08	0.99	0.53
SSA	0.06	0.07	1.93	0.15
SIS	0.00	0.03	0.42	0.25
Cooperation	1.49			
Equity weights	7.26			

Table 16: The regional marginal damage costs of carbon dioxide (in $/tC), for a pure rate of time preference of 1% per year and inequality aversion of 2.0

	Sovereign	**Altruism**	**Compensation**	**Good neighbour**
USA	0.91	43.83	33.76	430.14
CAN	0.07	24.36	33.28	242.95
WEU	1.54	32.88	32.35	314.90
JPK	0.30	53.23	27.95	529.68
ANZ	0.06	18.78	33.15	187.29
EEU	0.12	2.47	17.89	23.64
FSU	0.80	2.52	24.32	17.97
MDE	0.38	1.53	9.82	11.81
CAM	0.26	3.57	17.28	33.34
SAM	0.23	4.41	15.11	42.06
SAS	1.07	1.49	17.28	5.27
SEA	1.27	2.99	16.42	18.54
CHI	7.49	9.18	12.70	24.40
NAF	0.43	1.02	13.39	6.36
SSA	0.57	0.76	18.85	2.47
SIS	0.07	0.43	8.54	3.62
Cooperation	15.56			
Equity weights	45.11			

Table 17: The regional marginal damage costs of carbon dioxide (in $/tC), for a pure rate of time preference of 1% per year and inequality aversion of 1.5; inequality aversion does not affect the money discount rate

V Optimal Dynamic Carbon Taxation

1. Introduction

It is almost a common place in the economics of climate change that a good response to the challenges posed by global warming would be a harmonized, global tax on greenhouse gas emissions that increases over time roughly with the discount rate (e.g. Nordhaus, 2007c). Many details of such proposal are hotly discussed, but one aspect receives relatively little questioning in the economic literature: should a carbon tax really be harmonized across the world, i.e. should the same tax rate on carbon emissions be enforced in all countries?

The classical role of a Pigouvian tax on an economic activity that creates an externality is to correct the inefficiency associated with damages that are not reflected in market prices of goods. Traditionally distributional consequences are not dealt with at this stage, but rather it is assumed that other instruments can or will be used to “make up” for any unwanted distributional consequence caused by the correction of the externality. This is in the spirit of the Kaldor-Hicks criterion (Kaldor, 1939; Hicks, 1939), i.e. that distributional issues ought to be separated from questions of economic efficiency. While there is a convincing argument that within one jurisdiction a government that could impose a tax on an externality does also have the necessary means (e.g. the income tax) to correct any undesirable distributional consequence caused by such a Pigouvian tax, this argument does not apply equally to cross-national cases of externalities or public goods. Climate change as a truly global public good is a classical example of that.

An early discussion of this problem was provided in Chichilnisky and Heal (1994)[34]. They contrasted optimal marginal abatement costs of carbon emissions in a multi region setting when lump sum transfers are possible between different regions with a situation in which such transfers are ruled out. They found that in the latter optimal marginal abatement costs were different in each region, whereas with lump sum transfers the classical result of equated marginal abatement costs prevailed. They used a static model around a global public bad as an approximation to the climate change problem, but given the inherent dynamic nature of the climate problem, they mostly derived basic theoretical results that as such are hard to apply to concrete climate change policy questions.

Sandmo (2006) investigates the question of optimal Pigouvian taxes in relation to a global externality, again in a static utilitarian framework. He comes to a similar conclusion as Heal and Chichilnisky: Unless one assumes that lump sum transfers between regions are possible, optimal Pigouvian taxes on the externality producing activity should not be harmonized or equalized across countries, but rather poor countries should impose lower taxes than rich countries.

The basic result that under certain welfare functions and an absence of lump sum transfers marginal abatement costs ought not to be equated has been discussed in a number of other papers as well. Most of these treatments stick to a static description of the problem, which makes their results not immediately applicable to a simulation of a stock externality problem like climate change with an integrated assessment model. Eyckmans *et al.* (1993) show not only that marginal abatement costs might differ

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[34] Sheeran (2006) provides an extended discussion of the same result.

between world regions in an optimum for specific welfare functions, but also discuss how various choices of welfare weights correspond to different results from negotiation processes. Shiell (2003b) acknowledges the basic result in Chichilnisky and Heal but argues that with a permit market the necessary lump sum transfers can always be obtained via the initial allocation of permits and that therefore differentiated marginal abatement costs could be avoided[35]. In this paper I look at a situation where this option is for whatever reason not possible. I will not give a stringent argument for this, but it seems at least plausible that large wealth transfers from rich to poor countries via initial allocation rules in a permit market might be politically infeasible.

Other papers have dealt with equity in climate change abatement in broader terms. Tol (2001) and Tol (2002c) look at optimal emission abatement under a variety of different welfare functions. Böhringer and Helm (2008) look at equity with respect to abatement costs only.

In this paper I build upon those results and extend them such that they can readily be employed for the analysis of climate change. On a theoretical level, I extend the analysis into a dynamic setting with a global stock externality, thus allowing an application to climate change. In doing so I also clarify how the discount rate is modified in an optimal setting that does not allow for lump sum transfers between regions. In a second step I then apply the integrated assessment model *FUND* to the problem and derive numerical estimates of optimal tax rates on carbon emissions, the corresponding optimal emission trajectory and optimal temperature targets. In a final step I do a sensitivity analysis of the results with respect to the key preference parameters of the pure rate of time preference and the inequality aversion.

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[35] Shiell (2003a) uses a similar set up of welfare functions, dynamic optimization and regional disaggregation as used in this paper, but by assumption rules out differences in marginal abatement costs between regions, thereby focusing on a different question than I try to answer in this paper.

The rest of the paper is structured as following: In section 2, I present a theoretical model of optimal marginal abatement costs of a global public bad in a setting with and without lump sum transfers and derive key necessary conditions for an optimal emissions trajectory. In section 3 a brief description of the integrated assessment model *FUND* is given. Section 4 presents results and section 5 concludes.

2. Theory

Let $x_{t,r}$ be carbon emissions in year t in region r. Total emissions in year t are defined as $X_t \equiv \sum_r x_{t,r}$. Greenhouse gas concentrations S in each year are characterised by a transition function g

$$S_{t+1} = g\left(S_t, X_t\right) \tag{5.1}$$

Concentrations depend on previous concentrations and current emissions from all regions.

Per capita consumption $c_{t,r}$ in year t in region r is

$$c_{t,r}\left(S_t, x_t\right) = \frac{C_{t,r}\left(x_{t,r}\right) - D_{t,r}\left(S_t, X_t\right)}{P_{t,r}} \tag{5.2}$$

where $C_{t,r}$ is total consumption, $D_{t,r}$ is climate change damage and $P_{t,r}$ is population.

Consumption is assumed to depend on emissions, where we assume that $C_{t,r}\left(0\right) = 0$, that there is an emissions level $\overline{x}_{t,r}$ that maximizes consumption and that $C_{t,r}$ is strictly concave. It follows that for all emission levels between 0 and $\overline{x}_{t,r}$, increasing emissions will increase consumption, i.e. $C'_{t,r}\left(x\right) > 0$ for all $x \in \left(0, \overline{x}_{t,r}\right)$. C is calibrated such that the optimal emissions level $\overline{x}$ and its corresponding income C follow the business as usual scenario of the *FUND* model.

Damage in period t depends both on the stock of carbon in the atmosphere at that time. Due to the formulation of the transition function, S_t only accounts for emissions in periods before t, but actual carbon concentrations at t also depend on emissions in t. Therefore damage in period t is a function of both S_t as well as X_t concentrations , as well as on total emissions of all regions in the current period.

2.1. Optimal emissions path

The optimization problem of a global planner is given as

$$\begin{aligned} &\max_{\{x_t\}_{t=0}^{T}} \sum_{t=0}^{T} \delta^t \sum_r P_{t,r} U\left(c_{t,r}\left(S_t, x_t\right)\right) \\ &s.t. S_0 = \bar{S}_0 \end{aligned} \tag{5.3}$$

for a standard utilitarian welfare function, with $\bar{S}_0$ being the carbon concentration at the start of the optimization period. $0 < \delta < 1$ is the per period discount factor. We also assume that the utility function U has the usual iso-elastic form:

$$U(c) = \begin{cases} \ln c & \text{for}\,\eta = 1 \\ c^{1-\eta} / 1 - \eta & \text{for}\,\eta \neq 1 \end{cases} \tag{5.4}$$

The Bellman equations[36] for this problem are

$$V_t\left(S_t\right) = \max_{\{x_{t,r}\}_r} \sum_r P_{t,r} U\left(c_{t,r}\left(S_t, x_t\right)\right) + \delta V_{t+1}\left(S_{t+1}\right) \quad \forall t \tag{5.5}$$

for each time t, with $V_t\left(S_t\right)$ as the value function for time t. The first order conditions for the maximization problem of the value function for year t are

$$\frac{\partial}{\partial x_{t,i}} \left(\sum_r P_{t,r} U\left(c_{t,r}\left(S_t, x_t\right)\right) + \delta V_{t+1}\left(S_{t+1}\right) \right) = 0 \quad \forall i. \tag{5.6}$$

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[36] The problem could of course also be solved by simply using Lagrange multiplier, given the finite time horizon of the model. A dynamic programming approach seems nevertheless easier and less convoluted.

Using standard finite time horizon dynamic programming practice, we start deriving first order conditions at the end of the time horizon T, and then derive first order conditions for earlier time steps t going back in time until we reach $t = 0$. Given the complexities of the integrated assessment model used for this exercise, I do not derive an analytical solution for the value function, but rather find first order conditions that I can then use in a numerical search algorithm for the optimal emissions path.

Let a marginal emission of carbon in year t cause marginal damage MD in year s and region r, i.e.

$$MD_{s,r}\left(t\right) \equiv \begin{cases} \dfrac{\partial D_{s,r}\left(S_s, X_s\right)}{\partial X_s} & \text{for } t = s \\ \dfrac{\partial D_{s,r}\left(S_s, X_s\right)}{\partial S_s} & \text{for } t < s \end{cases} \tag{5.7}$$

With some manipulation we can rewrite the first order conditions as

$$C'_{t,i}\left(x_{t,i}\right) = \sum_{s=t}^{T} \delta^{s-t} \sum_{r} \underbrace{\left(\frac{c_{t,i}\left(S_t, x_t\right)}{c_{s,r}\left(S_s, x_s\right)} \right)^{\eta}}_{a} MD_{s,r}\left(t\right) \quad \forall i \tag{5.8}$$

This is a variation of the familiar rule that marginal abatement costs should equal marginal damage costs, but with some important modifications. On the left hand side are marginal abatement costs for a specific region i in year t. The right hand side of the equation is the weighted sum of marginal damages happening in every year after t in all regions. There are two weights applied, first the pure time preference factor $\delta^{s-t} = 1 \big/ \left(1+\rho\right)^{s-t}$ with the pure rate of time preference ρ. The second weight after the summation sign over regions (part a) is a combination of distributional weights and the growth part in the standard Ramsey discount rate. Two different interpretations can help understand this second weight.

To see the first we rewrite both weights for a specific region r and time s as

$$\underbrace{\delta^{s-t}\left(\frac{c_{t,i}\left(S_t,x_t\right)}{c_{s,r}\left(S_s,x_s\right)}\right)^{\eta}}_{a} \approx \underbrace{\left(\frac{c_{t,i}\left(S_t,x_t\right)}{c_{t,r}\left(S_t,x_t\right)}\right)^{\eta}}_{b} \underbrace{\left(\frac{1}{1+\rho+\eta g\left[c_{t,r}\left(S_t,x_t\right),c_{s,r}\left(S_s,x_s\right),s-t\right]}\right)^{s-t}}_{c} \tag{5.9}$$

Here $g\left(c_1,c_2,t\right)$ is defined as the average constant growth rate at which per capita consumption would grow from c_1 to c_2 over a time span of t years.[37] Part c is the standard Ramsey type discount factor for region r, based on per capita growth of the region where the damages occur.

Part b is a distributional weight that is applied to the net present value of damage in a particular region. The distributional weight given to marginal damages occurring in the region for which we have marginal abatement costs in the equation will always be one, so that abatement and damages are valued equally and consistently (Anthoff *et al.*, 2009). Marginal damages in other regions receive a distributional weight that will be >1 (<1) for regions with lower (higher) per capita consumption than the regions for which abatement costs are calculated.

To see the second interpretation we rewrite part a and the time discount factor as:

$$\underbrace{\delta^{s-t}\left(\frac{c_{t,i}\left(S_t,x_t\right)}{c_{s,r}\left(S_s,x_s\right)}\right)^{\eta}}_{a} \approx \left(\frac{1}{1+\rho+\eta g\left[c_{t,i}\left(S_t,x_t\right),c_{s,r}\left(S_s,x_s\right),s-t\right]}\right)^{s-t} \tag{5.10}$$

The expression on the right hand side of equation (5.10) is just the standard Ramsey type discount rate with a per capita growth rate that goes from the current level of the

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[37] g is defined by the equation $c_1\left[1+g\left(c_1,c_2,t\right)\right]^t = c_2$.

abating region to the per capita consumption of the region and the time where the marginal damage is occurring. Note that in principal this discount rate can be negative, when abatement costs are calculated for a region with a high current per capita income and damages that occur in a lower per capita region relative to that.

We can now ask ourselves how optimal marginal abatement costs for different regions will look like. Another rearrangement of equation (5.8) gets us

$$C'_{t,i}\left(x_{t,i}\right)=\underbrace{\left[c_{t,i}\left(S_t,x_t\right)\right]^{\eta}}_{d}\sum_{s=t}^{T}\delta^{s-t}\sum_{r}\left[c_{s,r}\left(S_s,x_s\right)\right]^{-\eta}MD_{s,r}\left(t\right) \tag{5.11}$$

for marginal abatement costs in region i. Notice that except for part d all terms on the right hand side of the equation are the same for all regions. This allows for an easy interpretation: Optimal marginal abatement costs are higher for higher per capita consumption regions, and that effect is stronger for higher inequality parameters η, where higher inequality also increases the difference between the optimal marginal abatement costs of different regions.

2.2. Efficient emissions path

We now derive efficient abatement costs. Unlike the previous section, we ignore distributional questions between regions this time. The welfare economic rationale for such an approach would be the assumption that lump sum transfers are feasible and that any desirable distributional outcome can be achieved in a second step via such lossless transfers, after the externality has been internalized via a Pigouvian price signal – that is, the Coase (1960) Theorem holds.

Following the standard approach in the literature we replace our objective function with a new version that includes so called Negishi-weights

$$\begin{aligned}&\max_{\{x_t\}_{t=0}^{T}} \sum_{t=0}^{T} \delta^t \sum_r \lambda_{t,r} P_{t,r} U\left[c_{t,r}\left(S_t, x_t\right)\right] \\ &\text{s.t. } S_0 = \bar{S}_0\end{aligned} \tag{5.12}$$

We calibrate the Negishi weights λ such that in our base case run marginal utility is equalized across all regions at each time step. In order to achieve this we follow the standard procedure (Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000) and set

$$\lambda_{t,r} = \left(\frac{c_{t,r}}{\sum_i C_{t,i}\left(x_{t,i}\right) \big/ \sum_i P_{t,i}} \right)^{\eta} = \left(\frac{c_{t,r}}{c_t} \right)^{\eta} \tag{5.13}$$

where we define c_t to be world average per capita consumption at time t.

The new Bellman equations are

$$V_t\left(S_t\right) = \max_{\{x_{t,r}\}_r} \sum_r \lambda_{t,r} P_{t,r} U\left[c_{t,r}\left(S_t, x_t\right)\right] + \delta V_{t+1}\left(S_{t+1}\right) \quad \forall t \tag{5.14}$$

The new first order conditions are, after some algebraic manipulation

$$C'_{t,i}\left(x_{t,i}\right) = \sum_{s=t}^{T} \delta^{s-t} \sum_r \left(\frac{c_t\left(S_t, x_t\right)}{c_s\left(S_s, x_s\right)} \right)^{\eta} MD_{s,r}\left(t\right) \quad \forall t, i \tag{5.15}$$

for all time periods. Note that in this case in each time step marginal abatement costs are equal for all regions, given that the right hand side of equation (5.15) is the same for all regions. The weight given to the marginal damage term is reduced to the standard Ramsey discount factor

$$\delta^{s-t} \left(\frac{c_t\left(S_t, x_t\right)}{c_s\left(S_s, x_s\right)} \right)^{\eta} = \left(\frac{1}{1+\rho} \right)^{s-t} \left(\frac{1}{1+\eta g_s} \right)^{s-t} \approx \left(\frac{1}{1+\rho+\eta g_s} \right)^{s-t} \tag{5.16}$$

with g_s being the annual growth rate of world average per capita consumption from time t to s.

3. The Model

FUND (the Climate Framework for Uncertainty, Negotiation and Distribution) is an integrated assessment model linking projections of populations, economic activity and emissions to a simple carbon cycle and climate model, and to a model predicting and monetizing welfare impacts. Climate change welfare impacts are monetarized in 1995 dollars and are modelled over 16 regions. Modelled welfare impacts include agriculture, forestry, sea level rise, cardiovascular and respiratory disorders influenced by cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems (Link and Tol, 2004). The source code, data, and a technical description of the model can be found at http://www.fund-model.org.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. Version 3.4, used in this paper, runs from 1950 to 3000 in time steps of one year. The primary reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, the welfare impacts of climate change are assumed to depend in part on the impacts during the previous year, reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical impacts and monetized welfare impacts of climate change tend to be misrepresented in the first few decades of the model runs. The 22nd and 23rd centuries are included to provide a proper long-term perspective. The remaining centuries are included to avoid endpoint problems for low discount rates, they have only a very minor impact on overall results.

The period of 1950-1990 is used for the calibration of the model, which is based on the *IMAGE* 100-year database (Batjes and Goldewijk, 1994). The period 1990-2000 is based on observations (http://earthtrends.wri.org). The 2000-2010 period is interpolated from the immediate past. The climate scenarios for the period 2010-2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett *et al.*, 1992). The period 2100-3000 is extrapolated.

The scenarios are defined by varied rates of population growth, economic growth, autonomous energy efficiency improvements, and decarbonization of energy use (autonomous carbon efficiency improvements), as well as by emissions of carbon dioxide from land use change, methane emissions, and nitrous oxide emissions.

Emission reduction of carbon dioxide, methane and nitrous oxide is specified as in Tol (2006b). Simple cost curves are used for the economic impact of abatement, with limited scope for endogenous technological progress and interregional spillovers (Tol, 2005b).

The scenarios of economic growth are perturbed by the effects of climatic change.[38] Climate-induced migration between the regions of the world causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The tangible welfare impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. As a result, climate change reduces long-term economic growth, although consumption is particularly affected in

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[38] Note that in the standard version of FUND population growth is also perturbed by climate change impacts. That particular feature was switched off in the runs for this paper because endogenous population changes cannot be evaluated with the kind of welfare function investigated.

the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the effect of carbon dioxide emission reductions on the economy and on emissions, and the effect of the damages on the economy caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt *et al*. (1992).

The radiative forcing of carbon dioxide, methane, nitrous oxide and sulphur aerosols is determined based on Shine *et al*. (1990). The global mean temperature, T, is governed by a geometric build-up to its equilibrium (determined by the radiative forcing, RF), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. Regional temperature is derived by multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn *et al.*, 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996).

The climate welfare impact module, based on Tol (2002a; b) includes the following categories: agriculture, forestry, hurricanes, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages are triggered by either the rate of temperature change (benchmarked at 0.04°C/yr) or the level of temperature change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol, 2002b).

In the model individuals can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all welfare impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income.[39] The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set to be three times the per capita income (Tol, 1995a; 1996), the value of immigration is 40 per cent of the per capita income in the host region (Cline, 1992). Losses of dryland and wetlands due to sea level rise are modelled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 (cf. Fankhauser, 1994). The wetland value is assumed to have a logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other welfare impact categories, such as agriculture, forestry, hurricanes, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer

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[39] Note that this implies that the monetary value of health risk is effectively discounted with the pure rate of time preference rather than with the consumption rate of discount (Horowitz, 2002). It also implies that, after equity weighing, the value of a statistical life is equal across the world (Fankhauser *et al.*, 1997).

of impacts measured in their ‘natural’ units (cf. Tol, 2002a). Modelled effects of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol, 2002b).

The welfare impacts of climate change on coastal zones, forestry, hurricanes, unmanaged ecosystems, water resources, diarrhoea, malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (cf. Tol, 2002b).

Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth) and heat-related disorders (with urbanization), or more valuable, such as ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) (cf. Tol, 2002b).

4. Results

In this section I will present results for an optimal tax scheme in which lump sum transfers between regions are assumed to be possible and one where there are no transfers. These correspond to the two welfare functions presented in section 2. After presenting some results for key indicators like tax rates, emission rates and temperature development, I will present sensitivity analysis for a number of key parameters.

4.1. Central results

Figure 17 contrasts tax rates for the different regions of *FUND* in the year 2005 for a specific calibration of the utility function (pure rate of time preference of 1% and η of 1). In the case with the possibility of transfer payments, optimal tax rates (or marginal abatement costs) are equal in all regions at $23/tC[40]. When transfer or compensation payments are ruled out, tax rates differ greatly between regions, with optimal tax rates for rich regions (ANZ, CAN, WEU, USA and JPK) increasing up to $179 for Japan, while the tax rate decreases in all other regions, to below $2 for very poor regions like sub Saharan Africa. China's optimal tax is almost reduced by 50% to $12.

As income differences between regions change over time, so does the spread of tax rates between different regions. Figure 18 shows optimal tax rates for a few selected regions in the year 2050 and 2100 for the same utility function calibration as previous. For the scenario with lump sum transfers the optimal tax increases to $60 in the year 2050 and $148 in the year 2100 for all regions. The assumed rapid economic growth of China in the scenario makes for a dramatic adjustment of its optimal tax rate over time: In the year 2050 the tax without transfers payments is just 15% below the global tax rate in a scenario with lump sum transfers (compared to 50% in the year 2005), and in the year 2100 China would actually have a higher tax on carbon emissions in a scenario without transfers compared to one with.

Figure 19 demonstrates what these tax rates imply in terms of emissions reductions per region. The graph shows the reduction of emissions in percent in the year 2050 for each

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[40] All results are in 1995 USD.

region compared to its emissions in a business as usual scenario.[41] In the scenario with lump sum transfers the question in which regions reductions occur is only determined by the cost of emission reductions, i.e. regions with a lot of low cost mitigation opportunities will show large reductions in emissions while regions with only costly mitigation options will reduce less. In regions such as the former Soviet Union, where mitigation can be achieved at low cost, the assumption of no lump sum transfers leads to a situation where those low cost abatement opportunities are not picked up, given that they would be paid for by the relatively low income population of that region. On the other hand, rich regions will mitigate a lot more, although it is costly, given that in the utilitarian welfare calculus those high costs do get less weight when they occur to the relatively wealthy population of the United States.

While the differences between regions vary greatly between a scenario with lump sum transfers and one in which this is ruled out, the total emission reduction stays almost the same at around 19%. While the difference is small, the assumption that no compensation will take place actually leads to a lower total optimal worldwide reduction in emissions. This is a somewhat surprising result, previously there was a sense that taking equity between regions explicitly into account in climate change policy would lead to more stringent mitigation policies. As the results in this paper show, at least under one widely used ethical framework, utilitarianism, this need not be the case. Inequality aversion and a concern for equity will in general give more weight to both impacts and mitigation costs in poor regions than in high income regions. The poor are especially vulnerable to climate change impacts and it has been shown repeatedly that when one only looks into impacts of climate change, a concern for equity increases damage estimates (c.f. Fankhauser *et al.*, 1997; Pearce, 2003; Tol *et al.*,

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[41] In particular these are not reductions compared to a historic base line point (like 1990 or today).

2003; Anthoff *et al.*, 2009), from which one might conclude that more mitigation would be justified under such an approach. The analysis in this paper on the other hand also gives higher weight to mitigation costs in poor regions. If a lot of cheap mitigation options are located in poor regions, such a treatment will have the effect that lower mitigation is appropriate when a concern for equity is present. As the results in this paper show, the latter effect dominates and overall mitigation is lower with a concern for equity.

4.2. Sensitivity analysis

Do these findings vary for different calibrations of the welfare function, in particular for different choices for the pure rate of time preference and inequality aversion? Table 18 shows the resulting temperature increase above pre-industrial temperatures in °C in the year 2100 for the business as usual scenario and contrasts it with the temperature increase that would result if one would choose the optimal mitigation path for various calibrations of the utility function.

The first general result is that for a high pure rate of time preference of 3% there is hardly any difference in the optimal temperature target in the year 2100 over both different preference parameters and scenarios with and without transfer payments, while even the difference between a business as usual scenario and optimal policy scenarios is small. Note also that some of the combinations should not be taken too serious, in particular one would not want to combine a high pure rate of time preference with a high inequality aversion, given that this would lead to real interest rates that are above the observed market rate, unless total factor productivity growth has been overestimated (cf. Nordhaus, 2008 for a careful discussion).

A second general conclusion is that for higher choices of inequality aversion, in general less stringent temperature targets are optimal.[42] While this result would not be surprising if inequalities between regions were neglected (in which case higher inequality versions would simply increase the discount rate), it does not follow analytically for a setup as used in this paper, where higher inequality aversion between regions might have led to a different result. As such the findings in this paper support the conclusion that while higher inequality aversion might alter the distribution of mitigation efforts between regions, overall it will not lead to more stringent optimal global mitigation targets.

When comparing a transfer with a no transfer scenario, the results for different utility function calibrations is more nuanced. While for an inequality aversion of 1, the optimal temperature target is always less stringent if one assumes that no transfers are possible, this result reverses for higher inequality aversion choices. While higher inequality values have been suggested as reasonable for purely intertemporal decisions (Dasgupta, 2008), they would further widen the gap between actually wealth transfers between rich and poor regions and what the optimal wealth transfer according to the welfare function would be (Okun, 1975). The difficulty of using one parameter to both specify inter- as well as intra-temporal inequality aversion (and in non-deterministic models risk aversion as well) has been recognised in the literature, but not yet been resolved (Saelen *et al.*, 2008).

5. Conclusion

In this paper I contrast a first-best world in which an optimal emissions path is calculated purely based on an efficiency criterion, i.e. under the assumption that any distributional consequences of a specific policy can be dealt with at a later stage with

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[42] With one minor exception, but that is so small that it seems not important.

different (and costless) instruments, with a look at a specific ethical framework and a global decision maker that is constraint in its policy options. In particular, I assumed in a second step that a global decision maker has the ability to set mitigation paths for all regions, but does not have any instruments at hand to compensate for unwanted distributional disturbances caused by the emission control policy. In this second scenario I looked at a specific welfare function, namely a classical utilitarian one, and derived optimal emission reduction pathways for different regions.

The results show that the two cases have dramatically different emission reductions targets per region, but at the same time the overall global optimal emission path is affected a lot less by these considerations. In particular, taking account of equity between regions as I did in this paper does not change the optimal global emission path in a dramatic way from the emission path that is calculated when only taking efficiency into consideration.

At the same time the approach in this paper has severe limitations. First, it only takes two extremes into account: Either all transfers between regions are ruled out or they are assumed to have no limits as pure lump sum transfers. These two choices clearly constitute the boundaries of the problem, in reality one can imagine much more nuanced frameworks, with partial compensation payments between regions, payments that are not lossless and transfers only between specific regions.

Secondly, I base the analysis of the situation without transfers on a utilitarian welfare function, without any philosophical justification for it. There is no good reason for this other than this is common practise in most of the literature on the economics of climate change. Once one leaves the world of pure efficiency, the question of *which* ethical framework to pick becomes of high importance. In this paper I do not argue that the specific utilitarian welfare function I used is the appropriate one, I only show that under that specific choice distributional questions are of significant importance to the optimal marginal abatement costs.

Finally, this paper ignores any problems of incentives of different regions, i.e. the game theoretic problem of reaching an actual agreement to mitigate climate change emissions is ignored. At the same time I see a contribution of this paper to that literature: in any attempt to come up with some global agreement that circumvents the free-riding problem associated with a global public bad like climate change there is a need for a benchmark optimal solution. What is the optimum that *should* be achieved by a achieved by an international agreement? This is principally a normative question, and I hope this paper demonstrates that purely looking at an efficient outcome might not do the magnitude of the distributional problem justice.

6. Acknowledgements

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7. Figures

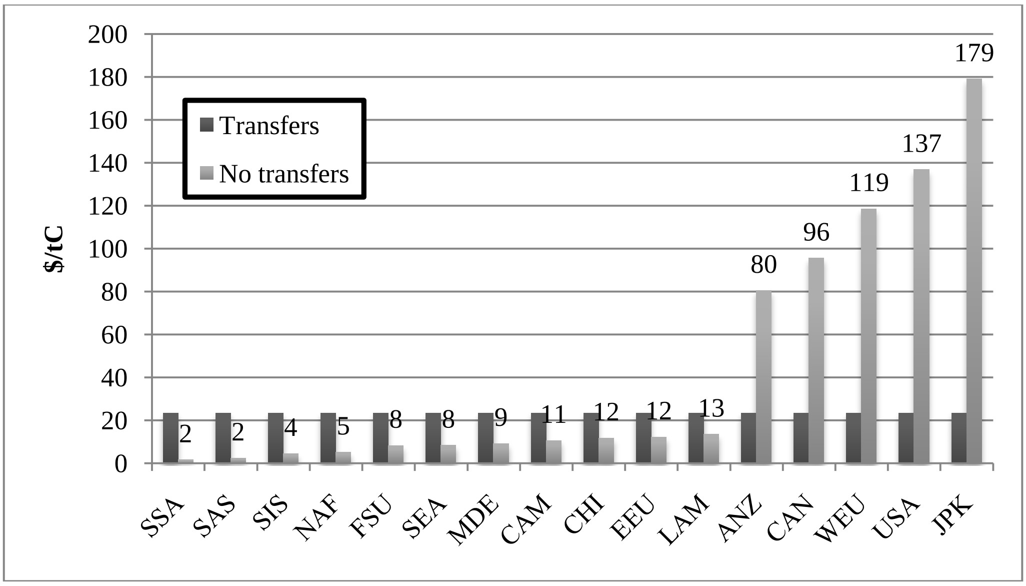

Figure 17: Optimal tax per tC in the year 2005 for prtp=1% and η=1

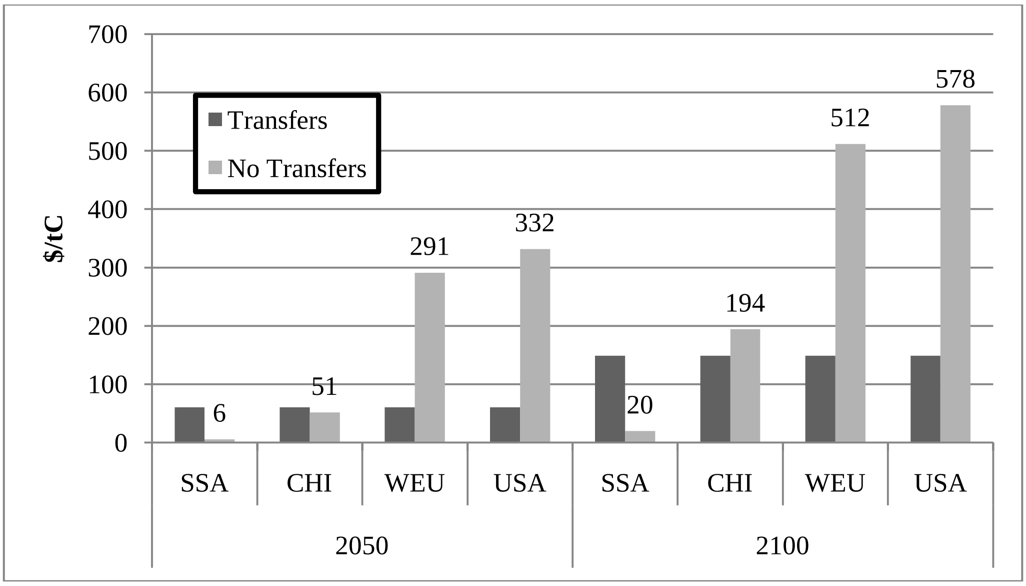

Figure 18: Optimal tax per tC for selected regions in the year 2050 and 2100 for prtp=1% and η=1

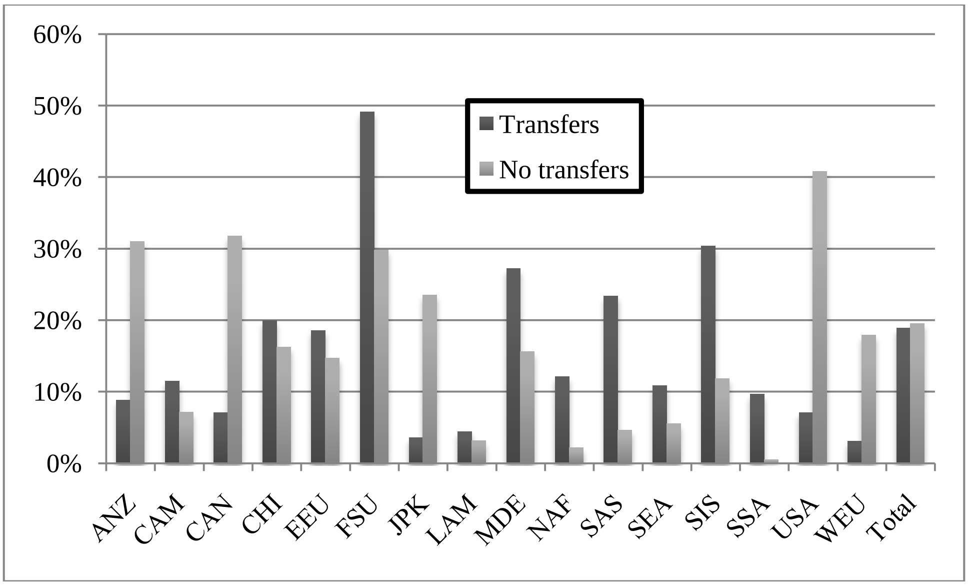

Figure 19: Reduction in emissions compared to business as usual scenario in the year 2050 for prtp=1% and η=1

8. Tables

Business as usual warming: 3.17		
Utility calibration	**No transfers**	**Transfers**
η=1		
prtp=0.1%	2.41	2.34
prtp=1.0%	2.92	2.91
prtp=3.0%	3.12	3.12
η=1.5		
prtp=0.1%	2.65	2.75
prtp=1.0%	2.96	3.03
prtp=3.0%	3.13	3.13
η=2		
prtp=0.1%	2.69	2.98
prtp=1.0%	2.95	3.09
prtp=3.0%	3.13	3.14

Table 18: Temperature increase above pre-industrial in °C in the year 2100 for no policy intervention (business as usual) and optimal policies for different calibrations of the utility function

Overall Conclusion and Outlook

In chapter 1 we define various balanced growth equivalences, and apply them to compute the total impacts of climate change and the benefits of emission reduction with the integrated assessment model *FUND*. We thus replicate the core of the *Stern Review* analysis, conduct a wider sensitivity analysis than run by the *Stern Review*, clarify analytically the concept of balanced growth equivalence when applied to climate change and produce an up to date estimate of total impacts of climate change. We find that the impacts of climate change are sensitive to the pure rate of time preference, the rate of risk aversion and inequality aversion, the level of spatial disaggregation, the inclusion of uncertainty, and the socio-economic scenario. Compared to the *Stern Review*, our results span a wider range in both directions, thereby questioning the claim that the high impact estimates obtained by the *Stern Review* are robust. We find that the guess of the *Stern Review* that a regional welfare function might increase overall damage estimates by a quarter (Stern, 2007, p. 187) is very conservative. In our runs, the introduction of a regional welfare function, in particular in combination with a high risk aversion, has a much larger effect on the results. Finally, we show that the *Stern Review* was wrong to equate the impact of climate change and the benefits of emission reduction – their “optimal” climate policy does not maximise welfare in the mathematical sense of the word. Qualitatively, this was known. Quantitatively, we show that this is a big mistake.

The results in chapter 1 also highlight areas that need more research work. This includes improved socio-economic and climate scenarios, and better and more complete estimates of the impacts of climate change. In particular, disentangling intertemporal substitution from risk aversion and inequality aversion is a high priority (e.g., Carlsson *et al.*, 2005). With only one parameter to control three important effects, as commonly used in climate policy analysis, model- and scenario-specific ambiguities emerge. The fat tails that showed up in some of our results with high risk aversion and a regional welfare function are another area for further research.

The results in chapter 3 continue the investigation of some of the themes that emerged as important in chapter 1, but this time with an emphasis on estimates of marginal damages, i.e. the social cost of carbon. We conduct a systematic sensitivity analysis with respect to risk aversion and the pure rate of time preference that spans the whole range of values discussed in the literature. Stern (2007) tried to argue philosophically for specific choices of discount rates and risk aversion parameters, which is one way to narrow down the broad range of results we find in our sensitivity analysis with respect to both parameters. We bypass that debate in this chapter by exploring the ramifications of actual decision makers and actual developed economies. We find that aversion to risk is as important in determining SCC estimates as time preference. We find high estimates for the SCC given operational combinations of risk aversion and time preference even with a model that incorporates relatively conservative damage estimates (including benefits early on) and autonomous adaptation driven by regional economic development.

Chapter 2 looks at a specific impact category. The analysis in that chapter suggests that if sea-level rise was up to 2m per century, while the costs of sea-level rise increase due to greater damage and protection costs, an optimum response in a benefit-cost sense remains widespread protection of developed coastal areas. We also show that the benefits of protection increase significantly with time due to the economic growth assumed in the SRES socio-economic scenarios. Due to the different assumptions about population and gross domestic product, the socio-economic scenarios are also important drivers of these costs. In terms of the four components of costs considered in *FUND*, protection dominates, with substantial costs from wetland loss under some scenarios. The regional distribution of costs shows a few regions experience most of the costs, especially South Asia, South America, North America, Europe, East Asia and Central America. Under a scenario of no protection, the costs of sea-level rise increase greatly due to land loss and population displacement: this scenario shows the significant benefits of the protection response in reducing the overall costs of sea-level rise.

The equity-weighted results highlight how important it is to not only consider the absolute magnitude of damage but also who will be affected. The welfare loss of even small damages to poor societies can be enormous. There is no consensus within the economic literature that equity-weighted damages ought to be used when policy instruments like Pigouvian taxes are designed, and hence the results presented here should not be used for policy design without further investigation. But there is little doubt that as a measure of actual welfare loss, equity-weighted results are much more accurate than pure monetary damage estimates. The question of what to do about the discrepancy in severity of impacts to poor and rich people is an ethical one. In calculating damage estimates, though, these differences should be made explicit to not under- or overstate the true welfare loss that climate change might cause, as we have done with the equity-weighted results in this chapter.

In chapter 4 we continue our exploration of marginal damage estimates. Climate change is a global problem, but decisions are made by national decision makers. In previous papers, researchers have discussed the appropriate carbon tax for a global decision maker. In chapter 4, we discuss the appropriate carbon tax for a national decision maker. We distinguish between four different cases. First, the national decision maker does not care about what happens abroad. Second, the national decision maker is altruistic towards foreigners. Third, the national decision maker compensates damages done abroad. Fourth, the national decision makers feels responsible for damages done abroad, but cannot compensate. Carbon taxes are lowest in the first case (sovereignty). They are highest in the fourth case (good neighbour) for the richest regions, and in the third case (compensation) for the poorest regions. Middle income regions may face the highest carbon taxes under international cooperation. This order is robust to the choice of the pure rate of time preference and the inequality aversion, but carbon taxes are higher if the pure rate of time preference is lower, and carbon taxes tend to be higher if the inequality aversion is higher.

Further research in this field would certainly be welcome. The analysis here should be reproduced with other integrated assessment models. A wider range of utility and welfare functions should be explored, and the link between the utility function and the willingness to pay for climate change impacts should be investigated. The interactions between risk and inequity aversion should be added. The resolution of the model should be refined, and further interactions between actors should be modeled. And of course, the implications of our research for greenhouse gas emission reductions, both in a cooperative and a non-cooperative setting, need to be investigated.

In the final chapter, I contrast a first-best world in which an optimal emissions path is calculated purely based on an efficiency criterion, i.e. under the assumption that any distributional consequences of a specific policy can be dealt with at a later stage with different (and costless) instruments, with a look at a specific ethical framework and a global decision maker who is constrained in his policy options. In particular, I assumed in a second step that a global decision maker has the ability to set mitigation paths for all regions, but does not have any instruments at hand to compensate for unwanted distributional disturbances caused by the emission control policy. In this second scenario I looked at a specific welfare function, namely a classical utilitarian one, and derived optimal emission reduction pathways for different regions.

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