Equity Weighting and the Marginal Damage Costs of Climate Change

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Summary

Climate change would impact different countries differently, and different countries have different levels of development. Equity-weighted estimates of the (marginal) impact of greenhouse gas emissions reflect these differences. Equity-weighted estimates of the marginal damage cost of carbon dioxide emissions are substantially higher than estimates without equity-weights; equity-weights may also change the sign of the social cost estimates. Equity weights need to be normalised. Our estimates differ by two orders of magnitude depending on the *region* of normalisation. A discounting error of equity weighted social cost of carbon estimates in earlier work (Tol, *Energy Journal*, 1999), led to an error of a factor two. Equity-weighted estimates are sensitive to the resolution of the impact estimates. Depending on the assumed intra-regional income distribution, estimates may be more than twice as high if national rather than regional impacts are aggregated. The assumed scenario is important too, not only because different scenarios have different emissions and hence warming, but also because different scenarios have different income differences, different growth rates, and different vulnerabilities. Because of this, variations in the assumed inequity aversion have little effect on the marginal damage cost in some scenarios, and a large effect in other scenarios.

Keywords: Marginal Damage Costs, Climate Change, Equity

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1. Introduction

Impacts from climate change will be spread across time and space. The search for economically efficient mitigation and adaptation strategies is one of the key challenges for today's policy makers. Looking for an efficient greenhouse gas emission profile from the perspective of a global decision maker requires careful consideration of the socio-economic environments that will bear the impacts of climate change. One particular concern is the widely disparate incomes of the people affected. Economic theory assumes a declining marginal utility of consumption, i.e. the same absolute consumption change results in a smaller welfare change for a rich person than a poor person. Incorporating this theoretical model into climate change impact models has a significant effect on efficient policy choices for a global decision maker.

This paper presents new results from FUND, an integrated assessment model, that takes different income levels in different world regions and at different times into account when calculating marginal damage figures for greenhouse gas emissions. A new theoretical model is presented that allows the incorporation of income level data that is obtained at a finer grid than the one used in previous versions of FUND. Sensitivity to a key ethical parameter, inequality aversion, is tested as well. A discussion of the theoretical interaction of the growth component of the social discount rate and equity weights as described in the literature is presented in the theoretical section. In addition to the discussion of the interaction of the social discount rate with equity weights, it is argued that social cost of carbon estimates should be normalized with the marginal utility of consumption of a specific region, if the marginal damage costs are later to be used in a cost-benefit analysis for projects in that region. All marginal damage figures are calculated for five different socio-economic development scenarios in order to test sensitivity to parameters like population and GDP growth.

The article is structured into a discussion of the previous literature, the presentation and development of the theoretical model, the presentation of key results from using FUND, the numerical model, and finally a discussion of the findings and its consequences on policy choices.

2. Previous literature

There are a number of cost-benefit models that calculate the so-called ‘social cost of carbon’, which generally refers to the expected present value damage of a (metric) tonne of CO_2 emissions along a particular path (e.g. business-as-usual). Examples include Nordhaus and Boyer (1999), Cline (1992), Fankhauser (1995), Tol (1997) and Hope (2003). A number of papers have dealt specifically with the question of equity weighting in relation to calculations of the social cost of carbon. Pearce, Cline et al. (1996) brought forward the idea that equity weights should be used when calculating the social cost of carbon. More recently, Stern (2006, p. 159) also argued that global damage estimates ought to be based on a framework similar to the one used in this paper, but did not actually use it in its calculations, due to time constraints. Fankhauser, Tol et al. (1997) and Pearce (2003) presented equity weighting corrected social cost of carbon estimates, but their results may be misleading, as will be argued in this paper. Azar and Sterner (1996) and Azar (1999) present the most complete theoretical treatment of equity weights in the context of climate change. However, the quantitative results in these papers are based on a stylised two region model, and hence do not provide reliable estimates of global damages. Shiell (2003) calculates optimal global greenhouse gas emissions under various ethical assumptions, including different weights for different world regions.

This paper only investigates a utilitarian social welfare function. Other ethical positions have been applied to climate change as well, for a discussion see Tol (2001), Tol (2002) and Kemfert and Tol (2002). The question of distributional weights has also been discussed in more general terms previously. Harberger (1978) and the discussion that followed (Harberger 1980; Layard 1980; Squire 1980) looked at distributional weights in the context of commodity taxation, investment projects and optimal income taxation. Before using the social cost of carbon figures calculated in this paper to design policy instruments, similar analysis ought to be conducted on the effects of the weights used in this paper on the policy instrument in question. More recently Johansson-Stenman (2005) concluded that the question whether distributional weights ought to be used in cost-benefit analysis cannot be answered in general, but should rather be informed by the specific circumstances of the proposed project or policy instrument.

Boadway (1976) examines a welfare criterion that not only takes efficiency but also equity into consideration. A key feature of his solution is that no detailed knowledge of winners and losers is needed for this criterion to work, but rather taking into account the distribution characteristics of goods. Of course, in the case of climate change, such an indirect approach is not needed: Integrated assessment models like FUND calculate damages per world region, which allows fairly good identification of income characteristics of the losers of global warming.

Mirrlees (1978) has a short section on welfare weights and externalities, arguing that in the case of e.g. environmental externalities weights ought to be used in social cost-benefit analysis. At the same time he points out two problems one might encounter: Estimated prices for non-market goods might already reflect income distribution and therefore conflict with distributional weights. And secondly, a regulator might set unwanted incentives when using welfare weights in cost-benefit analysis. One could for example imagine a particularly backwards region that would be favoured when appraising social projects because income in that region is very low. Instead of encouraging people to leave that region, policy determined by regional income levels might create incentives to stay at a hostile place. Given the magnitude of climate change, the latter warning seems outside the realm of economic analysis and a more appropriate question for other disciplines.

3. Theoretical model

Damages caused by the emission of a (metric) tonne of carbon today are spread across time and space. In order to calculate the marginal damage of greenhouse gas emissions today all damages that are caused by those emissions need to be added up. Two theoretical ideas are considered in the aggregation of damages in this paper. First, the standard economic assumption of diminishing marginal utility implies that the same monetary damage causes more grief to a poor than a rich person. This step is often called "equity weighting" of costs and benefits. Second, damages at different times need to be discounted to determine their respective net present values. There are two components to discounting. The first is that consumption in the future is likely to be higher than consumption today (even accounting for climate impacts), so diminishing marginal utility implies that the same monetary damage will cause less grief in the future. The second is that we might wish to place a lower weight on utility in the future, to account for social impatience or extinction risk, which is specified by a pure rate of time preference (or 'utility discount rate').

This paper determines discounted and equity-weighted estimates of climate change damages. The combination of discounting and equity weighting needs to be done with care, since the two concepts overlap in their theoretical justification.

3.1. The social welfare function

The intuition that individual marginal utility of consumption is declining with increasing consumption *c* can be expressed by an iso-elastic utility function:

$$U(c) = \frac{c^{1-\varepsilon}}{1-\varepsilon} \tag{1}$$

ε is commonly referred to as the consumption elasticity of marginal utility. For decisions under uncertainty, ε is also the individual coefficient of relative risk aversion. On the assumption that individuals have a utility function like (1), the value of ε can be found by empirical research: one can infer from behaviour how averse individuals are to reductions in consumption, or to risk.[1]

Assuming that the social welfare function (SWF) is individualistic, nondecreasing, symmetric and additive (see Cowell and Gardiner 1999 for an excellent discussion), the SWF can be written as

$$W = \sum_{i=1}^{n} U\left[C\left(i\right)\right] \tag{2}$$

where $C\left(x\right)$ is consumption of agent *x* and *n* is the population size.

Note that the value of ε also impacts how averse we are to inequality in consumption. For instance, ε = 0 corresponds to inequality neutrality, i.e. there is no social benefit to reducing consumption inequality, because an absolute change in consumption counts the same, whether it befalls the rich or the poor. In contrast, for ε→∞, achieving equality dominates any other objective such as raising general consumption levels; this is because a change in consumption of the poorest member of society always dominates consumption changes of others. In other words, ε→∞ implies that the effective social welfare function is equivalent to a Rawlsian SWF, such that $W = \min\left\{U\left[C\left(i\right)\right]\right\}$. Values between those two extremes correspond to ethical positions with various degrees of inequality aversion. If ε=1 so that $U\left(c\right) = \log c$, for instance, relative changes in consumption receive equal weight.

It is crucial to understand the connection between the elasticity of marginal utility and inequality aversion. If marginal utility did not decline with increased wealth levels the motivation for aversion to inequality would be much weaker. An individual utility function with a constant marginal utility implies that a given change in consumption always has the same effect on a person, irrespectively of whether that person is rich or poor. At the same time, there is no reason to assume that our aversion to inequality should simply be specified by the consumption elasticity of marginal utility. While the results from empirical tests of the consumption elasticity of marginal utility are interesting and certainly relevant in the discussion of an appropriate level of social inequality aversion, there is no logical reason that the inequality aversion value must equal our best estimate of the consumption elasticity of marginal utility – Fankhauser et al. (1997) use a more general version of (2) that allows risk and inequity aversion to deviate. Others have argued that society's ethical preferences can be discovered by looking at the policies in place. Looking at the tax code allows one to reveal an implicit value for the inequality aversion used at a particular time (Cowell and Gardiner 1999). Examining levels of foreign aid might reveal implicit aversion to inequality between nations. There are very good reasons to argue that climate change policy should be consistent with other government policies – the level of inequality aversion used in climate policy should be consistent with that revealed by the tax code and foreign aid decisions. Nevertheless, this conclusion is not a logical necessity. One could easily imagine a situation with a tax code that is unfair – mirroring this would be questionable. It is almost impossible to determine the appropriate level of inequality aversion (and hence ε in this paper), without some discussion of the relevant ethics.

3.2. Dynamic aggregation

When looking at a dynamic setting, i.e. one where consumption flows are spread across time, discounting of future consumption is necessary. The traditional Ramsey-type optimal growth model has two components determining the weights for future consumption: again, future consumption is converted into some measure of utility by a social utility function; secondly that utility is weighted with an exponentially decreasing time preference factor. Since the SWF that was developed in the previous section already employs an iso-elastic social utility function, the only thing left in order to extend it into the dynamic setting is the addition of the time preference factor:

$$W = \sum_{t=0}^{T} \sum_{i=0}^{n(t)} U\left[C(t,i)\right](1+\rho)^{-t} \tag{3}$$

In this equation *n(t)* is the number of people alive at time *t*, *T* is the time period under consideration,[2] ρ is the pure rate of time preference and $C(s, j)$ is the consumption of agent *j* at time *s*.

Differentiation of (3) with respect to a consumption change of agent *i* at time *t* gives marginal social welfare of consumption:

$$\frac{\partial W}{\partial C(t,i)} = C(t,i)^{-\varepsilon} (1+\rho)^{-t} \tag{4}$$

3.3. Marginal damage cost of carbon dioxide

The social cost of carbon is commonly specified as the social cost of an incremental emission of a greenhouse gas today. Because greenhouse gases are long-lived, the damages caused by a marginal emission will manifest themselves as a change in consumption at every future point in time *t*, for each of the total number of people *n(t)* living at that time. Consumption therefore depends on the emission path over time:

$$C\left[s, j, E(v)\right] \tag{5}$$

where $E(v)$ is the emission of greenhouse gas at time $v<s$ and *C* is consumption of individual *j* at time *s* for a given emission scenario *E*.

The marginal change in consumption *D*, or damage, for an individual *i* at time *t* from a marginal change in emissions at time *r* therefore is

$$D(t,i,r) = \left. \frac{\partial C\left[s, j, E(v)\right]}{\partial E(r)} \right|_{s=t,\, j=i} \tag{6}$$

In order to calculate the total change in social welfare from a marginal change of emissions at time *r*, each individual damage *D* needs to be converted into social utility by multiplying it with the appropriate marginal social welfare as calculated in (4), and then summing over time and individuals:

$$V(r) := \frac{\partial W}{\partial E(r)} = \sum_{t=r}^{T} \sum_{i=1}^{n(t)} D(t,i,r) \frac{\partial W}{\partial C\left[t,i,E(v)\right]} \tag{7}$$

Note that equation (7) rests upon the assumption that we are calculating a marginal change in emissions. Under a non-marginal change, such as radical shifts in global climate policy, the approximation underlying (7) is likely to be inapplicable. Finally, using (4) gives

$$V(r) = \sum_{t=r}^{T} \sum_{i=1}^{n(t)} D(t,i,r) C(t,i,E)^{-\varepsilon} (1+\rho)^{-t} \tag{8}$$

$V(r)$ therefore is the marginal change in net present social welfare from a marginal change in emissions at time *r*.

3.4. Monetisation

Often, attempts to calculate damages from climate change are done in order to use them in cost-benefit analysis. The value obtained by (8) can be used directly in a cost-benefit analysis that is done with social utility as the metric. Obviously the same weights employed in the calculation of the marginal social utility loss of greenhouse gas emissions should also be applied to any other change in consumption levels – cost or benefit – that is considered in the particular cost-benefit analysis.

While there is no flaw to this approach, it is not very convenient. The extra step of ensuring that all consumption changes under consideration are weighted with the same weighting scheme might sometimes be hard to achieve, particularly when other consumption changes are only available in an aggregate form. Ideally, one would present the social cost of carbon in a metric that allows direct comparability with other consumption changes, instead of social utility changes.

Normalising the result obtained in (8) using the marginal social utility of consumption today (t=0) of a particular agent x results in

$$V_x(r) = \frac{1}{\partial W / \partial C\left[0, x, E\left(v\right)\right]} \sum_{t=r}^{T} \sum_{i=1}^{n(t)} D\left(t,i,r\right) C\left(t,i,E\right)^{-\varepsilon} (1+\rho)^{-t} \tag{9}$$

which equals

$$V_x\left(r\right) = \sum_{t=r}^{T} \sum_{i=1}^{n(t)} D\left(t,i,r\right) \left[\frac{C\left(0,x,E\right)}{C\left(t,i,E\right)}\right]^{\varepsilon} (1+\rho)^{-t} \tag{10}$$

Note that V in (8) is measured in utility, whereas V_x in (10) is measured in money. Since the normalisation is just a multiplication of all costs and benefits by a positive constant, the set of policies that passes a cost-benefit analysis before and after the normalisation is identical. But if the social cost of carbon is only to be compared to other consumption changes $MC\left(t,x\right)$ that affect agent x, the net present value of those changes reduces to

$$\sum_{t=0}^{T} MC\left(t,x\right) \left[\frac{C\left(0,x\right)}{C\left(t,x\right)}\right]^{\varepsilon} (1+\rho)^{-t} \tag{11}$$

Assuming growth in consumption is constant at rate g, it follows that $C\left(0,x\right) / C\left(t,x\right) = \left(1+g\right)^{-t}$ and $\left[C\left(0,x\right)/C\left(t,x\right)\right]^{\varepsilon} \approx \left(1+\varepsilon g\right)^{-t}$. Substituting to (11) yields the standard equation for calculating the net present value for consumption changes over time for agent x. Thus, normalisation with the marginal utility of consumption of agent x allows direct comparison of the social cost of carbon figure with consumption changes for that agent that are discounted into their net present value equivalents.

It is therefore suggested that marginal damage figures from climate change should be normalized with the marginal utility of consumption of the agent (or marginal utility of average consumption of a region) that is engaging in a cost-benefit analysis, since this will allow direct comparison with other costs and benefits to that agent. Note, however, that if this agent is any other than the global social planner, other agents' damages are evaluated as if they fell on oneself, a Kantian perspective.

3.5. Previous methods

Previously, equity weighted marginal damage figures have been calculated with FUND (Tol 1999),[3] for which a different approach was used. For every year *t*, an equity weight was calculated for every agent *i*:[4]

$$\left[\frac{\bar{C}_W(t)}{C(t,i)}\right]^{\varepsilon} \tag{12}$$

where $\bar{C}_W(t)$ is average per capita income of the world at time *t*.

In addition, a discount factor was calculated for every individual *i* at time *t*:

$$\left[\frac{C(0,i)}{C(t,i)}\right]^{\varepsilon}(1+\rho)^{-t} \tag{13}$$

Both the equity weight and the social discount factor were then applied to the marginal damage for each region over time, before they were aggregated:

$$V^*(r)=\sum_{t=r}^{T}\sum_{i=1}^{n(t)}D(t,i,r)\left[\frac{\bar{C}_W(t)}{C(t,i)}\right]^{\varepsilon}\left[\frac{C(0,i)}{C(t,i)}\right]^{\varepsilon}(1+\rho)^{-t} \tag{14}$$

Note that there are two differences between (14) and (11). Firstly, normalisation is with the utility of the world average agent in (14) and with any agent in (11). Secondly, normalisation is with present utility in (11) and with current utility in (14). That is, in (11), damages are evaluated as if they fell on today's income distribution. In (14), that assumption is not there, as the damage is monetised based on the future income distribution. However, (14) is incorrect. If current damages are translated to the equity-weighted global average, then the global average discount rate should be used, and not the regional discount rate as in (14).

3.6. Spatial resolution

None of the integrated assessment models used to understand climate change impacts works on an individual agent resolution. Instead, impacts are calculated separately for different world regions. FUND, for example, calculates impacts for 16 world regions; others operate on an even coarser grid.

In order to accommodate this fact, (10) needs to be changed such that instead of using $D(t,i,r)$ (i.e. the damage function that operates on an individual agent basis), a regional damage function $D_R(t,i,r)$ is used that returns the damage for the whole region *i* at time *t* for a marginal change of emissions at time *r*. Instead of using individual consumption levels for the social utility function, average per capita consumption levels $\bar{C}_R(t,i)$ for region *i* need to be used. Finally, the monetisation is done relatively to a specific region x, that is with the average marginal social utility of consumption of region x:

$$V_x'(r) = \sum_{t=r}^{T} \sum_{i=1}^{n} D_R(t,i,r) \left[\frac{\bar{C}_R(0,x)}{\bar{C}_R(t,i)} \right]^{\varepsilon} (1+\rho)^{-t} \tag{15}$$

Here *n* is the number of regions considered. In FUND, *n* = 16.

One unfortunate consequence of (15) is that the equity weighting part of the social utility function will diverge from the correct weight with a decrease in spatial scale (Fankhauser, Tol et al. 1997). In contrast to (10), which is theoretically correct, (15) only takes into account inequalities in consumption levels between regions, while different consumption levels within regions are ignored. This is a pity, because data about consumption levels are available at a more detailed level — average per capita income levels are known minimally at a national level so that ideally that knowledge should be taken into account when calculating the social cost of carbon.

3.7. Aggregation coefficient

Looking at only one region *j* at time *t* for the moment, and assuming that not only the average consumption levels for its countries, but also detailed damage information on a per country basis is available, the following is true:

$$W_R(t,j) = \sum_{i=1}^{n^j} D_N(t,i)\left[\frac{1}{\bar{C}_N(t,i)}\right]^{\varepsilon}(1+\rho)^{-t} \tag{16}$$

Here *nj* is the number of countries in region *j*. $D_N(t,i)$ is the damage and $\bar{C}_N(t,i)$ is the average consumption in country *i* at time *t*.

One can assume that the damage to each country within that region is a fraction of the total damage $D_R(t,j)$ of the region *j*:

$$D_N(t,i) = \alpha(t,i)D_R(t,j),\ with\ \alpha(t,i) \geq 0\ and\ \sum_{i=1}^{n^j}\alpha(t,i) = 1 \tag{17}$$

Therefore the welfare change for that region amounts to

$$W_R(t,j) = D_R(t,j)\sum_{i=1}^{n^j}\alpha(t,i)\left[\frac{1}{\bar{C}_N(t,i)}\right]^{\varepsilon}(1+\rho)^{-t} \tag{18}$$

Assuming that damages are uniformly distributed to all individuals in region *j* is captured as

$$\alpha(t,i) = \frac{P_N(t,i)}{P_R(t,j)} \tag{19}$$

Where $P_N(t,i)$ is the population size of nation *i* at time *t*, and $P_R(t,j)$ is the total population of region *j*, i.e. $P_R(t,j) = \sum_{i=1}^{n^j} P_N(t,i)$. The average per capita consumption $\bar{C}_N(t,i)$ of country *i* is defined as

$$\bar{C}_N(t,i) = \frac{C_N(t,i)}{P_N(t,i)} \tag{20}$$

Where $C_N(t,i)$ is the total consumption of nation *i*. Substituting (19) and (20) into (18) gives

$$W_R\left(t,j\right)=D_R\left(t,j\right)\sum_{i=1}^{n^j}\frac{P_N\left(t,i\right)}{P_R\left(t,j\right)}\left[\frac{P_N\left(t,i\right)}{C_N\left(t,i\right)}\right]^{\varepsilon}(1+\rho)^{-t} \tag{21}$$

This is equivalent to

$$W_R\left(t,j\right)=D_R\left(t,j\right)\frac{1}{P_R\left(t,j\right)}(1+\rho)^{-t}\sum_{i=1}^{n^j}\frac{P_N\left(t,i\right)^{1+\varepsilon}}{C_N\left(t,i\right)^{\varepsilon}} \tag{22}$$

Dividing this by the damage of the region that is weighted with the average marginal social utility of that region and the time preference factor gives a coefficient that can be applied to weighted, regional damage figures:

$$E\left(t,j\right)=\frac{\left[\bar{C}_R\left(t,j\right)\right]^{\varepsilon}}{P_R\left(t,j\right)^{1}}\sum_{i=1}^{n^j}\frac{P_N\left(t,i\right)^{1+\varepsilon}}{C_N\left(t,i\right)^{\varepsilon}} \tag{23}$$

$E\left(t,j\right)$ is a weight for region *j* at time *t* that corrects to some degree the error introduced by calculating average consumption levels at the regional level, if more detailed information is available. At least for the present, all data required to calculate this coefficient is available, namely population and income figures on a national level.

Putting this aggregation coefficient into (15) gives the final equation that allows one to calculate the marginal damage of greenhouse gas emissions, normalised to average consumption of region *x*:

$$V_x''\left(r\right)=\sum_{t=r}^{T}\sum_{i=1}^{n}D_R\left(t,i,r\right)\left[\frac{\bar{C}_R\left(0,x\right)}{\bar{C}_R\left(t,i\right)}\right]^{\varepsilon}(1+\rho)^{-t}E\left(t,i\right) \tag{24}$$

4. Results

4.1. The model

This paper uses version 2.8 of the *Climate Framework for Uncertainty, Negotiation and Distribution* (FUND). Version 2.8 of *FUND* corresponds to version 1.6, described and applied by Tol (1999, 2001, 2002a), except for the impact module, which is described by Tol (2002b,c) and updated by Link and Tol (2004). A further difference is that the current version of the model distinguishes 16 instead of 9 regions.[5] Readers familiar with FUND can skip this section.

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 account for the fact that climate change does not stop in 2100.

The period of 1950-1990 is used for the calibration of the model, which is based on the *IMAGE* 100-year database (Batjes & Goldewijk, 1994). The period 1990-2000 is based on observations (WRI, 2000). The climate scenarios for the period 2010-2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett, Pepper et al. 1992). The 2000-2010 period is interpolated from the immediate past, 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 decarbonisation 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 (WRI, 2000). 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. 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, an option not considered in this paper.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, 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, forthcoming).

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 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 (2002b,c) 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, 2002c).

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, 1995, 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 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, 2002b). 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, 2002c).

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, 2002c).

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, 2002c).

FUND also includes instruments for and costs of reducing the emissions of carbon dioxide, methane, and nitrous oxide. It can perform cost-benefit analysis, cost-effectiveness analysis, and equity analysis. These parts of the model are not used in this paper.

4.2. Scenarios

The theoretical model described in the previous section has been used to calculate the marginal damage per ton of carbon emitted within the period 2000-2010 with the integrated assessment model FUND. Results for FUND are presented for five different exogenous scenarios. Four of those are based on work by the IPCC (Nakicenovic and Swart 2000) and one – the default scenario for FUND – was developed by Tol (1999). The default scenario is very close to the EMF Standardised Scenario, which lies somewhere in between IS92a and IS92f (Leggett, Pepper et al. 1992). All five scenarios have been extrapolated to the year 2300. Two aspects of the scenarios are of special importance in the context of equity weighting, namely, population growth and economic development. They are of great consequence because they directly drive the equity weights derived for each region and year. Figure 1 and 2 show population and per capita income development for the full time period of FUND for the scenarios used.

FUND's default scenario assumes a continuous population growth coupled with moderate per capita income growth. It is generally very similar to scenario B2. Both scenarios feature less rapid and more diverse technological change than some of the other scenarios. B1 has the lowest population of all scenarios. Population peaks at around 2050 and steadily declines thereafter. At the same time, strong economic growth happens all around the world, mainly in service industries. This scenario also assumes great strides in energy efficiency in all sectors and reductions in material intensity. A1b has even higher economic growth than B1. A2 has the lowest economic growth (Nakicenovic and Swart 2000).

4.3. Results

Table 1 shows the baseline figures for these five scenarios. Results are shown for different pure rate of time preference values. While some philosophers and economists argue in favour of a pure rate of time preference of 0% (Broome 1992; Cline 2004), the general consensus in the literature supports higher rates (Arrow, Cline et al. 1996; Portney and Weyant 1999). The 0% numbers are nevertheless presented here. By comparing the various equity weighted numbers that are calculated with the 0% pure rate of time preference, one can have an isolated look at the effect the different marginal social utility functions have on the results, i.e. what effect the different equity weighting schemes have by themselves. This is helpful since the interaction between time preference discounting and equity weighting is neither linear nor predictable (see Tol, 2002, and below).

The unweighted numbers are discounted using the social discounting methodology, so consumption level changes over time are taken into account on a per region basis but not between regions.

Table 2 presents the basic equity weighted set of marginal damage figures for marginal carbon emissions. The numbers are normalised with average US marginal utility of consumption for the year 2000. This is an arbitrary choice and others have presented equity weighted climate change damage figures that are normalised with marginal utility of optimally distributed consumption (Fankhauser, Tol et al. 1997; Cline 2004). It is important to note that different choices do not amount to different optimal emission strategies or change any cost-benefit analysis in a utilitarian framework as used for this paper. The choice of US marginal utility makes the consequences equity weighting would have for US policy very clear since US mitigation costs need only to be discounted in order to be comparable to these results. Table 3 presents equity weighted damage figures that are calculated using the method employed in Tol (1999)[6] – see Equation (14). Table 4 shows equity weighted results that are normalised with per capita income of the other regions of FUND. While Table 4 shows the importance of the choice of the normalisation region, the difference between the numbers in

Table 3 and those in Table 4 that are normalised with world average per capita consumption is significant in its own right. The explanation for the latter is to be found in the change in the way the equity weights are calculated.

If one only considers the pure rate of time preference of 0%, one could get the impression from Table 1 and 2 that introducing equity weights produces a roughly linear increase in marginal damage figures, for US calibrated figures in the range of 10-15 times the original number. But with a pure rate of time preference of 3%, the effect of equity weighting depends largely on the base scenario used. While FUND predicts benefits for all five scenarios for a pure rate of time preference of 3%, equity weighting sometimes increases those benefits (A1b, B1 and B2) while it decreases benefits in others (FUND) and changes the results from benefit to damage in A2.

The weights given to different world regions at different times, based only on the different consumption levels, are shown in Figure 3. Note that the pure rate of time preference is 0%, so Figure 3 reflects only the impact of the marginal utility of consumption weight. One striking feature is that Sub-Saharan Africa (SSA) gets significantly higher weights throughout the whole time period under consideration, while other regions slowly narrow the differences over time. With higher pure rates of time preference, the fact that consumption differences do not align in the very far future has less and less weight on the overall result.

Figure 4 disaggregates the marginal damage figure for scenario A2 and a pure rate of time preference of 3% by region for the time period from today until 2300. It can be seen that the relatively small damages in SSA get a very high weight, even with the high pure rate of time preference of 3%.

4.4. Regional income inequality correction

The data presented so far only take into consideration differences in average per capita income of the 16 regions of FUND. Income inequalities within regions are ignored. Table 5 presents equity weighted marginal damage figures that are corrected with an aggregation coefficient as described in Section 3.7. The figures are based on the SRES A1B scenario. The aggregation coefficient for the year 2000 is calculated from average per capita income figures at the national level. Note that this affects different regions differently. Western Europe consists of many countries, but the regions "USA" and "Canada" are a single country. Intra-country income differences are ignored. Three different scenarios for the aggregation coefficient over time are presented.

The first scenario assumes no change in income distribution within each region. While the average per capita income of each region changes over time according to the IPCC scenarios, this scenario assumes that income inequalities within each region are preserved over time. The second scenario assumes that all inequalities within regions disappear over time, i.e. that income equality is reached in the year 2300. Inequalities for the years between 2000 and 2300 are a linear interpolation between the inequalities of today and perfect equality. The third scenario assumes that income inequalities within regions widen over time. All regions reach the same level of income inequality in the year 2300 that is the most extreme in the year 2000, namely the income inequality of the region "Small Island States". Again, inequalities for each region are interpolated linearly for the years between 2000 and 2300.

While the three scenarios are crude at best, they give a good indication of how sensitive the marginal damage figure is to the introduction of an aggregation coefficient. Results for a pure rate of time preference of 0% are affected the most by the implausible assumptions made in the three simple scenarios. All three scenarios converge toward highly unlikely income distributions for the year 2300 for each region. With a pure rate of time preference of 0%, results in those later years are given the same weight as results from earlier years. Damage figures for high pure rates of time preferences suffer a lot less from this defect. Damages in later years are discounted so much in the first place that implausible assumptions about inequality development within regions for the later centuries do not have much influence in the figures for the whole time period. Damages in earlier years, which dominate figures with a high pure rate of time preference, are corrected with an aggregation coefficient that is based largely on today's income distribution within regions that is based on real data.

4.5. Inequality aversion

Finally, different levels of inequality aversion are presented in Table 6. Pearce (2003) suggested values between 0.5 to 1.2 for the inequality aversion parameter in the context of climate change and those are contrasted with the base line results that were obtained by using inequality aversion of 1.

Since the inequality aversion parameter has effects along the time as well as along the spatial dimension the results are non-linear in response to an increase or decrease of inequality aversion. Depending on the economic scenario and the pure rate of time preference, sometimes lower inequality aversion parameters even increase the marginal damage figure. Various components explain this result: lower inequality aversion will increase the influence of economic gains in rich regions. Lower inequality aversion also leads directly to a lower discount rate since the expected economic growth over time is given less weight in calculating discount factors.

5. Discussion and conclusion

This paper presents equity weighted results that are based on a finer resolution (FUND’s 16 regions) than previous publications. A sensitivity analysis is conducted for sub-model resolution income distribution data. This introduction of the aggregation coefficient, and finer grid resolutions in general, are of special importance in the context of equity weighting: equity weights are supposed to reflect uneven income distributions, which by definition cannot be captured when using aggregated values for areas with highly diverse income inequalities. Previous equity weighted results[7] have also suffered from an inadequate combination of the equity weights and a social discount factor.

While more an issue of presentation, the normalisation method nevertheless appears to be important. Marginal damage figures that are normalised with world average marginal utility of consumption (Fankhauser, Tol et al. 1997; Pearce, Groom et al. 2003) face the danger of being compared to unweighted mitigation costs as if they were of the same unit. The likelihood of such confusion is greatly reduced when the social cost of carbon is normalised with the marginal utility of consumption of the region, for which the figure is to be used in subsequent analysis. Consequently, all equity weighted marginal damages were normalised with the marginal utility of consumption of an average US agent in the year 2000 for this paper. More generally, equity weighting explicitly assumes a social planner and a welfare function. The chosen perspective is crucially important. Different national decision makers would have different perspectives and choose different equity weight. Equity weights therefore do not overcome distributional concerns, or reconcile different positions – equity weights merely make such concerns explicit.

Two areas of uncertainty have also been analysed — the value for inequality aversion and income distribution within regions. Results from a sensitivity analysis have been presented for both areas, they point towards the importance of further investigation of both matters. Particularly, it shows the importance of the intra-regional distribution of income and, by implication, climate change impacts; subnational income and impact distribution would be important too. At the moment, it is a lack of data that prevents further analysis.

We here assume that risk aversion and inequality aversion are the same. Separating them is straightforward (cf. Fankhauser et al., 1997, 1998). It is more important, however, to improve the empirical basis for international inequality aversion. Lange et al. (forthcoming) make a useful start.

This paper has also confirmed that equity weights significantly change the results of the calculation of the marginal damage of greenhouse gas emissions, and hence that equity is a prime concern in climate policy.

Notes

[1] Not all utility functions combine the coefficient of risk aversion with the elasticity of marginal utility. Kreps-Porteus-Selden preferences disentangle the two concepts: see Kreps and Porteus (1978) and Selden (1979).

[2] A finite period is chosen for this paper, mainly for pragmatic reasons: The models used have a finite time period, and consumption in the very far future has almost no effect on numerical results, due to the time preference factor.

[3] Note that Fankhauser et al. (1997) only compute equity-weighted *total* damages.

[4] Fankhauser et al. (1997) only talked about regions, average income per region, not individual agents. Since the discussion in this paper has so far dealt with individual agents, the formulas have been adapted.

[5] A full list of papers, the source code and a technical description of the model can be found at http://www.fnu.zmaw.de/FUND.5679.0.html.

[6] Note that the numbers are very different from the ones reported in Tol (1999). The numbers in Table 3 were calculated using the same equity weighting method that was employed in Tol (1999). Other parts of FUND have been significantly changed since and explain the discrepancy between the figures in Tol (1999) and Table 3.

[7] With the exception Azar and Sterner (1996). Unfortunately their results are more of academic interest, since they use a two region model.

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Figures

Figure 1: Population

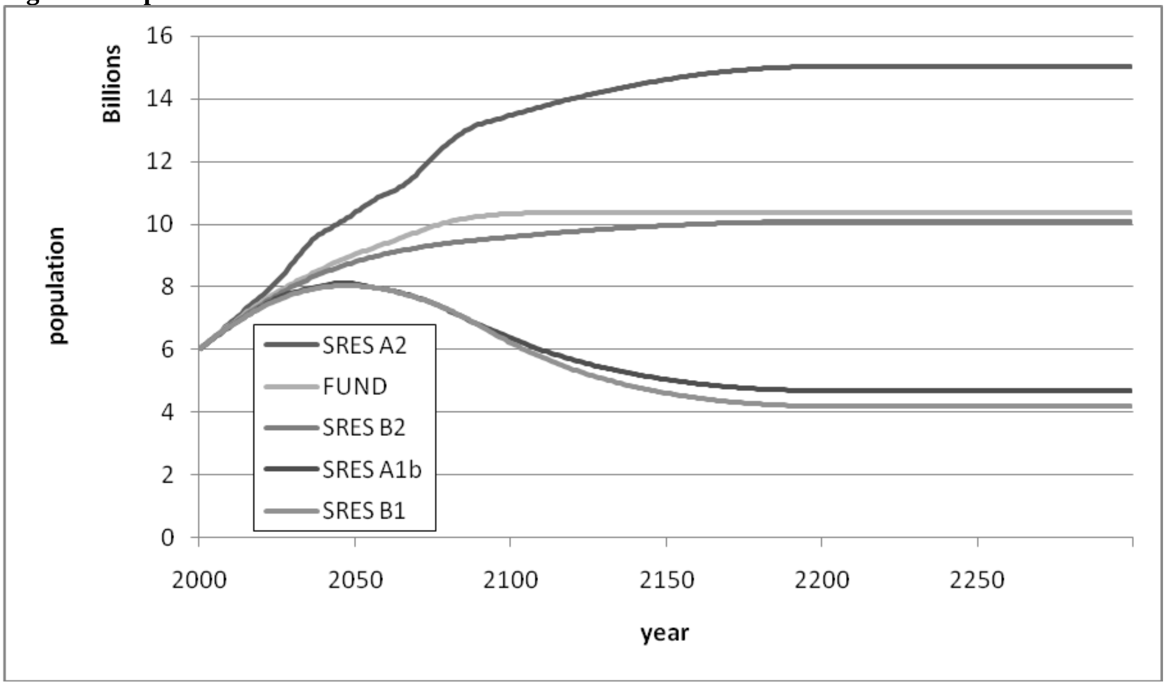


Figure 2: Average per capita income

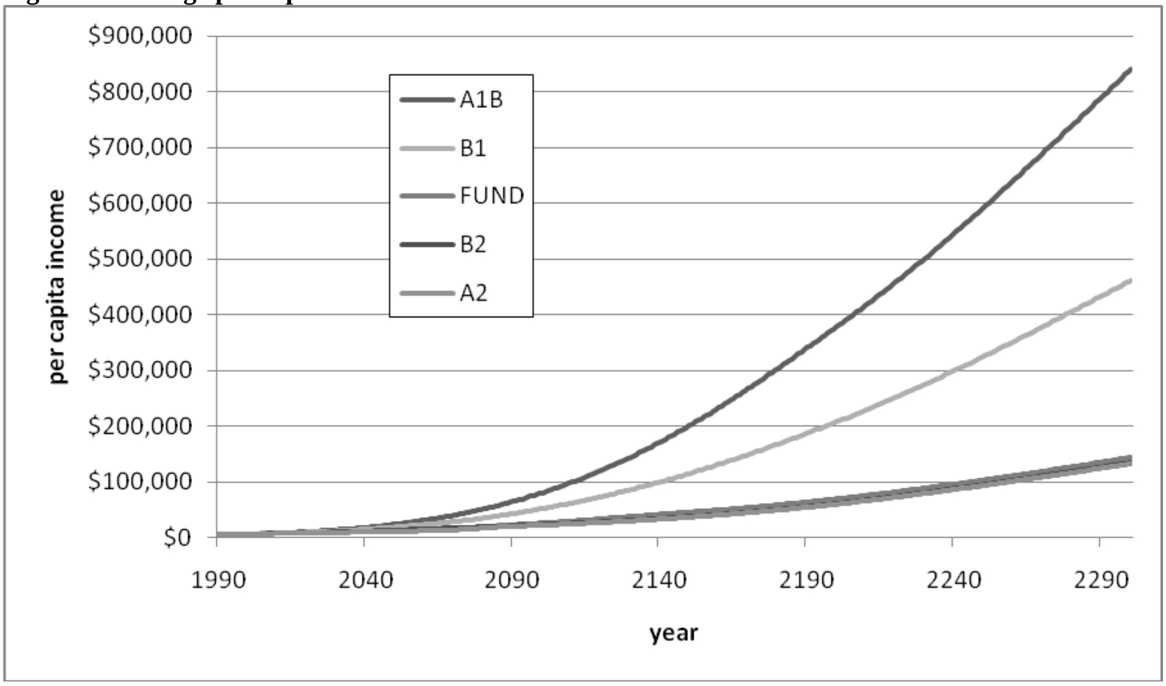


Figure 3: Weights for A2 and pure rate of time preference of 0%

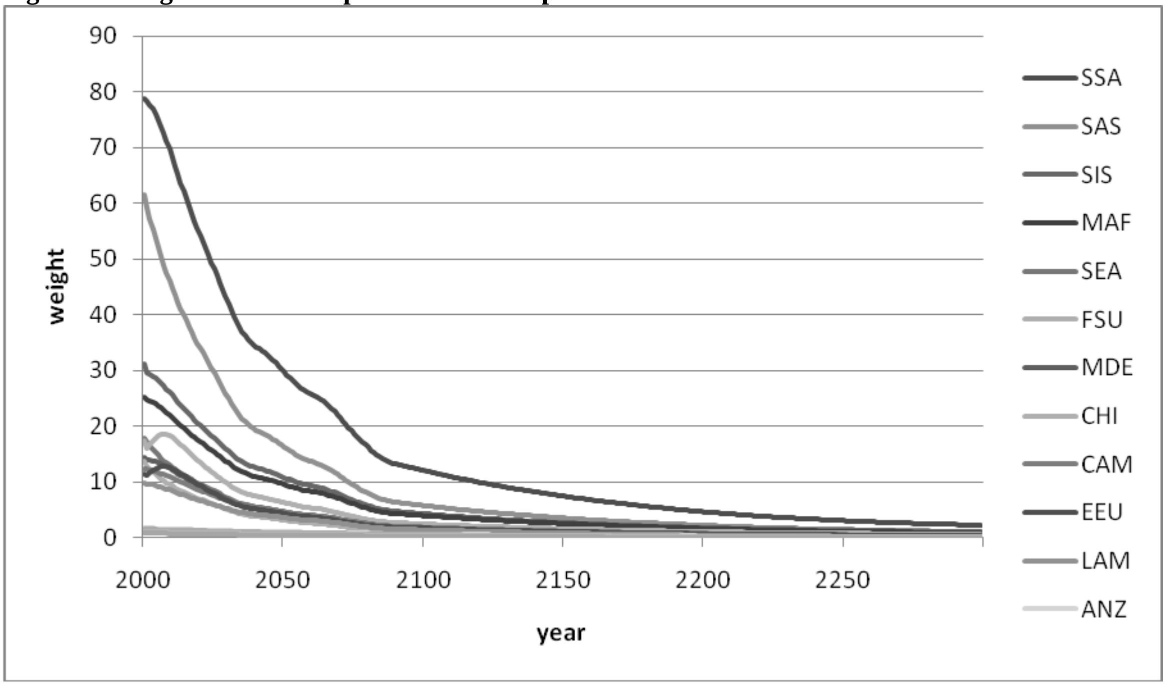
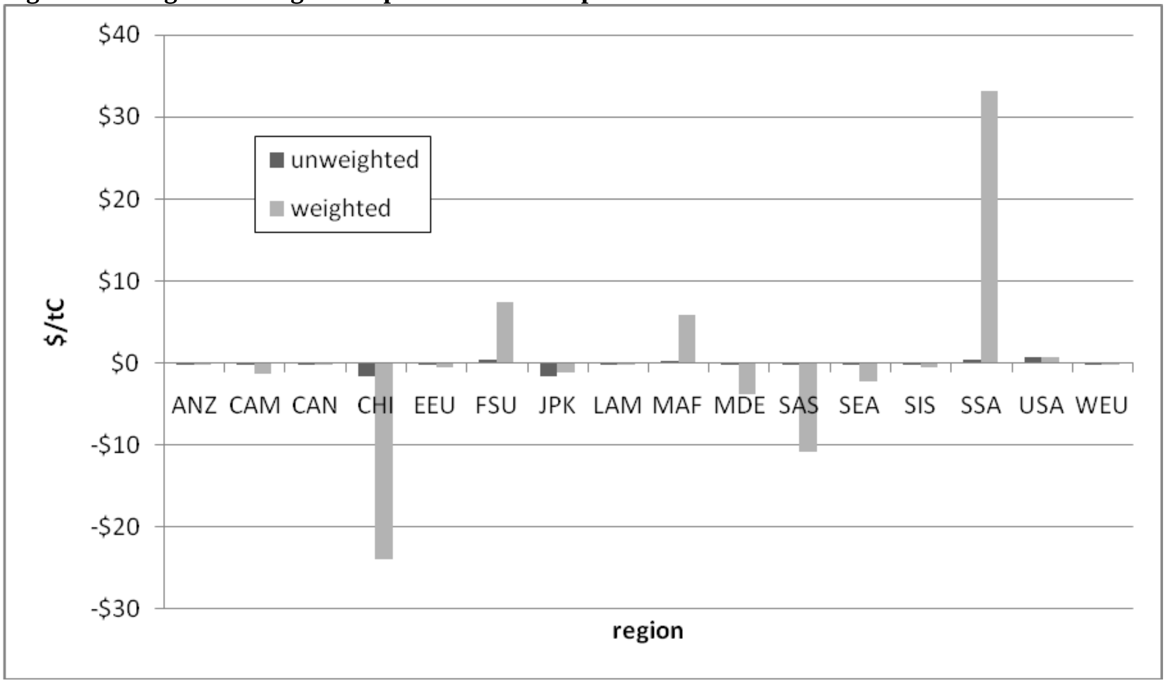


Figure 4: Marginal damage for a pure rate of time preference of 3% with A2 scenario



Tables

Table 1: Unweighted marginal damage in $/tC

	Pure rate of time preference		
Scenario	*0%*	*1%*	*3%*
FUND	73.9	15.0	-2.6
SRES A1b	26.3	3.5	-3.8
SRES A2	111.5	21.8	-2.4
SRES B1	13.1	-1.6	-5.3
SRES B2	69.8	12.7	-3.1

Table 2: Equity weighted marginal damage in $/tC

	Pure rate of time preference		
Scenario	*0%*	*1%*	*3%*
FUND	1,097.3	263.1	-0.7
SRES A1B	269.4	47.0	-31.6
SRES A2	1,610.2	350.6	2.5
SRES B1	163.3	3.4	-45.7
SRES B2	1,019.4	211.6	-12.7

Table 3: Equity weighted marginal damage in $/tC, using the method described in Tol (1999)

	Pure rate of time preference		
Scenario	*0%*	*1%*	*3%*
FUND	$73.5	$17.1	-$2.9
SRES A1B	$26.2	$3.4	-$4.5
SRES A2	$128.6	$27.6	-$1.9
SRES B1	$12.2	-$2.3	-$6.6
SRES B2	$64.9	$12.7	-$2.9

Table 4: Results normalised with per capita income of different world regions for scenario A1B in $/tC

	Pure rate of time preference		
Region of per capita income normalisation	*0%*	*1%*	*3%*
World average	50.3	8.8	-5.9
ANZ	157.1	27.4	-18.4
CAM	21.7	3.8	-2.5
CAN	187.3	32.7	-21.9
CHI	19.7	3.4	-2.3
EEU	23.4	4.1	-2.7
FSU	15.6	2.7	-1.8
JPK	354.2	61.9	-41.5
LAM	27.7	4.8	-3.2
MAF	10.7	1.9	-1.3
MDE	18.6	3.3	-2.2
SAS	4.4	0.8	-0.5
SEA	15.1	2.6	-1.8
SIS	8.6	1.5	-1.0
SSA	3.4	0.6	-0.4
USA	269.4	47.0	-31.6
WEU	234.0	40.9	-27.4

Table 5: Equity weighted marginal damage with regional equity coefficient in $/tC (based on SRES A1b scenario; normalized at US average income)

	Pure rate of time preference		
Inequality	*0%*	*1%*	*3%*
No change	351.9	62.5	-40.0
More equality	306.7	50.6	-42.5
Less equality	499.8	96.9	-37.1
Results without regional equity coefficient			
	269.4	47.0	-31.6

Table 6: Equity weighted marginal damage by inequality aversion in $/tC (normalized at US average income)

	Pure rate of time preference		
	0%	*1%*	*3%*
FUND			
ε=1.0	1,097.3	263.1	-0.7
ε=0.5	1,304.2	263.9	13.6
ε=1.2	1,146.0	295.7	-9.4
SRES A1b			
ε=1.0	269.4	47.0	-31.6
ε=0.5	740.7	153.7	2.8
ε=1.2	187.7	12.3	-56.3
SRES A2			
ε=1.0	1,610.2	350.6	2.5
ε=0.5	1,680.7	312.9	13.3
ε=1.2	1,731.9	407.2	-2.7
SRES B1			
ε=1.0	163.3	3.4	-45.7
ε=0.5	400.0	68.3	-10.7
ε=1.2	106.7	-29.1	-74.3
SRES B2			
ε=1.0	1,019.4	211.6	-12.7
ε=0.5	1,206.6	225.7	6.0
ε=1.2	1,031.7	223.8	-24.3

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