Social Cost of Carbon: Equity Weighting

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Except where otherwise stated and acknowledged I certify that this Dissertation is my sole and unaided work.

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Acronyms and abbreviations

C	Carbon
CO_2	Carbon dioxide
DEFRA	Department for Environment Food and Rural Affairs, UK
DICE	Dynamic integrated climate-economy
FUND	The Climate Framework for Uncertainty, Negotiation and Distribution
GDP	Gross domestic product
IPCC	Intergovernmental Panel on Climate Change
MD/tC	Marginal damage per ton of carbon in 1995 US dollars
NPV	Net present value
prtp	Pure rate of time preference
RICE	Regional integrated model of Climate and the Economy
tC	Ton of carbon
WTP	Willingness to pay

Variables and functions

b	Calibration factor for the utility function
B(t)	Benefit at time t
c	Consumption
$\check{c}$	Average per capita consumption
C(t)	Cost at time t
D(t)	Marginal change in consumption at time t
$\check{D}(t)$	Average marginal per capita consumption change at time t
P(t)	Population at time t
PF(t)	Time preference factor at t
t	Time
u(c)	Utility for consumption c
$u_c(c)$	Marginal utility at consumption level c
U_i	Welfare of individual i
W	Social welfare
ε	Elasticity of the marginal utility of consumption
ρ	Pure rate of time preference

Regions in FUND

ANZ	Australia & New Zealand
CAM	Central America
CAN	Canada
CHI	China, Korea and Mongolia
EEU	Eastern Europe
FSU	Former Soviet Union
JPK	Japan & South Korea
LAM	Latin America
MAF	Med. Africa
MDE	Middle East
SAS	South Asia
SEA	Southeast Asia
SIS	Small Island States
SSA	Sub-Saharan Africa
USA	United States of America
WEU	Western Europe

Abstract

Equity weighting enables fair comparison of monetary damages that accrue to regions with very different income levels. This is especially appropriate in the context of climate change where damages are likely to affect people with very diverse levels of wealth. This thesis makes both theoretical and practical contributions to the literature on climate change economics.

The theoretical foundation of equity weighting is advanced in two areas. Firstly, this thesis develops a new conceptual analysis of equity weighting that demonstrates the relationship between equity weighting and discounting. This new model also shows clearly that the way equity weighted results have been presented in the literature is open to misinterpretation and suggest a way of presenting equity weighted marginal damage figures that does not suffer from this problem. Secondly, the model for equity weighting is significantly enhanced when it is applied to aggregated damage figures for whole regions. An aggregation coefficient is derived that corrects errors that are introduced when regionally average data sets and scenarios are used.

All theoretical ideas have then been implemented in two leading impact assessment models (FUND and RICE) in order to test the magnitude of change these theoretical advances cause to the social cost of carbon figures. A significant amount of work was spent on improving FUND, not only in the area of equity weighting, but also in making in- and outputs more user friendly and implementing many other improvements to the model.

Results from modelling suggest that the effect equity weighting has on the social cost of carbon figures has been underestimated significantly in the literature. New, corrected, results are presented. At the same time, it is outlined why, in policy decision making, equity weighted numbers must be used differently than unweighted damage figures.

1 Introduction

During the last decade the topic of climate change slowly made its way from obscurity into the limelight of scientific research and the general public. Today some argue it is the biggest problem mankind faces, while others deny the phenomena entirely. After three comprehensive reports on climate change by the Intergovernmental Panel on Climate Change (IPCC), the group that doubts any serious climate change is no longer part of the consent reached by the scientific community represented by the scientific working group of the IPCC (Houghton et al., 1990; Houghton et al., 1995; Houghton et al., 2001).

While there is consensus that the earth's climate is going to change due to actions taken by man, the issue is nevertheless complicated by many complexities and uncertainties on almost any level. Uncertainties exist about the precise natural changes that will occur during the next couple of centuries, about the socio-economic development the different world regions will experience during that time and about fundamental ethical questions of how to make good decisions in the face of damages that will occur over a time frame of many hundred years and will effect many different generations and people with vastly different living standards.

This thesis tackles the question how damages to people with very different income levels can be compared with each other.

1.1 Climate change

The general principles of the earth's climate system are well understood today. The primary source of energy comes from the sun in the form of light, i.e. short wave radiation. Some of the energy coming from the sun is scattered back into space by atmospheric molecules and some is reflected (as light) from the earth's surface. But the vast majority will reach and heat the earth surface. It is one of the basic laws of physics that a body being warmed needs to balance the incoming energy by emitting the same amount of energy back. The earth therefore radiates energy back into space in the form of thermal radiation. Unlike the sunlight, this energy faces a barrier on its way out into space, the so called greenhouse gases and water vapour. The set of substances that block outgoing thermal radiation is actually quite diverse, ranging from the most important gas CO_2, over water vapour to methane to various other - less significant - gases. All of these contribute to the so called greenhouse effect. The substances discussed so far all absorb energy in the thermal wavelength range, in which the outgoing energy from the earth attempts to reach space. Since the greenhouse gases are governed themselves by the energy balance law, they will emit exactly the same amount of energy that they absorb, like the earth does with incoming solar radiation. The greenhouse gases emit energy into all directions: Some into space, but some also back to the earth surface. This alters the energy balance for the earth surface. A balance is not only needed for the incoming solar radiation, but also for the thermal radiation that was originally emitted by the earth and is now reemitted towards the earth by the greenhouse gases. Consequently, the earth surface warms more and emits more thermal energy than it would without the greenhouse effect. The greenhouse effect does indeed make life on earth possible in the first place, without it average temperatures on the earth surface would be too low for most ecosystems one can observe today on earth (Houghton, 1997).

The system described so far is calibrated such that the earth surface temperatures stay within the temperature ranges that are suitable for life on earth. One of the driving parameters is the concentration of greenhouse gases in the atmosphere. The magnitude of the greenhouse effect is a direct function of greenhouse gas concentrations, and therefore, it is assumed that temperature on earth is very sensitive to greenhouse gas concentrations. The worry expressed in the IPCC reports is that humans are changing those greenhouse gas concentrations on such a scale that the temperature on earth will increase significantly, which would, in turn, cause many more dramatic changes to natural earth systems. The main reason for concern is today's CO_2 emission caused by humans, which has dramatically increased, compared to pre-industrial emission levels. CO_2 emissions have, especially in the developed world, increased over the last 200 years because of a bigger demand for energy that was mainly fed by burning fossil fuels like oil and coal. The exact relation between CO_2 emissions and concentrations is governed by various time lags, so that the effect of increased greenhouse gas concentrations manifests itself long after its cause, namely increased greenhouse gas emissions. Today, increased concentrations can be attributed to emissions 30 years ago. There is little doubt that emissions now and in the future will lead to dramatically higher greenhouse gas concentrations in the future that will increase average temperatures across the world (Houghton et al., 2001).

An increase in temperature is not a bad thing in itself. Detailed impact studies are needed to evaluate what such a change will cause in turn and whether it results in a benefit or a cost to society. Working group II of the IPCC attempts to shed light on these questions (McCarthy et al., 2001). Again, the scientific uncertainties are huge in this area. Temperature increases can directly change the dynamic of many very complicated and not well understood systems, like the ocean circulations (Houghton et al., 2001). But it is not only the sheer complexity of some of the systems that will be changed by climate change that make predictions of impacts difficult, it is also the number of different areas that will be affected. Biological systems vary widely in different world regions and there are very few general studies that attempt to assess impacts for a specific sector on a world wide basis (Tol, R. 2004, pers. comm., 26 April). More of these general studies would be needed in order to evaluate total impacts from climate change.

1.2 The social cost of carbon

Economists attempt to derive one central number from all insights into climate change and the effect it will have on present and future generations around the world. This central number is called the social cost of carbon and ideally aggregates all changes caused by CO_2 emissions all over the world over the next couple of centuries.

This is an ambitious project, but it becomes important when governments attempt to sort out optimal policies that deal with carbon emissions. Reducing carbon emissions is, in many cases, associated with an economic cost. An optimum policy will attempt to balance that mitigation cost with the damages avoided when less carbon is emitted into the atmosphere. An optimal policy will reach a level of CO_2 emissions at which the mitigation costs needed to reduce emissions to that level equal the damage avoided by the amount of reduction in emissions. Any other level of carbon emissions would not be optimal and should be avoided by governments (Kolstad, 2000). In order to make an informed decision about the optimum level of carbon emissions, one therefore needs to know how much damage will be caused by emitting CO_2 today, as well as how much mitigation of emissions will cost. The social cost of carbon forms the first part of that insight, namely the damage caused by emissions. Even if governments do not explicitly take the social cost of carbon into their policy consideration, one can argue that they, nevertheless, implicitly use a value in their policy making process. Assuming that a policy is aiming for optimum results, one can derive an implicit assumption about the social cost of carbon simply by looking at the level of carbon emissions aimed for by the policy, setting that into relation with all the other costs or benefits of a policy and then calculating the social cost of carbon value for which the policy would be optimal. Since, after all, using a value cannot be avoided when making policy decisions, it seems to be more promising to attempt to evaluate the social cost of carbon by research, rather than to implicitly use a non informed value.

The social cost of carbon is mostly presented as the marginal damage caused by the emission of one extra ton of carbon today. It is important to keep in mind that this value will change for different levels of carbon concentrations, i.e. it will change over time. The marginal damage caused by an extra ton of carbon emission in 10 years will be higher than the damage caused by an emission today, because the relationship between greenhouse gas concentrations and damages is non-linear. The range of values for the marginal damage of carbon emissions that can be found in the literature is huge. A recent survey of 103 estimates of the social cost of carbon from 28 studies shows a range from -$2.5/tC to $350/tC, i.e. from a small benefit from carbon emissions to very high costs due to climate change (Tol, 2004). Tol also calculated the mean value for only the results from peer reviewed studies, which is $43/tC with a standard deviation of $83/tC (certain studies were given more weight than others by Tol, according to a rich set of criteria devised by Tol). Much of the range can be explained by different discount rates, but other areas contribute to the uncertainties as well (Downing et al., 2004 gives a systematic overview of the uncertainties).

The social cost of carbon can also be used in cost-benefit analysis, i.e. when individual projects are to be evaluated. Once one knows the marginal damage caused by a ton of carbon emission, one can calculate the total damage due to increased climate change caused by a project from its CO_2 emissions. These costs should then, like any other project cost, simply be included in the cost-benefit analysis.

1.3 Aims and research question

This thesis is concerned with the question how damages in different world regions can be added up into one figure for the whole world. The particular question is how damages to people with different income levels can be compared and combined in such a way that one can calculate the social cost of carbon for the whole world.

The idea that damages to people with different wealth levels should be weighted differently in the context of climate change has been brought forward in the second assessment report of the IPCC (Pearce et al., 1996). A number of authors have developed theoretical models concerning the question how such equity weights can be derived and applied to the social cost of carbon (Fankhauser et al., 1997; Azar and Sterner, 1996; Azar, 1999; Pearce, 2003).

This thesis takes the theoretical work done so far and adds two new aspects to the theory of equity weighting. The first is a unified model for equity weighting and discounting, where the growth component of the discount rate is replaced with a more general equity weight methodology. The new methodology is developed and presented in section 2.1.2, putting it in the context of existing equity weighting schemes developed in the literature. The second theoretical addition is a mathematical model that improves the level of detail of equity weights when the social cost of carbon is calculated based on a very coarse regional grid, i.e. when the world is divided into very few regions. The new model enables one to take inequities within, not only between regions into account. The new model is presented in section 2.1.6.2, again putting it into the context of aggregation methodologies demonstrated in the literature so far.

Both theoretical ideas are then tested with empirical data. The new general equity weighting methodology is tested in two different integrated assessment models with various scenarios. The work on aggregation and equity weighting was tested with one model. Both parts of the theory required extensive changes to the models, which are described in section 2.2. This thesis was part of a larger research project that included many more improvements to the models than just the introduction of the new equity weighting theory. These additional improvements were used for the results in this thesis as well and are also briefly described in that section.

The question that this thesis attempts to answer is how - on a theoretical level - equity weighting should be implemented in the context of the social cost of carbon and how it changes marginal damage figures predicted by impact assessment models.

The relevant literature on equity weighting and general economic valuation issues is incorporated throughout the development of the new theoretical models.

2 Methodology

This thesis has a theoretical and a modelling part. Both have distinct methodological characteristics which will be outlined in this chapter. Since all modelling is based on the theoretical work, the first step is a detailed exposition on the theory of equity weighting. After an introduction to the state of the art of equity weighting two novel theoretical ideas will be presented in the first half of this chapter. All theoretical advances were then implemented in integrated assessment models in order to test their effect on optimal emission paths and the social cost of carbon. A detailed description of the changes and enhancements implemented in two integrated assessment models for this thesis form the second part of this chapter.

2.1 Theory of equity weighting

2.1.1 Introduction

The concept of equity weighting can be easily grasped and justified by a simple example. For a person that has a high income, e.g. £5,000 per month, a change of income by £1 will most likely have a less drastic effect on welfare than the same change in income would have on a person with a low income, e.g. an income of £100 per month. Whenever one is trying to evaluate a policy that would change income of people with different income levels, one has to decide whether to consider these different income levels in the decision or not. Climate change policies certainly fall into that category. They not only have an impact on many different generations (which will most likely have different income levels) but also people in different world regions with vastly different per capita incomes.

A number of authors have either argued that equity weighting should be done in the context of climate change policy (Pearce et al., 1996; Pearce, 2003; Azar and Sterner, 1996) or at least recognised that this issue is of significance in the context of climate change policy (Nordhaus, 1994). Nevertheless, the question whether to equity weight damages at all doesn't have a simple answer and will be discussed in section 2.1.7.

The number of studies that have implemented some form of equity weighting is even smaller and different studies use different ways to equity weight. Section 2.1.2 will present a novel approach on how to do equity weighting.

2.1.2 Utility and welfare

The intuition expressed in the introduction of this chapter now needs to be formalised into a model. The basic framework used for the following discussion is outlined by Nordhaus and Boyer (1999). It is assumed that only one single type of good is produced that can either be consumed or invested. All climate change policy options are expressed as choices on how much of that good to invest. It is assumed that climate change mitigation will require investment and therefore leave less of the produced commodity for consumption at the time of investment, while mitigation measures will decrease damage from climate change in the future and therefore increase production of the commodity in the future. If societies decide to consume more today, damages in the future will increase and therefore the amount of the commodity that could be used for investment or consumption will be lower for future generations. The metric used for this one commodity is money.

The notion of consumption used in this discussion is very broad. It includes everything a person might derive pleasure from. This includes market goods, for which the willingness to pay (WTP) can be observed by market prices, as well as non-market goods, e.g. beautiful landscapes and controversial topics like the value of a statistical life, which is used to value the loss of life (Fankhauser et al., 1998).

The intuition that a £1 change in consumption to a rich person is less drastic than to a poor person can be expressed by a conventional isoelastic utility function of the following form:

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

where *u(c)* is the utility a person will experience from a flow of consumption *c*, while *ε* is the elasticity of the marginal utility of consumption. The elasticity of marginal utility of consumption is an indicator of the social valuation of different levels of consumption (Cowell and Gardiner, 1999). This form of utility function has exactly the property we require to model our intuition, namely that the same absolute change in consumption constitutes a smaller change in utility for high levels of consumption, compared to low levels of consumption. The metric of the values from *u(c)* is not money anymore, but rather utility.

It follows that marginal utility of consumption therefore is:

$$u_c(c) = c^{-\varepsilon} \tag{2}$$

at a consumption level of *c*.

(1) can be used to convert a consumption level of one person at a specific point in time into a level of satisfaction for that person. In order to evaluate the marginal change in utility for a marginal change in consumption for a specific person at time *t*, one can simply multiply the marginal damage figure with the marginal utility of consumption (2) at the consumption level of that person. Then if *D* is a marginal change in consumption for a person at a specific point in time, it follows that:

$$u_c(c)D \tag{3}$$

is the marginal change in utility for a person with a consumption level of *c* at the time of the consumption change[1].

This very simple concept of utility needs to be extended in order to deal with climate change because impacts from climate change will not all accrue at the same time and will affect many

[1] This is actually a simplifying approximation. The precise change in utility is $\int_{c}^{c+D} u_c(x)\,dx$. Since *D* tends to be very small at any time *t* when calculating the marginal social cost of CO_2 emissions, all models use the simpler equation (3).

different people. A number of simplifying assumptions will be made to accomplish that. They are not uncontroversial but are commonly made in economic analysis of climate change and are a reasonable compromise between an accurate model of reality and ease of use of the models.

The main assumption in the step towards a dynamic setting, i.e. one where consumption over a period of time is investigated, is that utility is time separable and can be added up. Therefore, in order to come up with the utility experienced in a given period of time, one will look at the utility experienced at every single time point within the period, calculate the utility for that point in time and integrate those utilities over time. It is assumed that the utility experienced from a certain level of consumption depends only on the consumption at this time and is completely independent of any previous or future consumption or utility experienced from previous or future consumption. The assumption of time separability was employed by Ramsey (1928) and has been an important component of neo-classical growth models, such as Solow's (1970), ever since. All models reviewed for this thesis adhere to this form of utility function as well (Nordhaus and Boyer, 1999; Hope, 2003; Tol, 2002b; Tol, 2002a).

A time separable utility function does not imply that all flows of utility at different points in time should have the same weight. While there is one school of thought that argues for just that (Ramsey, 1928; Broome, 1992; Cline, in preparation), others take the opposite side and argue that future utility should be weighted (Nordhaus and Boyer, 1999). Fundamentally, the question whether future utility flows should be discounted or not is an ethical question. There are good arguments for both sides, ranging from observations about the observed market, fundamental ethical positions and potential solutions in the form of declining discount rates (Groom et al., in preparation). A complete discussion of discounting in the context of climate change is beyond the scope of this dissertation. Guo (2004) investigates many different discounting schemes in relation to the social cost of carbon calculated from FUND, one of the models used for this thesis.

In order to make the results from this study comparable to other published numbers on the social cost of carbon, the utility values from damages in the future will be discounted with different constant pure rate of time preferences. Utility will be discounted with a time preference factor that falls for any pure rate of time preference >0. The assumption here is that there is a consistent set of preferences over time, namely that earlier enjoyment is preferable to later one. This assumption ignores the problem that climate change damages will accrue to different generations and that it is highly unlikely that different generations have a consistent set of preferences on pure utility discounting factors (Portney and Weyant, 1999). The simplifying assumption made here is that all people considered live throughout the entire period for which damages of climate change are evaluated. In choosing this route, a difficult ethical problem is ignored, but it allows easy comparison of the effects of equity weighting as suggested in this thesis with the results from other authors that make this assumption as well (Tol, 1999b; Hope, 2003; Nordhaus and Boyer, 1999). The time preference factor used in this thesis therefore is:

$$PF(t) = e^{-\rho t} \tag{4}$$

Where $PF(t)$ is the time preference factor at time t and ρ is the pure rate of time preference. In order to convert any change in utility at time t into the discounted change in utility this factor $PF(t)$ needs to be applied.

To calculate the total utility for a person i over the time period for which the damages from climate change shall be calculated, one converts all consumption flows over time to utility, multiplies the utilities with the pure time discounting factor for the time point of the consumption and adds all the resulting discounted utility flows up. Treating time as continuous, one gets the total welfare experienced by a person, depending on the consumption levels for that person:

$$U_i = \int_0^T u\left[c_i\left(t\right)\right] PF\left(t\right) dt \tag{5}$$

Where U_i is the total utility or welfare experienced by individual i for the time period from 0 to T (i.e. from now to time T, where one is going to cut of the analysis) and $c_i(t)$ is consumption of person i at time t.

Assuming a consumption change function $D_i(t)$ that returns a change in consumption for individual i at time t, the change in utility for person i is given by:

$$\Delta U_i = \int_0^T u_c\left[c_i\left(t\right)\right] D_i\left(t\right) PF\left(t\right) dt \tag{6}$$

The next step is to extend the discussion from one person to many. In order to aggregate utility experienced by many individuals into one measure of welfare, a social welfare function (SWF) needs to be defined. There are many different social welfare functions, but once again the choice between those is an ethical one that can only be settled by choosing a specific ethical position. The most commonly used social welfare function in the context of climate change is a utilitarian welfare function:

$$W = \sum_{i=1}^{n} U_i \tag{7}$$

where n is the total number of people. Such a welfare function gives the same weight to every individual. Other welfare functions have been tested with climate change models, as well (Tol, 2001), but in order to make results from different models comparable, a welfare function of the form (7) is used for this thesis.

Combining (1), (6) and (7) one gets this form for the social welfare function:

$$W = \sum_{i=1}^{n} \int_{0}^{T} \frac{c_i(t)^{1-\varepsilon}}{1-\varepsilon} e^{-\rho t} dt \tag{8}$$

In analogy to (6), one can now calculate the welfare change for a given consumption change function $D_i(t)$:

$$\Delta W = \sum_{i=1}^{n} \int_{0}^{T} u_c\left[c_i(t)\right] D_i(t) e^{-\rho t} dt \tag{9}$$

2.1.3 Calibration

The values we receive from the utility function (1) are not given in a metric that corresponds to any metric used in the real world. In particular, the metric is not money (which is the metric used for consumption). The need to convert utility values back into monetary values if one is going to compare those values with other monetary values has been recognised in the literature (Azar and Sterner, 1996; Azar, 1999), but is often not mentioned explicitly when equity weighted numbers are presented (Pearce, 2003; Clarkson and Deyes, 2002; Fankhauser et al., 1997).

The fundamental conceptual reason for this can be explained as follows: The utility function (1) in the social welfare function (8) can be replaced with any other utility function that is a transformation of a certain type of the utility function (1), without changing the solution of an optimisation of the social welfare function nor changing any results that might be obtained by using (9) in a cost-benefit analysis.

The allowed transformation of the utility function is any linear transformation:

$$\tilde{u}(c) = a + bu(c), b \in \Re^{+} \tag{10}$$

For a proof that any transformed utility function like (10) will not change the result of any cost-benefit analysis, see Appendix A: Transformed utility function and cost-benefit analysis.

2.1.4 Utility function for policy choices

While it has been shown that the choice of the utility function is arbitrary and that any number of linear transformations of an isoelastic utility function give the same results in cost-benefit considerations, the choice of the right utility function is nevertheless an important one. The UK government has issued a number of reports on the social cost of carbon that attempt to clarify how eventual damages from CO_2 emissions should be included in policy decisions (Clarkson and Deyes, 2002; Downing et al., 2004). Cost-benefit analysis is one of the key instruments used by the British government, and consequently, one of the goals of those studies is to outline how damages from climate change should be included in cost-benefit analysis.

The introduction of equity weighting poses a particular challenge in this setting because it requires the application of the weights to the benefits and costs of a project under review. The central number in the literature on the social cost of carbon is the marginal cost of CO_2 emissions (Pearce et al., 1996). This number is then used in a variety of decision methods, and one of them is cost-benefit analysis. Depending on whether CO_2 emissions are going to be increased or decreased in a project under review, the marginal damage figure will determine either the costs of the additional CO_2 emissions or the avoided damage, i.e. the benefits, of the decreased emission. Either way, the figure for the marginal damage will only shape either the costs or the benefits in the analysis and not both. Other factors, most likely mitigation costs, determine the other side of the equation in the cost-benefit analysis. Introducing equity weights only for the marginal damage figures and not for the other costs or benefits in the cost-benefit analysis would be inconsistent and flawed. It would essentially amount to comparing utility changes with consumption changes, which is a meaningless endeavour.

The way marginal damage numbers are presented in most of the leading papers on the social cost of carbon, namely that they only present the social cost of carbon side, is problematic once equity weighting is introduced. Often, figures that aren't equity weighted are directly compared to figures that are equity weighted, as if the latter numbers could just replace the unweighted numbers in a cost-benefit analysis (Fankhauser et al., 1997; Clarkson and Deyes, 2002; Pearce, 2003)[2]. But this is only going half way. In order to use the equity weighted social cost of carbon in a cost-benefit analysis, any other cost or benefit that is used in the analysis needs to be changed, i.e. equity weighted, as well. This will, in most cases, change the results even further than an analysis of the social cost of carbon by itself would imply.

The situation is further complicated by the fact that any of an indefinite number of isoelastic utility functions can be used to introduce equity weights, as has been shown before. Saying that a particular number for the social cost of carbon is equity weighted is not very helpful, unless one makes explicit what transformation, if any, of the basic isoelastic utility function (1) is used to derive that equity weighted figure. That information is necessary for others that would like to use the marginal damage number in a cost-benefit analysis, in order to weight any other consumption changes of the project consistently.

Things would be a lot easier if equity weighted marginal damage figures for CO_2 emissions could be presented in such a way that they could be compared directly with non equity weighted figures and any other costs or benefits, like mitigation costs. This would be most valuable in policy and political debate, where details are often ignored and equity weighted numbers are compared with other monetary figures all the time, regardless of whether that is appropriate or not (as an example see Pearce, 2003).

Achieving this would be extremely simple if all the other changes in consumption (other then the social cost of carbon) that are being considered in the cost-benefit analysis happen at the same point in time and only affect a single person. Using the consumption level $c_r(t_0)^{\varepsilon}$ for that reference person at the time t_0 of all the other consumption changes as b in (10), this is the utility function:

[2] There are some noteworthy exceptions to that practice (Azar and Sterner, 1996; Azar, 1999).

$$u(c) = c_r(t_0)^{\varepsilon} \frac{c^{1-\varepsilon}}{1-\varepsilon} \tag{11}$$

Note that $c_r(t_0)^{\varepsilon}$ is a constant. The marginal utility of consumption therefore is:

$$u_c = c_r(t_0)^{\varepsilon} c^{-\varepsilon} \tag{12}$$

The marginal utility of consumption for person r at time t_0 is therefore:

$$u_c\left[c_r(t_0)\right] = c_r(t_0)^{\varepsilon} c_r(t_0)^{-\varepsilon} = 1 \tag{13}$$

If, as assumed, all consumption changes that are to be compared with the social cost of carbon happen to person r at time t_0, weighting these changes is made a lot easier, since the weight for those changes is 1. This greatly simplifies cost-benefit analysis. The equity weighted social cost of carbon can be directly compared to any other cost or benefit, since the weight of 1 for those does not change them.

In practice, mitigation costs or any consumption changes that are going to be compared to the damages from CO_2 emissions will never happen at a single point in time. But this phenomenon is well known in cost-benefit analysis which is not concerned with equity weighting at all, and solved by the concept of net present value (NPV). Keeping the assumption that all changes in consumption (except for the damages from CO_2 emissions) will accrue to a single representative individual r, one gets a single cost function $C_r(t)$ for that individual. The traditional economic method of integrating over time and calculating the net present value of all the costs is:

$$NPV = \int_0^T C_r(t) \frac{c_r(0)^{\varepsilon}}{c_r(t)^{\varepsilon}} PF(t)\, dt \tag{14}$$

The number obtained by (14) can be compared directly to any equity weighted social cost of carbon, if (11) is chosen as the utility function for the equity weighting. This is true because

(14) is equivalent to methodology introduced in (6) for a one person case, if the utility function (11) is used.

This method can be extended one step further: Assuming that more than one person has to pay for the cost of a certain policy, but at the same time assuming that those individuals have exactly the same consumption level at any point *t* in time, one can, once again, use the traditional method to calculate the net present value of those costs:

$$NPV = \sum_{i=1}^{k} \int_{0}^{T} C_i(t) \frac{c_r(0)^{\varepsilon}}{c_r(t)^{\varepsilon}} PF(t)\, dt \tag{15}$$

Where k is the number of people that have to pay the costs of the policy, $c_r(t)$ is the consumption level of all those individuals at time t, and $C_i(t)$ is the cost to person i at time t. This, again, gives exactly the same result that one would obtain by using the equity weighting method with (11) as the utility function, only this time the equation (9) for more than one person.

The result so far is that one can compare equity weighted damages from climate change directly to the net present value of the mitigation costs if the following conditions are true: Mitigation costs are only paid by a group of people in which each individual has exactly the same consumption path over time. Secondly, the utility function for the equity weighting of the social cost of carbon needs to be calibrated to the consumption level of those individuals at time *0*.

This situation is remarkably close to the decision situation of most governments that attempt to include the social cost of carbon in their cost-benefit analysis. Typical examples are subsidies to renewable energy production. The costs of such a policy will only be felt by the people living in the country that introduces such a policy, e.g. the UK. While there are huge differences in consumption levels in typical developed countries, the differences within one developed country appear small in comparison to the differences to developing countries.

Those countries will benefit from any such policy due to the avoided damages from climate change. While ignoring the differences in consumption levels in the country that carries the costs of the policy is not correct, a reasonable approximation to the precise analytical solution is to use the average consumption level of the people of the paying country as the calibration factor *b* in the utility function (10), and compare the equity weighted numbers for the benefits of the policy with the net present value of the costs to the paying country. The simplifying assumption used in this construction is that the consumption level for all individuals of the paying country is the same at any time t, namely the average of the real consumption levels of the people of that country.

Therefore the following suggestion is proposed by this thesis: When equity weighted numbers are going to be used in policy decisions, the utility function should use the average consumption level at time *0* of the country that is engaging in the cost-benefit analysis as the factor *b* in (10) to calculate the marginal damage of CO_2 emissions. This allows direct comparison with eventual costs that the country considering the policy will have to pay, as long as their net present value is calculated. Such a calibration will be called a calibration to the income level to that specific country from this point on.

Two of the leading authors on the social cost of carbon present their equity weighted numbers based on a different utility function, namely one that uses the world average consumption level at time *0* as the calibration factor for the utility function (Fankhauser et al., 1997; Pearce, 2003). There is of course nothing wrong with this approach, as long as the mitigation costs are converted into the same utility metric, i.e. with the same calibration factor for the utility function.

2.1.5 Compensation payments

There is one special feature of a cost-benefit analysis employing equity weights that is worth mentioning: Direct money transfer between people that are affected by the proposed project can change the outcome of the cost-benefit analysis. This is not normally a feature of a cost-benefit analysis, but when projects affect people with different marginal utility of consumption and equity weights are used, one might need to include it in the analysis. A money transfer between two individuals would be represented as a decrease in consumption for one, and an increase of consumption for the other person in the model used so far. Ignoring transaction costs, the increase and decrease would be of the same magnitude.

An example can illustrate this point. Assuming two persons, of whom one is rich (*r*) and the other is poor (*p*), a given project proposal is represented by the functions $B_r(t)$, $B_p(t)$, $C_r(t)$ and $C_p(t)$, namely the costs and benefits for the two individuals accruing from the project. Let's further assume that the poor person is constantly poor throughout the period considered, and the rich person is constantly rich, for example that:

$$\begin{aligned} c_p(t) &= £10 \\ c_r(t) &= £100 \end{aligned} \tag{16}$$

The original project proposal costs the rich person a constant amount of money and also negatively affects the poor person. The huge benefits only accrue to the rich person, like in the following situation:

$$\begin{aligned} C_r(t) &= £50 \\ C_p(t) &= £5 \\ B_r(t) &= £80 \\ B_r(t) &= £0 \end{aligned} \tag{17}$$

As it stands, this project proposal would not pass a cost-benefit analysis with equity weighting (it would pass a standard cost-benefit analysis without equity weighting, though). Due to the lower initial consumption level of the poor person, any change in consumption to that person will have a weight ten times higher than the same change in consumption would have to the rich person. The net change in consumption for the rich person would be +£30 and -£5 for the poor person at any point in time. But changes in consumption of the poor person will be given ten times more weight than changes to the rich person, and therefore the cost to the poor person would outweigh the benefit to the rich person. At the same time, the situation can easily be changed if the rich person is willing to pay compensation to the poor person. A payment of £3 from the rich person to the poor person changes the whole analysis and outcome of the cost-benefit procedure. The net change in consumption for the rich person would decrease to +£27, and increase to -£2 for the poor person. Even though the weight of the damage to the poor person will be ten times higher, the equity weighted benefit to the rich will outweigh the equity weighted costs with the transfer payment.

2.1.6 Aggregation

The model developed so far is based on a basis of detailed knowledge about individual consumption patterns and damage distribution that is not, and never will be, available to researchers that attempt to evaluate policy decisions on climate change. Neither the scenarios for future economic growth and CO_2 emissions commonly used (Nakicenovic and Swart, 2000), nor the literature on impacts of climate change provide information on a per person level. In the context of equity weighting, two separate bodies of knowledge are important: Knowledge about economic situation, i.e. consumption levels, and knowledge about the damages that need to be weighted, i.e. the marginal consumption changes from climate change. The most detailed data about the former (that is available consistently for the whole world) are GDP numbers per country, often going into more detail in the form of gini coefficients or income quintiles (Deininger and Squire, 1997). While there are no projections on a world wide basis for the future at that level of detail, this data on the current situation is still a lot better than what is available on possible impacts from climate change. While there is a huge amount of literature on impacts that focuses on specific localities, these studies cannot be used without problems for any assessment of the global situation without extrapolating in an irresponsible way. Researches that are attempting to build global impact assessment models are therefore left with few studies that often stop at a regional level, i.e. not even at a per country level (Tol, R. 2004, pers. comm., 26 April).

To this date, all global impact assessment models have therefore operated at the least common denominator, namely the regional level (Nordhaus and Boyer, 1999; Fankhauser et al., 1997). The economic model for this aggregation at a regional level will be presented in the following section. An extension to that model, which can incorporate the more detailed information available on income distribution on a per country basis, will be developed in the section after that.

2.1.6.1 Aggregation at the regional level

The two functions in the original model that provide the data the model is based on are the projection for consumption levels for individuals $c_i(t)$ and the marginal changes to consumption levels to individuals (i.e. damages from climate change) $D_i(t)$. Assuming that the only data available is average consumption and average damage on a regional level, those two functions need to be replaced by new functions that operate at a regional level. The average consumption per person at time *t* in region *r* be $\breve{c}_r(t)$ and the average change in consumption per person $\breve{D}_r(t)$.

Unless the utilitarian ethical framework would be given up, there is one more information needed to adequately sum the weighted damages given by the regional damage function. Since utility of every person should be taken into consideration in the utilitarian framework, population sizes per region are needed, so that the various average damage figures per region can be weighted according to the number of people that are affected by those damages. Population for region *r* at time *t* be represented by $P_r(t)$. Obviously the following is true for consumption levels:

$$\sum_{i=1}^{P_r(t)} c_i(t) = \breve{c}_r(t) P_r(t) \tag{18}$$

Namely that adding up the consumption levels for all individuals living in region *r* (if they were known) equals the average consumption level multiplied by the population size for that region. This can be extended to the marginal damage case: The total marginal change of consumption for a specific region equals the average marginal change of consumption for that region multiplied by the population size.

This principle also holds once one looks at utility instead of consumption changes. It is correct to calculate the marginal change in utility for a region by multiplying the average change in utility with the population size of that region.

The method used in the literature to calculate the average change in utility is simple (Fankhauser et al., 1997; Pearce, 2003):

$$u_c\left[\breve{c}_r(t)\right]\breve{D}_r(t) \tag{19}$$

The average damage $\check{D}_t(t)$ is weighted with the marginal utility of consumption at the average consumption level of the region.

Combining (19) and (9) gives the total welfare change, when the data is aggregated at the regional level:

$$\Delta W = \sum_{r=1}^{R}\int_{0}^{T} u_c\left[\breve{c}_r(t)\right]\breve{D}_r(t)P_r(t)e^{-\rho t}dt \tag{20}$$

R is the total number of regions considered. All existing global impact models that implement equity weighting and all literature on equity weighting is based either directly on (20) or some slight modification (Fankhauser et al., 1997; Azar and Sterner, 1996; Azar, 1999; Pearce, 2003).

2.1.6.2 Partial aggregation at the national level

While climate change damage estimates that can be used in global impact models are only available at the regional level, much more detailed knowledge about income distribution is available. This section develops a novel theoretical approach to include more detailed income distribution data into the damage aggregation methodology outlined in the previous section.

The equation (20) works well if income is distributed fairly evenly within each region. In that case, weighting damages with the average income of the whole region is very close to weighting the damages to each individual with the consumption level of that person. The results are very close to the theoretical model that does not use aggregation.

Things look differently when income levels are very unsymmetrical within regions. A region with a small group of people with very high consumption levels and a large group of poor people will most likely get equity weights that underestimate the true utility loss of the region when using average consumption levels to calculate the equity weights. Why is that so? There is little reason to assume that the wealthy part of the population of a region will suffer a disproportionate part of the overall damage of climate change in that region. On the contrary - it is most likely that the wealthy will have more means at hand to protect themselves from damages, for example by moving to parts of the region that are less vulnerable to the impacts of climate change. The assumption that the damages will be evenly distributed to the whole population of a region, i.e. that every individual of the region suffers exactly the same absolute change in consumption, is therefore probably still underestimating the damage inflicted onto the poor (Tol et al., 2003). But even with this very conservative assumption, the weights derived in (20) will underestimate the true level of utility loss. The average consumption level of the region can be massively changed by very few individuals, if income of those individuals is much higher than everybody else's. If that is the case, consumption changes for everyone in the region will be given a lower equity weight than they would get if the small group of rich individuals were no part of the community. This is an incorrect result, since the utility changes of the poor people should not change due to the existence of some wealthy people in the same region.

In order to correct this, the introduction of an inequality coefficient into the weighting is proposed. In a region where consumption is the same for every person, this coefficient should be 1, since the aggregation methodology of the previous section deals adequately with such a situation and the result doesn't need to be corrected any further. For any situation where income distribution is skewed in the region, that coefficient should be greater than 1, in order to correct the too small equity weight derived by taking average consumption of the region as the basis for the calculation.

The following section presents a mathematical solution to calculate this coefficient that relies only on knowledge about population sizes and GDP numbers for the countries that make up each region. This model lends itself well to the climate change problem, since both sets of data are available for the whole world.

2.1.6.2.1 Partial aggregation model

The coefficient will first be developed for a single point in time and later extended to the dynamic setting. Assuming for now that not only the average consumption level for each country, but also the precise damage to each country, is known, this is true:

$$\Delta W(t) = \sum_{i=1}^{n} \tilde{u}_c\left[\breve{c}_i(t)\right] D_i(t) \tag{21}$$

Where $\breve{c}_i(t)$ is average per capita consumption and $D_i(t)$ is total damage for country i. $\Delta W(t)$ is the total utility change for the region. $D(t)$ being the total damage for the region, one can assume that:

$$D_i(t) = \alpha_i(t) D(t), \; with \; \alpha_i(t) \geq 0 \; and \; \sum_{i=1}^{n} \alpha_i(t) = 1 \tag{22}$$

And get:

$$\Delta W(t) = D(t) \sum_{i=1}^{n} \alpha_i(t) \tilde{u}_c\left[\breve{c}_i(t)\right] \tag{23}$$

D(t) is the total damage for the region, while the rest of the right hand side of the equation is the equity weight. The assumption that damage is evenly shared by all members of the region is captured by:

$$\alpha_i(t) = \frac{P_i(t)}{P(t)} \tag{24}$$

Where $P_i(t)$ is the population size of country *i* and *P(t)* is the population size of the whole region, i.e. $P(t) = \sum_{i=1}^{n} P_i(t)$. The average per capita consumption $\breve{c}_i(t)$ is defined as:

$$\breve{c}_i(t) = \frac{c_i(t)}{P_i(t)} \tag{25}$$

Where $c_i(t)$ is total consumption for country *i*. Combining (23) with (25) and replacing the marginal utility function with its definition (10) one gets:

$$\Delta W(t) = D(t) \sum_{i=1}^{n} \frac{P_i(t)}{P(t)} b \left[\frac{c_i(t)}{P_i(t)} \right]^{-\varepsilon} \tag{26}$$

This can be transformed to:

$$\Delta W(t) = D(t) \frac{b}{P(t)} \sum_{i=1}^{n} \frac{P_i(t)^{1+\varepsilon}}{c_i(t)^{\varepsilon}} \tag{27}$$

In order to calculate the coefficient for a region that needs to be applied to the damage that is already weighted with the marginal utility of consumption based on the average consumption level of that region, the right side of (27) needs to be divided by $D(t)\tilde{u}_c[\breve{c}(t)]$. The result is the final coefficient that needs to be calculated for each region and can then be applied to the results obtained from damages that are equity already weighted at the regional level:

$$\frac{D(t)\dfrac{b}{P(t)}\displaystyle\sum_{i=1}^{n}\frac{P_i(t)^{1+\varepsilon}}{c_i(t)^{\varepsilon}}}{D(t)b\left(\dfrac{c(t)}{P(t)}\right)^{-\varepsilon}} \tag{28}$$

This simplifies to:

$$\frac{c(t)^{\varepsilon}}{P(t)^{1+\varepsilon}}\sum_{i=1}^{n}\frac{P_i(t)^{1+\varepsilon}}{c_i(t)^{\varepsilon}} \tag{29}$$

As the coefficient for a given region.

2.1.6.2.2 A preliminary assessment

A novel approach has been demonstrated that allows inclusion of detailed information about income distribution within regions for which damage estimates are known. The coefficient developed allows correction of equity weighted damage figures from climate change models that are equity weighted on the level of detail for which damage estimates are available, when more detailed, i.e. fine grained, information about income distribution is available. Damage that happens in regions that have an uneven income distribution will get more weight by using this model. This is desirable since it corrects damage numbers in such a way that they are closer to what they would be, could we apply the detailed model presented in section 2.1.2. Since damage and income information is not available on a per person level, the latter option is not viable in practice and the correction presented in this section is the next best alternative.

Probably the weakest assumption proposed in this section concerns the equal distribution of damage across all individuals living in a region. While this will obviously never be true, it is important to keep two points in mind: First, all models that attempt to globally aggregate damages from climate change make that assumption. And, as mentioned before, a more precise modelling of damage distribution would not run counter the results that are obtained from the method developed in this section. The method proposed in this section will increase the equity weighted marginal damage from the CO_2 figure that is obtained by using only regional averages, as would a more detailed look at damage distribution. The latter would only further strengthen the trend set by the method introduced in this section.

2.1.7 Should one equity weight?

The fundamental question that has not been answered so far is whether one should use equity weighting at all. There are two dimensions to this question: A discussion of economic efficiency and a consideration of political realities.

A policy is judged as efficient by economists if its results are such that nobody could be made better off without some else being made worse off. Aiming for efficiency in combination with equity weights for the social cost of carbon and the option for transfer payments will lead to exactly the same policies that would be reached by not using equity weights. Why is that? If a developed country conducts a cost-benefit analysis on a carbon intensive project and damages caused by it in the developing world are very high due to the high equity weights of poor regions, the option of transfer payments will change the results. The project owner will be willing to pay compensation for damage caused in the poor region up to the point where his compensation payments and his other costs equal the benefits he is expecting from the project. Even small compensation payments will do a lot of good in the poor region, since they are weighted with the high equity weights of the poor. If there is willingness to engage in such transfer payments, exactly the same policies will pass a cost-benefit analysis with equity weighting that would also pass a standard cost-benefit analysis.

While aiming for economic efficiency at the global level is a desirable goal, most governments are, in practice, not interested in maximising overall welfare for the whole world. Transfer payments that even out damages caused in developing countries are pretty unrealistic in practical political terms. Schelling argues that, since there is no willingness to take needs of the developing world into account in any other policy area, one could consistently assume that the same is true for climate change policies (1999).

If transfer payments are considered politically unrealistic, the introduction of equity weights serves an important role: It makes explicit the true level of damage caused by greenhouse gas emissions, if no compensations are to be paid. Some governments might react by simply ignoring damages in developing countries, i.e. optimising a social welfare function only for their own country. While this is a very problematic position from an ethical point of view, it still seems to be preferable to be explicit about such a decision, rather than pretending that needs of poor regions are taken into consideration, while they are underrepresented by not using equity weights. On the other hand, there are encouraging signals, e.g. the British governments officially encourages the use of distributional weights for policy evaluation, at least within the United Kingdom, thereby acknowledging that this is the correct way to do it from a methodological point of view (Great Britain H.M. Treasury, 2003).

2.2 Integrated Assessment models

Part of this thesis was extensive work on two leading integrated assessment models: FUND and RICE. Especially the work on FUND went well over what would have been required for this thesis. The reason for many of these changes were the requirements of the larger research project this thesis was part of and three other master theses that are based on FUND as well (Guo, 2004; Li, 2004; Downing et al., 2004; Ceronsky, 2004). Since all changes to FUND that were implemented for these other projects went into the results of this thesis as well, they will all be briefly explained.

2.2.1 FUND

"FUND: The Climate Framework for Uncertainty, Negotiation and Distribution" is a global integrated assessment model developed by Richard Tol. It exists since the mid 90ies and has been improved continuously ever since. This thesis took the newest version 2.8 as a starting point and made extensive enhancements to the model. This section will give a brief outline of the structure of FUND and then present the changes made to the model. FUND is used in many publications, which give a very detailed insight into all aspects of FUND, well beyond the brief exposition in this thesis (Tol, 1995; Tol, 1996a; Tol, 1996b; Tol, 1997b; Tol, 1997a; Tol, 1999a; Tol, 1999b; Tol, 2002b; Tol, 2002a; Tol, 2004; Tol, forthcoming; Downing et al., 2004; Link and Tol, 2004; Pearce et al., 1996; Tol et al., 1999).

FUND can be run in a variety of modes, from various optimisation methods to a calculation of the marginal damage from greenhouse gas emissions. The latter mode was used for this thesis; the result is what is generally called the social cost of carbon. In order to calculate the marginal damage, the model is run twice. The second run is almost identical to the first one, except that the model is forced with a marginally larger amount of CO_2 emissions. For the years 2000-2010, an extra million ton of carbon is emitted each year, totalling an extra 10 million ton of carbon compared to the first run. The damage calculated for the second run will be slightly different from the first run, and that difference is assumed to be the damage caused by the extra 10 million ton of carbon. By dividing that number by 10 million, this damage figure is normalised to the marginal damage per ton of carbon emitted. In theory, one could change the second run by only one ton of carbon emission, which would make the normalisation step unnecessary, but in practice such a small difference would be lost due to rounding errors in the program code.

The damage for each run is calculated by FUND's climate, impact and economic valuation modules. The modules are driven by exogenous scenarios that contain data on emissions, population size and economic development for a period of 300 years, starting in the year 2000. The climate module calculates greenhouse gas concentrations for every year based on the scenarios and various feedbacks. Based on the concentration values, temperature changes for 16 world regions are calculated. The impact module is driven by the temperature data and the economic data from the exogenous scenario parameters. Impacts are calculated for each year and region for 12 different sectors. These include sectors where market valuation methodologies can be used, like agriculture and energy costs, as well as so called non-market sectors, like diseases and biodiversity losses. Damage calculation for each sector can be fine tuned by various parameters that calibrate how sensitive each sector reacts to changes in temperature.

The output of the impact module is a damage for every year, region and sector. The damage is given as a consumption change, i.e. as a monetary damage. The economic module of FUND implements discounting and equity weighting on these results and aggregates the detailed damage figures into one total damage number for the whole time period and all regions.

As has been pointed out, there are many uncertainties involved in almost all areas of climate change research. FUND implements a so called monte carlo mode in order to quantify these uncertainties. For monte carlo mode, the model is run many times, usually 1000 times. Instead of using the same values for the parameters for every run, FUND samples a value for each of its parameters from a probability density function specified for each parameter for every run. This ensures that the model is run with slightly different values for all parameters each time. The resulting 1000 different marginal damage numbers form themselves a probability density function that gives an indication of the range in which the number for the social cost of carbon will most likely be embedded.

FUND 2.8 was originally programmed in Turbo Pascal. It consists of about 7,000 lines of code. The data of the exogenous scenario parameters are stored in extra files so that different scenarios can be quite easily run by replacing those files. When this project started, FUND was everything but user friendly. Much time and effort of this thesis was spent on making the outputs of FUND more accessible and making it easier to change input parameters. All output of FUND is formatted in such a way that it can be accessed with Excel now.

2.2.1.1 Improvements to FUND

Many aspects of FUND have been improved as part of this thesis. This section will give a brief overview of the work done on FUND.

The first step was to port FUND 2.8 from Turbo Pascal to Delphi 8. This solved a myriad of technical problems, mainly in the area of memory management and performance. Turbo Pascal was a 16 bit compiler that had many limitations which prevented FUND from accessing the complete physical memory available on modern computers and limited the number of files that could be opened at the same time. One of the consequences of these limitations was that the monte carlo mode was not functional since FUND 2.5, when the number of regions was increased to 16. Porting FUND to Delphi solved all these memory problems and increased the performance of FUND significantly, since the software is able to take full advantage of modern Pentium processors now[3].

Usability improvements to FUND are grouped around two main themes: Handling of parameters and management of output formats. While some parameters could easily be changed in FUND 2.8 by editing text files, the vast majority of parameters were initialised with hard coded values within the source code. Since it was essential for the larger project that each researcher could change the parameters by herself, the complete parameter input was replaced. All parameters are read from one Excel file which is clearly structured and allows for easy changes of parameterisation. For each parameter, one can either specify a constant value or a probability distribution. The latter option is crucial for the monte carlo mode, where values are sampled for each run of the model from these distributions. There are more than 700 parameters for FUND, and the new parameter module made handling those a lot easier and less time-consuming.

[3] FUND can actually also be compiled to run on 64 bit processors due to these changes, further increasing available memory and speed. Due to the lack of hardware this option was not used for this project.

FUND 2.8 wrote all outputs to one text file. In that text file, all marginal damage figures were already completely aggregated, i.e. the output of FUND consisted of exactly one number for each discounting scheme used. Two improvements were implemented. First, all output was written directly into Excel files so that tedious reformatting steps were cut out of the work process. Secondly, an option to output all damages in disaggregated form was added. This allows detailed analysis by year, region and sector into the damage distribution caused by one extra ton of carbon emitted. Disaggregated damage figures are automatically emitted as Excel pivot tables, giving researchers easy access to aggregated and disaggregated damage data at various levels of details. Due to the amount of data, disaggregated output proved to be challenging for monte carlo mode. One single scenario produced 57,600,000 individual marginal damage numbers (1000 runs X 300 years X 16 regions X 12 sectors), which amounts to about 2.5 GB of data, well beyond Excel's native capacity. A server solution was developed to deal with this situation: All data was imported into a SQL Server and then processed by a so called OLAP server (online analytical processing) which stored it in a special cube format that allows for fast access to the data from Excel pivot tables (see Microsoft, 2004 for a detailed introduction into OLAP technology). During the project, a remote server in Munich hosted up to 12 scenarios at the same time that could be accessed via Excel, totalling almost 700 million individual data points. The OLAP solution also precalculated average, median and standard deviation values (based on the 1000 runs each scenario was based on) for every single combination of year, region and impact sector.

All three core modules of FUND were improved as well. The climate module was enhanced so that a marine methane hydrate destabilization scenario and different climate sensitivities could be tested. The results and analysis of that work can be found in Ceronsky (2004). The impact module had not been tested with the monte carlo mode since version 1.6 of FUND and needed some work before it was robust enough to handle all possible parameterisations possible in the monte carlo mode[4]. Li (2004) uses the disaggregated results of the monte carlo mode to develop an economic argument on how uncertainties should be handled in climate change policy decisions. The economic module was enhanced with two new features. Firstly, about 60 new discounting schemes were implemented, many of which are described and analysed in Guo (2004). Secondly, the existing equity weighting module was replaced with a new one based on the theoretical work developed in section 2.1. Results of that work are presented in the next chapter.

2.2.2 RICE

The first integrated assessment model that ever attempted to calculate the global impacts of climate change was DICE "dynamic integrated climate-economy" (Nordhaus, 1992). DICE formed the basis for a new model called RICE, "Regional Integrated model of Climate and the Economy", which calculates the damages from climate change for different world regions. A detailed description of RICE can be found in Nordhaus and Boyer (1999) and the model is also available on the web (Nordhaus, 1999) as an Excel spreadsheet. The basic structure of RICE is similar to FUND, although it is based on bigger (that is, fewer) regions and its impact module is based on fewer sectors than FUND. Besides, it does not support uncertainty as systematically as FUND, since it has no equivalent to FUND's monte carlo mode.

2.2.2.1 Improvements to RICE

RICE did not implement any form of equity weighting in its published form. In order to use it as a control model for the results obtained from FUND, support for equity weighting was implemented. The improved RICE can easily be modified so that different transformations of an isoelastic utility function can be used. This enables two things: Firstly, damage results are weighted with a marginal utility of consumption that is based on one utility function for the whole world. The assumption here is that people in different world regions do not have vastly different utility functions. Secondly, the results can be calibrated so that they are in any utility

[4] The work on the impact module would not have been possible without Richard Tol's help.

metric. Damages expressed in utility can therefore be calibrated to any of the world regions' average marginal utilities so that they can be directly compared with monetary expenses in that region.

The second change was related to the utility discounting function in RICE. RICE used a declining pure rate of time preference, in order to model declining impatience over time (Nordhaus and Boyer, 1999). While this is probably a better approach than using a constant pure rate of time preference (Groom et al., in preparation), it would have made comparisons with the results obtained from FUND difficult, which used a constant pure rate of time preference. Since this thesis is not about utility discounting, using a constant pure rate of time preference for RICE as well seemed a reasonable compromise that would allow a clear presentation of the effect of equity weighting by itself. Therefore, RICE was modified to use a constant pure rate of time preference. As with FUND, a pure rate of time preference of 0%, 1% and 3% was used.

3 Results and discussion

Results of running FUND and RICE with the equity weighting schemes developed in the previous chapter will be presented and discussed in two steps. Firstly, the results of using a utility function that is calibrated to various world regions are compared with results that are either not equity weighted at all or use a utility function that is calibrated to world average consumption. Calibration results will be presented for FUND and RICE. Secondly, the effect of using the aggregation coefficient developed in section 2.1.6.2 will be demonstrated by using FUND.

3.1 Equity weighting and calibration

3.1.1 Results from 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. The default scenario is very close to the EMF Standardised Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al., 1992). All five scenarios have been extrapolated to the year 2300 by Tol. The work in this thesis is concerned with the question how the marginal damages calculated by impact assessment models are changed when equity weights are used. The analysis therefore focuses on comparisons between the results for various scenarios and models without and with different equity weighting schemes. It does not attempt to critically discuss the validity of the physical damage estimates predicted by the models, nor does the analysis include a discussion of whether the scenarios used are plausible. The next section will present the baseline results obtained without equity weighting and with FUND's old equity weighting mechanism. The section after that will compare the new results to those baseline numbers.

3.1.1.1 Baseline results

The total marginal damage figures for the five scenarios and three different pure rate of time preference (prtp) choices are shown in Table 1.

prtp	Default	A1b	A2	B1	B2
0%	$57.68	$20.70	$85.03	$9.24	$52.48
1%	$11.25	$2.46	$16.07	-$1.68	$9.05
3%	-$2.34	-$3.23	-$2.16	-$4.32	-$2.72

Table 1: MD/tC without equity weighting

A detailed description of the main differences and driving forces of each of those scenarios can be found in the relevant literature (Nakicenovic and Swart, 2000; Leggett et al., 1992). 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 Figure 2 show population and per capita income development for the full time period of FUND.

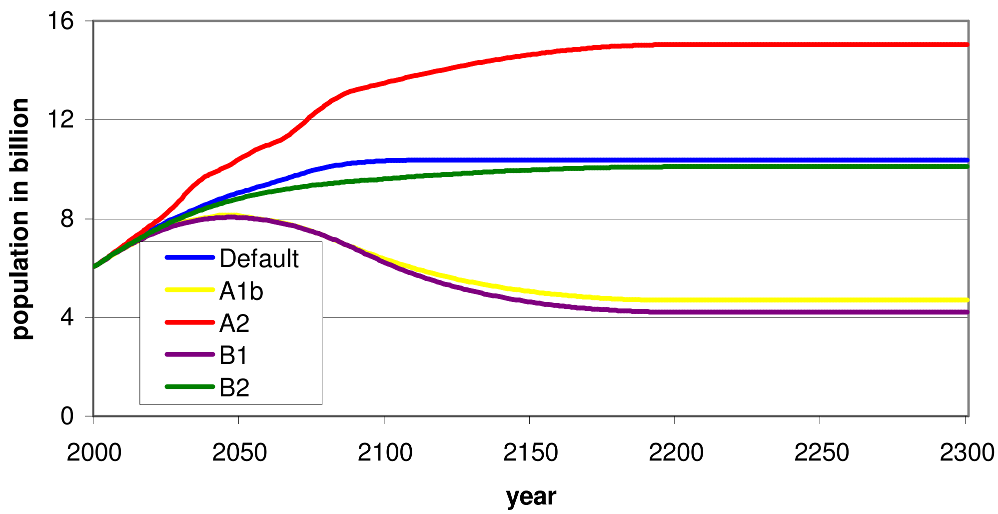

Figure 1: World population development

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 is the most optimistic 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 is even more optimistic about economic growth than B1, assuming rapid economic growth in all world regions. The b group from the A1 family of scenarios is based on a balance of all energy sources, i.e. it assumes neither complete disappearance nor complete dependence on fossil fuels. A2 is the most pessimistic scenario. Population explosion is coupled with slow economic growth along different growth paths in each region (Nakicenovic and Swart, 2000).

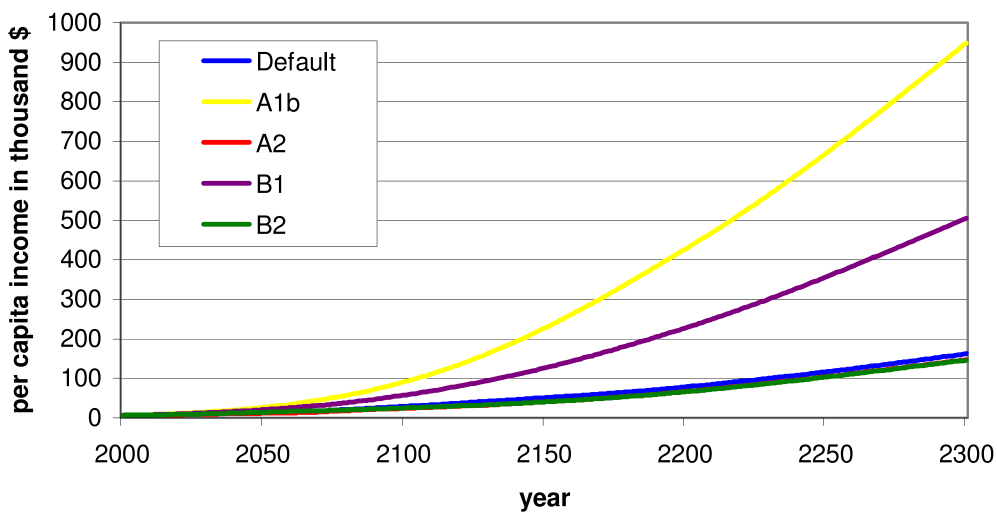

Figure 2: World average economic development

Equity weighting these figures with the methodology outlined in the literature (Fankhauser et al., 1997; Pearce, 2003), i.e. using a utility function that is calibrated to the world average income in the year 2000, gives the results shown in Table 2. As has been argued in the theoretical chapter, these numbers are in a specific utility metric and can't be compared to any other costs or benefits, unless those costs or benefits have been equity weighted into the same metric of utility as well.

prtp	Default	A1b	A2	B1	B2
0%	$181.25	$41.69	$269.45	$22.87	$168.26
1%	$40.99	$5.49	$55.46	-$1.92	$32.33
3%	-$1.77	-$6.55	-$1.30	-$8.77	-$3.74

Table 2: MD/tC, equity weighted, world average income calibrated

While the metric for these numbers prevents an easy application in policy decisions, there is nevertheless an interesting observation to be made. Whenever the marginal change from a ton of carbon emission is deemed to be damaging, i.e. whenever the marginal damage figure is positive, the equity weights increase the damage figure by a factor that lies between 2.01 and 3.64. This finding is in line with the general results found in government reports and other studies (Clarkson and Deyes, 2002; Pearce, 2003). For some pure rate of time preferences FUND predicts marginal benefits from carbon emissions. In those cases, the effect of equity weights is ambiguous. While, in most cases, the equity weighting increases the benefit predicted, it decreases benefits for the base and A2 scenario in the case of a pure rate of time preference of 3%. An explanation for this result can be found in the next section, when world marginal damage data will be disaggregated by sector and region.

A preliminary assessment so far is that equity weights do not always increase marginal damages figures from greenhouse gas emissions. For some scenarios, equity weights might either increase or decrease the number in comparison to the non equity weighted findings, depending on the choice of pure rate of time preference.

3.1.1.2 Calibrated results

Using a transformation of the utility function that calibrates damage figures into a West Europe monetary equivalent metric gives much more extreme results, as shown in Table 3.

prtp	Base	A1b	A2	B1	B2
0%	$868.36	$199.73	$1,290.92	$109.55	$806.14
1%	$196.36	$26.31	$265.73	-$9.22	$154.87
3%	-$8.47	-$31.39	-$6.24	-$42.03	-$17.91

Table 3: MD/tC, equity weighted, west Europe income calibrated

Unlike the numbers calibrated to world average income, these figures can be used directly in cost-benefit comparisons that involve costs or benefits to people living in an area with average income of West Europe, like the United Kingdom. Calibrating numbers such that they can be used in cost-benefit analysis within the United States gives even slightly higher results, due to the higher average income in the United States, as can be seen in Table 4.

prtp	Default	A1b	A2	B1	B2
0%	$999.50	$229.91	$1,486.02	$126.11	$927.97
1%	$226.01	$30.28	$305.89	-$10.61	$178.28
3%	-$9.74	-$36.13	-$7.18	-$48.38	-$20.61

Table 4: MD/tC, equity weighted, United States income calibrated

The numbers change dramatically once they are calibrated toward the other end of the income spectrum, namely one of the very low income regions, Sub-Saharan Africa, as shown in Table 5.

prtp	Default	A1b	A2	B1	B2
0%	$12.68	$2.92	$18.85	$1.60	$11.77
1%	$2.87	$0.38	$3.88	-$0.13	$2.26
3%	-$0.12	-$0.46	-$0.09	-$0.61	-$0.26

Table 5: MD/tC, equity weighted, Sub-Saharan Africa income calibrated

There is a great danger in presenting the equity weighted numbers this way. At first sight, the results calibrated to different world regions seem to imply a vast range for the social cost of carbon number. One might be tempted to classify this as one of the many uncertainties surrounding any estimation of the marginal damage from greenhouse gas emissions and present the range from the lowest value for a specific scenario, i.e. $2.87 for the default scenario with a prtp of 1% to its highest $226.01 as the certainty range. This would be completely wrong, since both figures represent exactly the same result for the marginal damage; the only difference is that they use a different metric for utility. As such, the difference between the various metrics for utility is a lot more like different currencies used to express the same marginal damage figure. Using the Sub-Saharan Africa income calibrated marginal damage figure in a United States cost-benefit analysis would yield exactly the same result as using the United States income calibrated marginal damage figure, as long as any monetary cost or benefit in the United States that is to be compared with the marginal damage figure is equity weighted into the same metric of utility, i.e. the Sub-Saharan Africa metric of utility. Using the default scenario and a prtp of 1%, the equity weight for any change in consumption in the year 2000 in the United States for a Sub-Saharan Africa utility metric is ~0.01267 (obtained by dividing the average income of Sub-Saharan Africa by average income of the United States in the year 2000), which is just the relation between the marginal damage expressed in Sub-Saharan Africa utility metric and the United States utility metric. Therefore, it is important to keep in mind that all equity weighted results presented so far will yield exactly the same project evaluation in the case of a cost-benefit analysis, they are just expressed using different monetary metrics of utility. Choosing the metric of the region whose mitigation costs are to be compared with the social cost of carbon brings the convenience that those mitigation costs do not have to be equity weighted before they are compared to the marginal damage figure.

3.1.1.3 Disaggregated results

The really interesting question is which regions gain more or less influence on the marginal damage figure due to the introduction of equity weighting. The results differ from scenario to scenario, due to the different assumptions about economic development that directly drive the equity weights for each region. The following analysis is based on a pure rate of time preference of 1%. While a pure rate of time preference of 0% would have left out any distortion from utility discounting from the analysis, it would have presented results that are dominated by whatever happens in the later centuries and thereby making assumptions about time preference that are probably not shared by today's policymakers. The analysis concentrates on the scenarios A2 and B1, in order to demonstrate the results of the two most extreme scenarios tested.

3.1.1.3.1 Scenario A2

Figure 3 compares the equity weighted marginal damage for scenario A2 with the unweighted figures. China has to bear most of the damages from climate change in this scenario, with and without equity weighting. While China is still the most important region in terms of damages, another region is lifted from having no big influence on the final damage number to the second place in terms of damage experienced by the introduction of equity weights, and that is Sub-Saharan Africa.

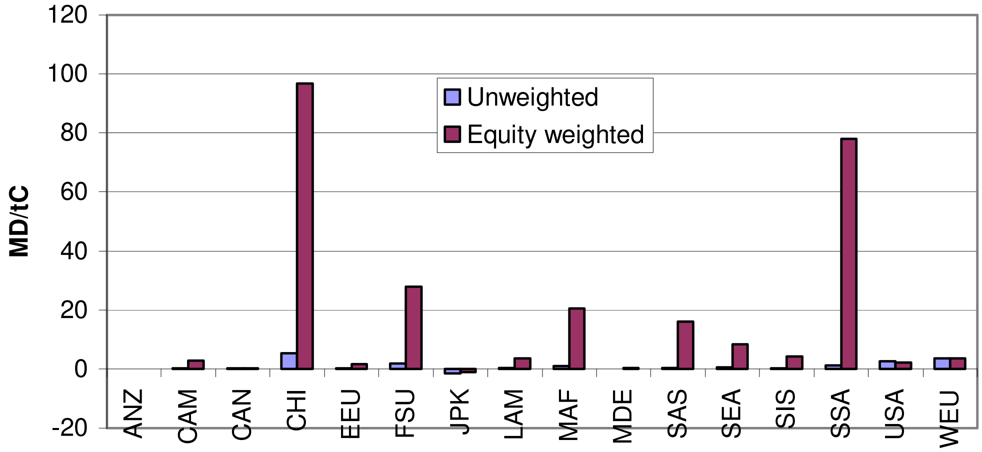

Figure 3: MD/tC, scenario A2

Sub-Saharan Africa is the region that actually gets the relatively highest increase in its damage figure from the introduction of equity weighting. Figure 4 shows the proportion of equity weighted to unweighted marginal damage figures for scenario A2 per region.

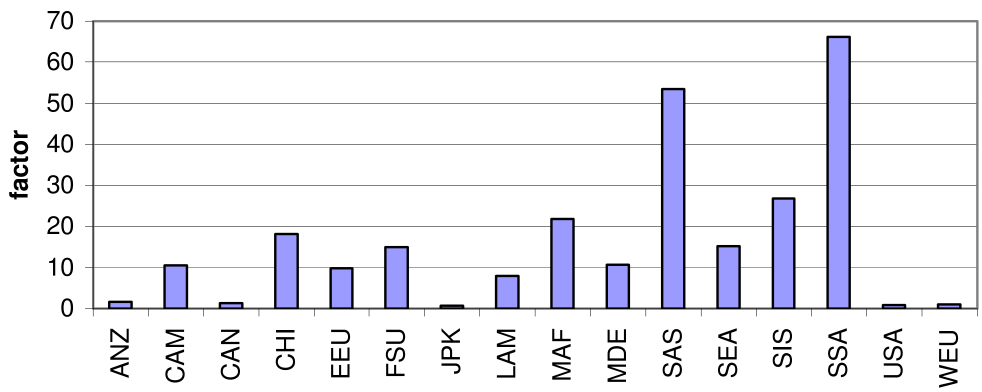

Figure 4: Proportion of equity weighted to unweighted MD/tC for scenario A2, prtp 1%

This graph shows clearly that the effect of equity weighting on China is less drastic than the effect on many other regions. This is explained by the fact that China's economic development (see Figure 5) is much stronger than economic development in regions with very high proportions of equity weighted to unweighted marginal damage figures.

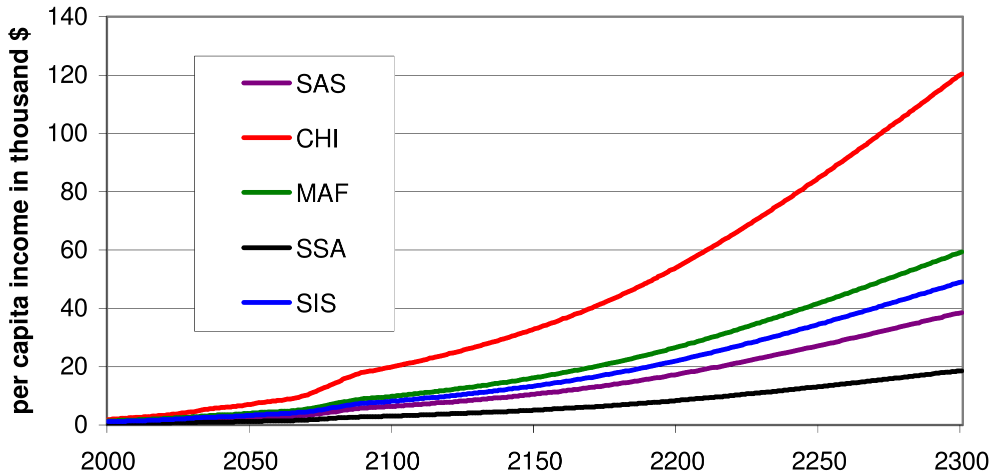

Figure 5: Per capita income for selected regions, scenario A2

The net effect of equity weighting therefore depends on two factors: Firstly, the average consumption for each region over time, which drives the proportion of equity weighted to unweighted marginal damage figures for every region. But some regions - like the small island states - have such a small share in the initial damage distribution between regions that their share in the equity weighted figure is still pretty small, even after very high equity weights have been applied to the damage accruing in such a region. Therefore, the second factor is how big the share of damages is for those regions that have high equity weights.

3.1.1.3.2 Scenario B1

Initially, the results for scenario B1 look very different (Figure 6) from those for scenario A2. Unlike the latter scenario, B1 predicts benefits from climate change for a number of regions, including China and south Asia. While the benefits predicted to those two regions mainly drive the very high benefit numbers obtained in the case of equity weighted results (a benefit of \$9.22/tC), they once again gain that weight for different reasons. South Asia does hardly play a role in the unweighted case, with a benefit of \$0.2/tC. In the equity weighted case, it is the second most important region with a benefit, after China. This is solely due to the fact that south Asia gets very high equity weights due to its poor economic performance in scenario B1.

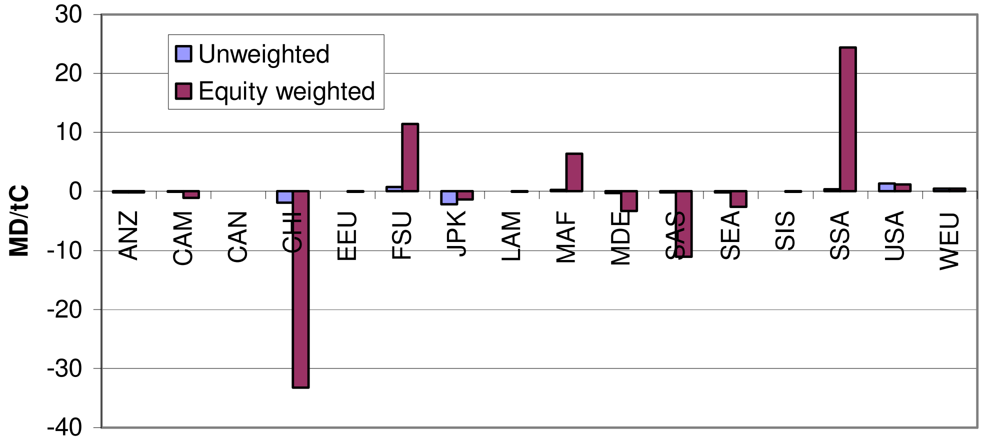

Figure 6: MD/tC, B1 scenario

Looking at the proportion between the unweighted and weighted damage figures gives a similar result as for scenario A2 (Figure 7). Again, China gets a higher equity weight than developed countries, but by no means close to some of the very poor regions, like Sub-Saharan Africa or south Asia. Therefore, China's dominance in the benefit share with equity weighting is, again, mainly due to its high initial share of the benefits predicted for scenario B1. The effect seen for Sub-Saharan Africa is principally the same as described for the A2 scenario, namely that a very small initial share of damage is given a very high equity weight due to the low average per capita income in that region.

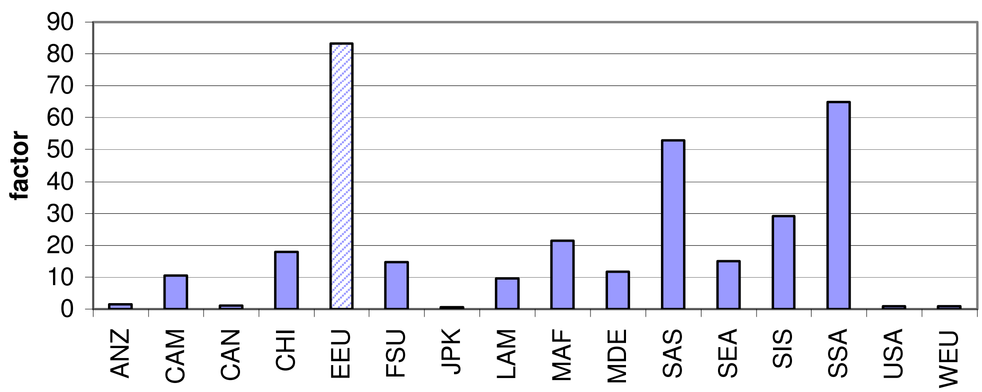

Figure 7: Proportion of equity weighted to unweighted MD/tC for scenario B1, prtp 1%[5]

[5] The factor for EEU is misleading in this graph. The overall damage to EEU is so small in both the equity weighted as well as the unweighted case that a high factor due to rounding errors is obtained. EEU equity

One final interesting observation can be made for scenario B1. Japan has the biggest benefit in the unweighted case with a benefit of $2.16. But that benefit for Japan is actually reduced to $1.42 by the introduction of equity weights. In this case, the other feature of equity weighting shows: If a country has an average per capita income higher than the per capita income used for the calibration of the utility function, net changes in consumption for that region will be given less weight than in the unweighted case.

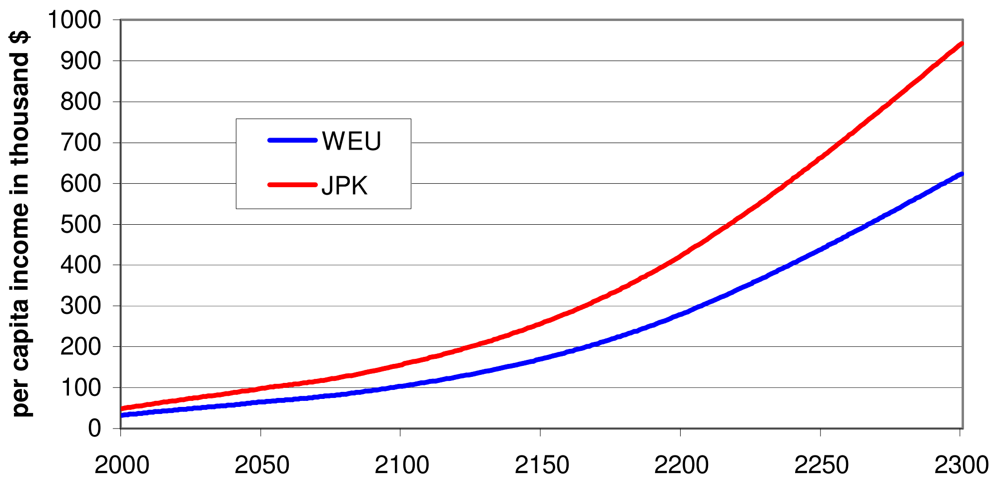

Figure 8: Per capita income for selected regions, scenario B1

Comparing average per capita income for the region used as the base case for the utility function calibration (west Europe) with Japan shows that just that is the case in scenario B1 (Figure 8).

3.1.2 Results from RICE

RICE was mainly used as a control case for the results obtained by FUND. By testing equity weighting in another model, an inter-model comparison and validation of the implementation details is possible. RICE does not support different scenarios for its analysis, so that the analysis is limited to the default scenario of RICE (see Nordhaus and Boyer, 1999 for a description of the scenario).

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weighted damages stand in a similar proportion to their unweighted equivalents for other pure rate of time preferences.

prtp	unweighted	equity weighted, avg utility metric	equity weighted, US utility metric	equity weighted, WEU utility metric	equity weighted, LI utility metric
0%	$90.96	$432.98	$1,048.56	$895.04	$18.72
1%	$23.85	$125.63	$304.24	$259.69	$5.43
3%	$5.01	$30.58	$74.06	$63.22	$1.32

Table 6: MD/tC, RICE results

Generally, RICE is less optimistic about the future than FUND. It predicts damages from climate change for all three pure rate of time preferences used and has a higher damage number for each pure rate of time preference than any of the FUND scenarios. These differences are due to different assumptions about the magnitude of impacts; the economic aggregation methodology is the same for both models. Table 6 presents the marginal damage predicted by RICE, using utility functions that are calibrated to different world regions. RICE uses different world regions; LI is RICE's low income region. It can best be compared to FUND's Sub-Saharan Africa region, not only including that region but also featuring similar income trends.

Utility metric	prtp	FUND	RICE
SSA/LI	0%	0.14-0.22	0.21
	1%	0.08-0.25	0.23
	3%	0.04-0.14	0.26
US	0%	11.10-17.68	11.53
	1%	6.33-20.09	12.76
	3%	3.33-11.20	14.78
WEU	0%	9.65-15.36	9.84
	1%	5.50-17.45	10.89
	3%	2.89-9.73	12.61

Table 7: Proportion of equity weighted to unweighted MD/tC

Since FUND and RICE use slightly different scenarios and equations for their impact modules, absolute equity weighted damage figures cannot be compared directly with each other in order to perform an inter-model comparison of results. Instead, the proportions of change from the unweighted damage numbers to the equity weighted figures need to be compared between the two models. Table 7 shows the proportions of change introduced by equity weights using different utility metrics. The numbers are obtained by dividing the equity weighted damage numbers for each utility metric and pure rate of time preference by the corresponding unweighted damage figures from the base case. For FUND, a range of proportions is presented, spanning the proportions obtained from the five different scenarios of FUND. The effect of equity weights in RICE lies within the range of the effect in FUND for all cases except for a pure rate of time preference of 3%, where the effect is in all cases slightly bigger in RICE than in FUND. Thus, the inter-model comparison yielded very similar results that verify the initial findings for FUND.

3.2 Aggregation coefficient

The aggregation coefficient developed in section 2.1.6.2 corrects for income inequalities within in regions that are lost due to the use of average per capita income numbers to derive equity weights for each region. The scenarios used by FUND do not project income inequalities within regions, nor have any other scenarios been developed for the time horizon used by FUND that would specify income development at the detailed level needed for the aggregation coefficient (namely at a per country basis). The results for the aggregation coefficient are therefore presented with crude scenarios for inequality development within each region that cover the main imaginable trends. All three scenarios start with coefficients for each region that are based on today's income inequalities within regions, that is all three scenarios start with coefficients that are based on real data.

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 perfect 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 small island states. Again, inequalities for each region are interpolated linearly for the years between 2000 and 2300.

These three scenarios form by no means plausible or even likely futures. They form a sensitivity analysis on the inclusion of more detailed income distribution details and give an idea of the range of results that will be obtained for more realistic scenarios. Using more plausible developments for income inequalities within regions that are aligned with the overall trends developed in the scenarios used for climate change modelling would be much preferable. But scenario development itself is a complicated and extensive modelling task that lies well outside the scope of this thesis.

prtp	Uncorrected	Less inequality	No change	More inequality
0%	$868.36	$992.41	$1,128.21	$1,608.14
1%	$196.36	$229.74	$258.05	$355.54
3%	-$8.47	-$11.80	-$8.88	$0.46

Table 8: MD/tC, default FUND scenario, equity weighted to WEU utility metric

Table 8 presents the results for the three scenarios of inequality development within regions and contrasts them to the numbers that are not corrected for inequalities within regions at all. 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 Conclusions

Introducing equity weights into the social cost of carbon discussion has important consequences, both at a methodological level as well as in terms of widening the range of predictions of the social cost of carbon.

The methodological conclusions of this thesis are twofold: First, one needs to pay special attention to the fact that equity weighted marginal damage figures can be presented in any number of utility metrics. Therefore one cannot use equity weighted social cost of carbon figures in follow up economic analysis (e.g. cost-benefit analysis) without being aware which metric is used and converting all other monetary numbers that are to be compared to the equity weighted social cost of carbon into the same utility metric. A partial solution is proposed in this thesis: By using equity weighted damage figures that are calibrated to the income level of the region for which the policy decision is made, the equity weight for that region is 1. Marginal damage figures can be compared directly to other costs or benefits of that region only in this case.

The second methodological conclusion is that using average income figures of very large regions to calculate the equity weights will not adequately represent inequalities. Using more detailed information and scenarios about income distribution within regions will significantly increase the effect equity weighting has. Averaging income data at smaller geographical entities gets equity weighted damage figures closer to the figure one would obtain when perfect knowledge about income distribution on a per individual basis were available and is therefore always preferable.

The empirical conclusion is that the effect equity weights have on the social cost of carbon has been widely misunderstood and underestimated. The practice of presenting equity weighted social costs of carbon in a utility metric calibrated to average world income can be seen as the main source of confusion. Often, these figures were directly compared to unweighted numbers, without explicitly mentioning that these numbers cannot be directly compared to any mitigation costs (Clarkson and Deyes, 2002; Pearce, 2003). The numbers presented in this thesis that are calibrated to west Europe income levels and can be compared to mitigation costs directly are almost five times higher than those calibrated to world average income and presented in the literature.

The question of the best utility metric to present marginal damage figures is important in order to avoid misapplication of equity weighted damage figures, but it does not change any result from cost-benefit analysis. The changes introduced by the aggregation coefficient, on the other hand, make a real difference regarding the results from cost-benefit analysis. Just taking into account inequalities in income distribution between countries within each region increases the social cost of carbon between 16% and 70% for a pure rate of time preference of 1%, depending on the scenario for income inequalities within regions. This still averages out any inequality within countries. This is especially problematic for some of the regions in FUND that represent only one country, like the US and China. Taking inequalities within those countries into the calculation would further increase the equity weighted social cost of carbon figure.

What remains is the question whether equity weighted damage figures for the social cost of carbon should be used for policy decisions. From an ethical point of view, there is very little doubt that equity weighting is appropriate. Once one accepts the fact that the marginal utility of income is declining and that what should be optimised are utility levels of all people, regardless of where they live, the argument for equity weighting is very strong.

At the same time, one needs to keep in mind that direct money transfers have their own dynamic in cost-benefit analysis that uses equity weighted figures (regardless of the utility metric used). Direct transfers of money from rich to poor countries are accounted as a much smaller utility loss to the donor than they are accounted as a utility gain for the receiver.

While the very high numbers for the United Kingdom, for example, would suggest that each of the proposed renewable energy and emission reduction targets would pass any cost-benefit analysis, this is only true as long as there is no willingness to pay compensation for the damages caused in poor regions. Compensation payments can easily change the results from many cost-benefit analyses due to the different ways they are converted into utility for the donating and receiving region.

Taking damages from climate change in poor regions seriously and - in policy decisions of the developed world - weighting them in such a way that utility and not monetary losses are compared inevitably means that rich countries either have to accept much higher social cost of carbon figures than are currently discussed in policy decisions or else show a willingness to compensate poor regions for damages caused by climate change. In many instances, the latter option will prove to be more practicable from an economical point of view, since even small compensation payments can cause a significant change of utility levels in poor regions.

Appendix A: Transformed utility function and cost-benefit analysis

In the case of a cost-benefit analysis, it can easily be shown that using a utility function of the form (1) will lead to the same decisions as using a linear transformation of that utility function, (10).

Costs and benefits of a policy each constitute a change in the consumption levels of the people affected by the policy. Putting costs and benefits into the framework that can be analysed with the social welfare function developed in the previous section, one gets two consumption level change functions, $C_i(t)$ and $B_i(t)$. $C_i(t)$ returns the decrease in consumption for person i at time t from the policy in question, $B_i(t)$ returns the increase in consumption for person i at time t. When the total benefits in welfare are larger than the total costs in welfare of a specific policy, that policy passes the cost-benefit test. Using (9), a policy passes the cost-benefit test if the following is true:

$$\sum_{i=1}^{n}\int_{0}^{T} u_c\left[c_i(t)\right]B_i(t)e^{-\rho t}dt > \sum_{i=1}^{n}\int_{0}^{T} u_c\left[c_i(t)\right]C_i(t)e^{-\rho t}dt \tag{30}$$

In order to show that any transformation of the form presented in (10) will not change the result of a cost-benefit analysis, the following must be true:

$$\begin{aligned}&\sum_{i=1}^{n}\int_{0}^{T} u_c\left[c_i(t)\right]B_i(t)e^{-\rho t}dt > \sum_{i=1}^{n}\int_{0}^{T} u_c\left[c_i(t)\right]C_i(t)e^{-\rho t}dt \Leftrightarrow \\ &\sum_{i=1}^{n}\int_{0}^{T} \tilde{u}_c\left[c_i(t)\right]B_i(t)e^{-\rho t}dt > \sum_{i=1}^{n}\int_{0}^{T} \tilde{u}_c\left[c_i(t)\right]C_i(t)e^{-\rho t}dt\end{aligned} \tag{31}$$

The marginal utility of consumption at a consumption level of c is the derivative of (10):

$$\tilde{u}_c(c) = bc^{-\varepsilon} \tag{32}$$

Replacing $\tilde{u}_c$ in (31) with its definition (32) gives this for the right hand side of the iff condition:

$$\sum_{i=1}^{n}\int_{0}^{T} bu_c\left[c_i(t)\right]B_i(t)e^{-\rho t}dt > \sum_{i=1}^{n}\int_{0}^{T} bu_c\left[c_i(t)\right]C_i(t)e^{-\rho t}dt \tag{33}$$

Since b is a constant, this can be simplified to:

$$b\sum_{i=1}^{n}\int_{0}^{T} u_c\left[c_i(t)\right]B_i(t)e^{-\rho t}dt > b\sum_{i=1}^{n}\int_{0}^{T} u_c\left[c_i(t)\right]C_i(t)e^{-\rho t}dt \tag{34}$$

b can only be positive, therefore all of (34) can be divided by b, which gives:

$$\sum_{i=1}^{n}\int_{0}^{T} u_c\left[c_i(t)\right]B_i(t)e^{-\rho t}dt > \sum_{i=1}^{n}\int_{0}^{T} u_c\left[c_i(t)\right]C_i(t)e^{-\rho t}dt \tag{35}$$

which is equivalent to the left side of the iff condition in (31) and completes the proof.

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