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Methodological aspects of recent climate change damage cost studies*

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Abstract

This paper discusses methodological aspects of recent climate change damage studies. Assessing the total and/or marginal damage costs of environmental change is often difficult and it is certainly difficult in the case of climate change. A major obstacle is the uncertainty on the physical impacts of climate change, especially related to extreme events and so-called 'low-probability high-impact' scenarios. The subsequent transposition of physical impacts into monetary terms is also a delicate step, given that climate change impacts involve both market and non-market goods and

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services, covering health, environmental and social values, and that impacts may be distant in time and space. The complexity of climate change cost assessment thus involves several crucial dimensions, including non-market evaluation, risk and uncertainty, baseline definition, equity and discounting. The paper discusses these issues and stresses the importance of political perspectives in integrated assessment research.

Keywords: Climate change damage costs; cost of inaction; methodological aspects; risk and uncertainty; discounting; equity.

1 Introduction

Socially efficient response strategies to the climate change problem require careful considerations of the costs and benefits of mitigation and adaptation measures. The policy challenge is twofold. First, the challenge is to minimize the total costs of mitigation, adaptation and residual climate change damage, and second, it is to distribute the associated burdens and gains in an equitable manner, both within and between generations. The benefits and costs of mitigation and adaptation measures have to be measured against some baseline, a hypothetical future 'no policy' scenario without mitigation and limited adaptation[1]. Recently, the term 'cost of inaction' has gained popularity in this context, although the term is slightly ambiguous[2]. A distinction can be made between assessments of total damage costs (adaptation costs plus residual damages) on the one hand, and marginal damage (including adaptation) costs on the other. Marginal climate change damage costs are sometimes referred to as the Social Costs of Carbon (SCC).

Assessing the total and/or marginal damage costs of environmental change is difficult and it is certainly difficult in the case of climate change. A major obstacle is the uncertainty about the physical impacts of climate change, especially related to extreme events and low-probability high-impact scenarios. The subsequent transposition of physical impacts into monetary terms is also a delicate step, given that climate change impacts involve both market and non-market goods and services, covering health, environmental and social values, and that impacts may be distant in time and space.

The complexity of climate change cost assessment thus involves several crucial dimensions, including non-market valuation, risk and uncertainty, baseline definition, equity, and discounting. This paper adds to a growing literature on methodological aspects of climate change damage cost assessment and the ways this assessment could or should be used in policy (c.f., Pearce et al., 1996; Pearce, 2003; Pittini & Rahman, 2004; Jacoby, 2004; Watkiss et al., 2005; Intergovernmental Panel on Climate Change, 2007). This paper builds on this literature and tries to make it accessible to the interested non-expert. The growing attention for the economics of climate change has made it impossible to cover

[1]The type and rate of adaptation in the 'no policy' scenario is problematic, as we will discuss later.

[2]See the discussion by Johnstone (2005).

all aspects of damage assessment. The focus of the paper is on those elements of damage assessment that we believe are currently in the centre of attention and that are of interest to a wider audience. This paper stresses the relative importance of the political or ethical judgments that necessarily underlay global assessments of extremely uncertain, long-term climate change damage.

2 Overview of recent research projects

The obvious importance of the subject of climate change impacts has elicited a large volume of research on this issue. The overwhelming majority of this research comes from the natural sciences. Research on the social and economic consequences of changes in climate has been far more limited. Within the limited number of economic studies, most studies have either addressed a limited number of possible impacts, a limited geographical area, or both. Studies that have attempted to assess total and/or marginal global damage costs are relatively rare. Tol (2005*a*) counted a total of 28 studies globally between 1991 and 2003, of which 18 could be classified as 'new' impact studies (the others borrowed impact estimates from other studies). Of these 18 new impact studies 10 had been peer-reviewed. Recent (post-2000) studies include Bosello et al. (2004*a*,*b*); Bosello (2005); Ceronsky et al. (2005); Darwin & Tol (2001); Li et al. (2005); Newell & Pizer (2004); Nordhaus & Boyer (2000); Nordhaus (2006); Rive et al. (2005); Stern et al. (2006); Tol & Verheyen (2004) and Tol & Dowlatabadi (2001). The number of researchers that carry out such studies, on both sides of the Atlantic, is also small[3].

The discussion of methodological issues will illustrate how our understanding in this field of research is still incomplete and permeated by uncertainty, and will indicate how different assumptions and choices in the methodology for cost assessment can lead to a very wide range of estimates. The definition of (in)action to climate change is in itself a complex concept, and is dealt with differently by the different studies. To provide a comprehensive picture of the state of the art in this field of research—illustrating gaps, achievements and scope for future work—the following section discusses the various aspects in greater detail and shows how recent studies have dealt with them.

3 Methodological issues

3.1 Scenarios

A scenario is a set of assumptions on future conditions that is coherent, internally consistent, and plausible. The Intergovernmental Panel on Climate Change (IPCC) makes a distinction between climate scenarios on the one hand, and non-climate scenarios on the other hand. Climate scenarios are usually derived from modeling experiments with General Circulation Models (GCM). An

[3] From the 28 studies reported in Tol (2005*a*); four of their authors were involved in more than one study, and one author (Nordhaus) was even involved in six studies.

important distinction can be made between models that compare two equilibrium states of the climate (e.g., a doubling of atmospheric CO_2 concentration or its radiative equivalent), or models that dynamically track transient changes in climate variables (using so-called coupled Atmosphere-Ocean General Circulation Models: AOGCM). Another important issue for damage assessment is the spatial aggregation of climate models and scenarios. A simple mean global change in temperature may hide important regional variations. A final important distinction is inclusion in the climate scenarios of extreme weather events (hurricanes, tornadoes, storm surges, droughts, floods), and low-probability, high-impact events (or 'climate surprises'), such as a disruption of the thermohaline circulation in the Atlantic Ocean, or the collapse of the West Antarctic ice sheet. These latter types of scenarios have a much higher uncertainty than the scenarios for "average" climate change.

Non-climate scenarios include socioeconomic scenarios, land-use and land-cover scenarios, and environmental scenarios. These non-climate scenarios are important as they determine the vulnerability of social and economic systems to climate change over time[4]. They also determine the development of global greenhouse gas emissions leading to a range of emissions scenarios used in GCMs. Many pioneer valuation studies estimated the damage cost of climate change by imposing certain climate change variables (e.g., mean temperature, sea level rise, at a certain point in time) on the present population and economy. In more advanced studies that make use of non-climate scenarios, a distinction can be made between studies that use exogenous scenarios and studies that employ an Integrated Assessment Model (IAM) to generate scenario values.

The use of fully dynamic IAMs is still quite rare in recent studies. Indeed, only a few among these studies adopt a dynamic modeling approach, linking the dynamics of the socio-economic system with realistic climate scenarios in an integrated assessment framework. Amongst these, Bosello (2005) and Nordhaus & Boyer (2000) explicitly acknowledge the need for dynamic, long-term modeling in order to analyze the complex global dynamics of climate change, including feedbacks and trade-offs with the economic system. Hope (2006) stresses the relative importance in IAMs of its climate sensitivity parameter that quantifies the (equilibrium) relationship between GHG concentration in the atmosphere and global mean temperature, for the magnitude of the computed climate change damage.

Notwithstanding recent improvements, more effort needs to be devoted to render the scenarios analyzed by the models more realistic. Ongoing work on detailed climate scenarios and on how to link them to economic modules should be strengthened to improve the framework for the damage cost assessment.

[4] Adams et al. (1999) show in an agricultural example how alternative assumptions on socio-economic developments may even change the sign of climate change impacts: from negative (costs) to positive (benefits).

3.2 Valuation approach

There are various techniques for the monetary valuation of climate change impacts. Some impact estimates (e.g., agriculture) can be directly based on market observations. Other impacts (e.g., health) can be indirectly measured on the basis of market prices for surrogate products or services. The challenge in these "revealed preference" instances is to find "future market prices" that are consistent with the underlying socioeconomic scenario. This requires a sound understanding of how willingness to pay varies with such circumstances as scarcity and income—this understanding is missing at present (Flores & Carson, 1997; Horowitz, 2002). For other impacts (e.g., species loss), no market values exist. Here, one has to rely on stated preferences, which introduces an additional set of difficulties and uncertainties (Carson, 1991).

All current studies of the economic impact of climate change use a mix of valuation methods, but there are no studies comparing the effect of alternative methods on the impact estimates. Because it is practically impossible to estimate each exposure-response relationship or value at the respective geographical location of a climate change impact, data from previous studies focusing on different locations and different policy contexts are inevitable. Furthermore, most climate change impacts will take place in the future, for which by definition no data are available. Therefore it is important to know when data from other studies can be used and under what conditions, and how to extrapolate values from today to tomorrow.

The majority of recent studies still adopt benefit transfer methods for the evaluation of climate impacts. However, benefit transfer is only as good as the data that are used to generate the transfer values—and benefit transfer is difficult even with solid estimates (Brouwer & Spaninks, 1999; Shrestha & Loomis, 2001, 2003). For this reason, more attention should be given to original valuation research in the context of climate change.

An example of such a study is Li et al. (2005) who analyze the willingness-to-pay (WTP) of American citizens for climate policy by means of the contingent valuation method. They find that the median American citizen is willing to pay about \$15/tC. Berrens et al. (2004) find a willingness to pay between \$200 and \$1760 per US household per year (0.2–2.3% of income) for US ratification of the Kyoto Protocol[5]. Hersch & Viscusi (2006) find that Europeans are willing to pay up to 3.7% more for petrol if that helps combat climate change. Viscusi & Zeckhauser (2006) find that Harvard students are willing to pay \$0.50/gallon (a 25% price increase) or 3% of their expected annual income for greenhouse gas emission reduction[6]. There is scope for more similar applications of WTP techniques, mainly to account for spatial and socio-economic differences in individuals' preferences.

[5] Manne & Richels (2004) estimate that the costs of US ratification would be 0.75% of GDP in 2010.

[6] This study also showed that these students underestimate projected warming in Boston by about 50%, while the authors made them believe that carbon dioxide emission reduction would be effective for slowing climate change in the next 30 years.

Essentially, the above studies estimate how much we are willing to pay (WTP) to purchase a better climate for our children and grandchildren. In fact, all climate change impact studies are based on this question. However, one may also estimates how much our children and grandchildren are willing to accept (WTA) from us as compensation for the worse climate that we impose on them. Brown (2005); Horowitz & McConnell (2002) and Sayman & Öncüler (2005) show that the difference between WTP and WTA can be substantial, particularly in the case of involuntary risks caused by third parties. No one has yet estimated the implications for climate policy.

The main conclusion is that more research is needed, on valuation methods in general, and on its application to climate change in particular.

3.3 Estimation approach

Economic impacts of climate change can be divided into direct and indirect impacts. Direct impacts concern the effects of climate change on production and consumption in one market. Indirect impacts concern the indirect effects of changes in production and consumption in this market on the rest of the economy through their effects on relative prices, including factor prices (income). Most studies to date have estimated direct costs under the assumption that indirect effects through changes in goods and factor prices would be negligible. With a few notable exceptions, mainly related to climate change impacts on agriculture and forestry, general equilibrium effects have only recently received attention. A number of recent studies has examined the economy-wide implications of sea level rise, extreme events, climate change impacts on tourism, and on health. While it is perhaps too early to draw firm conclusions from this body of research, the studies suggest that the indirect effects of climate change impacts can both enlarge and diminish the direct economic impacts of climate change. The distribution of gains and losses is another difference between direct costs and general equilibrium effects. Whereas direct costs are limited to those directly affected, markets would spread the impact to their suppliers, clients, and competitors as well as to financial markets.

Bosello et al. (2004*b*) estimate the economy-wide effects of climate-change-induced impacts on health through changes in labor productivity and public and private demand for health care, including the indirect costs of health impacts. They find that these indirect costs indeed are an important part of the cost considerations, as they may be positive or negative, showing the same sign as the health impacts themselves. As a consequence, Bosello et al. (2004*b*) conclude that direct costs are underestimates of the true costs of impacts. Hallagatte (2005) developed a non-equilibrium dynamic economic model to assess the macroeconomic consequences of extreme weather events in Europe. His conclusion is that dynamic processes can multiply direct damage costs by a factor of 20. Hallagatte (2005) finds that production losses are strongly (and non-linearly) dependent upon changes in the distribution of weather extremes and on the (practical) ability of the economy to repair damages quickly after each disaster.

An important new development with regard to the estimation of macroeconomic effects is the development of new data sets that depict economic activity at geographic grids rather than at national levels so that it can be better compared to location-specific climate data and the outputs of climate change models (Nordhaus, 2006).

The model underlying the Stern et al. (2006) study is basically a one-sector model (Hope, 2006), so that it cannot investigate indirect impacts between sectors. Stern et al. (2006) use estimates from others (especially Nordhaus & Boyer, 2000) on which they base their assessment of direct and indirect impacts.

3.4 Adaptation

Even though a great deal of work has been carried out in the field of vulnerability and adaptation, there are very limited studies that focus on the costs of adaptation. Climate change costing studies often focus on abatement and reduction costs (costs of mitigation) and pay little attention to adaptation costs. However, one cannot study the costs of climate change impact without also studying, or at least making assumptions about the costs of adaptation (Tol, 2005*b*; Watkiss et al., 2005). Studies focusing on costs of the impacts make widely differing assumptions about the amount of adaptation that will take place. While some of the early studies completely ignore adaptation, most of the recent studies consider arbitrary levels of adaptation, which ignores the fact that adaptation is a more general process involving the substitution of many inputs and outputs in response to changes in environmental conditions (Tol, 2005*b*; Dore & Burton, 2000).

The linkage between costs of adaptation versus costs of mitigation and residual damage is very weak. This linkage is, however, crucial to estimate the cost on inaction in the field of climate change. There is little in fact that shows (a) how adaptation costs compare to the potential damages of not adapting, and (b) how the adaptation costs would change if there was more mitigation.

Adaptation is complex and hard to capture adequately in an impact assessment mainly due to the dependency of vulnerability on local characteristics and uncertainty about future changes in climate and socioeconomic conditions (Füssel & Klein, 2002; Bouwer & Aerts, 2006). A difficult yet important task is to distinguish between adaptation costs that stem from efforts to reduce impacts due to anthropogenic-induced climate change and those from initiatives to lessen the effects of natural climate variability. A particular aspect is the difficulty of distinguishing impacts due to non-climate change reasons, such as such as socio-economic changes, regional climate variability, land-use changes and climate change caused by anthropogenic greenhouse gas emissions (Bouwer & Aerts, 2006)

Adaptation to climate change also strongly depends on the way in which impacts appear. The logical approach is to assess the range of possible impacts of climate change, according to different scenarios and types of climate effects, and relate this uncertainty to adaptation. For example, there are different levels of certainty with projections of future average temperatures, the risks of extreme weather events, and the risks of major climate discontinuities. While adaptation to gradual changes is relatively easy and may not cost much—especially in less vulnerable regions—adaptation to low-probability catastrophic events may be very costly and anticipatory adaptation may be impossible.

Given this complexity, adaptation is not always handled in the same way across studies: different studies assume different adaptation goals. For example, in some studies the (implicit) goal of adaptation in agriculture is to maintain current cropping patterns, others want to maintain current farmers' income, or adjust existing practices in the most efficient manner. Different adaptation goals lead to different adaptation costs and to different residual impacts. Various approaches are used to model adaptation (e.g., spatial analogies, micro-economic optimization). Impact studies mostly only take account of autonomous adaptation that occurs without explicit policy interventions by governments. Yet, governments are already embarking on adaptation policies, and are starting such policies well before critical climate change occurs.

Current adaptation frameworks do not address the effects of economic development on vulnerability and the potential for adaptation. In general, however, impacts of climate change and/or the capacity to adapt could be affected with the level of development and flexibility of the economy (Yohe & Tol, 2002). Hence, the future success and mode of adaptation (e.g., planned versus autonomous, public versus private) will depend on the assumed socioeconomic scenario.

Furthermore, the important trade-offs and links between mitigation and adaptation are hardly analyzed, impeding thereby the computation of a dynamically optimal balance between the two strategies. With a few exceptions (e.g., Bosello, 2005; Tol & Dowlatabadi, 2001), adaptation costs are not measured against the benefits of mitigation. This complicates the calculation of the cost of inaction as an important piece of information is missing (see Tol et al., 1998; Tol & Dowlatabadi, 2001; Bosello, 2005).

3.5 Aggregation: Temporal

Climate change is a slow process. Today's emissions will affect the climate for decades to centuries, and sea level for centuries to millennia. As cause and effect are separated in time, so are costs (of emission reduction) and benefits (of avoided climate change). The procedure making commensurate costs and benefits at different points in time is called discounting. Discounting is as common as it is controversial. See Arrow et al. (1996); Portney & Weyant (1999); Bradford (2001) and Pearce et al. (2003)for excellent discussions.

Individuals discount future gains or losses because of two reasons[7]. First, money earns interest. Second, people are impatient. The sum of the two is the discount rate of money. Impatience implies that there is non-zero discount rate of utility. The first reason, money earns interest, is widely accepted. Davidson

[7]People may also discount the future because it is more uncertain than the present, but in this case discounting is used as a shortcut for an uncertainty analysis.

(2006) is one of the few exceptions. On the second reason, there is virtual consensus too. All ethical arguments show that people should not discount (e.g., Broome, 1992; Koopmans, 1967; Ramsey, 1928). All empirical evidence shows that people do nonetheless; although it is difficult to estimate people's time preference, it is clear that it is substantially greater than zero (e.g., Newell & Pizer, 2004).

Climate change is a large-scale problem. Therefore, the discount rate of society is more relevant than the individual discount rate. The appropriate measure of the growth rate of money is the average growth rate of per capita consumption. Again, there is little dispute on this. Note that this implies that the money discount rate is not constant over time. Note also that economic growth may well be endogenous, that is, climate change may accelerate or decelerate growth (e.g., Fankhauser & Tol, 2005). Different policy scenarios would then have different discount rates. This is the mechanism behind decision making under catastrophic risk (e.g., Gjerde et al., 1999).

But should the social rate of discount also include a measure of impatience? Again, philosophers agree: Impatience is immoral. However, this implies that a government would deviate from the will of the people. The government often does that, or should do that, particularly when correcting market failures. In this particular case, it may be argued that the government is the guardian of future, yet unborn people. Nonetheless, a democratic government should be constrained by the preferences of its citizens, even if it is difficult to aggregate preferences. Again, the empirical evidence is clear: Governments are impatient (Evans & Sezer, 2004).

Discounting is more profound over long periods than over short ones. Discounting implies that climate change damages that occur in century or so are largely irrelevant. This realization has led people to rethink the fundamental principles of discounting, particularly (a) the notion that the procedure of discounting results from the intertemporal allocation of resources of an individual agent; and (b) the assumption that discounting is exponential.

To start with the individual perspective, Lind (1995) and Lind & Schuler (1998) argue that earmarked investment is a crucial assumption in discounting. The discount factor measures the trade-off between consumption now and consumption later, where consumption later is contingent on a specific investment plan. As the current generation cannot commit near-future generations to maintain their investments for the benefit of far-future generations, discounting breaks down between generations. Schelling (1995) agrees. The alternative is to decide explicitly on the resource allocation between generations. Chichilnisky (1996) shows that discounting coincides with a dictatorship of the present generation over future generations. Geralgh & Keyzer (2001) show that discounting is equivalent to the present generation owning all future resources. This is objectionable from a moral standpoint, but it is reality. This line of research has not led to practical alternatives to discounting.

Conventional discounting is exponential: The discount factor is $(1+r)^{-t}-t$, where r is the discount rate and t is time. Some people argue that the functional specification of conventional discounting is wrong. The first component is empirical. Conventional exponential discounting has that the relative difference between two years is always equal, regardless of their distance from the present. That is, the difference between year 10 and 11 is the same as the distance between year 100 and 101. However, many people would in fact argue that the difference between year 10 and 11 is equal to the difference between year 100 and 110. Such hyperbolic discounting (Cropper et al., 1992; Henderson & Bateman, 1995; Heal, 1997) is very similar to exponential discounting for short periods, but the difference is substantial for long periods. The similarity between exponential and hyperbolic discounting in the short run is important, because a switch to hyperbolic discounting would imply a drastic overhaul of long-term decisions only.

There are two further arguments for hyperbolic discounting (cf. Dasgupta & Maskin, 2005). The first is due to Weitzman (2001). He shows that, if one is uncertain what discount rate to use, then the lowest discount rate becomes increasingly dominant over time. The certainty-equivalent discount rate falls with time[8], and the difference between years shrinks in the more distant future. One may criticize this as a short cut for a full uncertainty analysis. However, Gollier (2002*a*,*b*) shows that the same is true if a government somehow aggregates the individual discount rates of its citizens. In the long run, the preferences of the person with the lowest discount rate become increasingly important, and the discount rate declines over time.

The main drawback of a declining discount rate is that decisions will be time-inconsistent. That is, the sheer progress of time would make one change a decision. This follows immediately. The decision in year 0 about savings and consumption in years 10 and 11 is driven by the relative welfare weight of those years, that is, the discount factor. In year 1, the decision on savings and consumption would change unless the relative welfare weight is unchanged. With exponential discounting, the discount rate is independent of time; with hyperbolic discounting, it is not.

Time consistency is a worthwhile property of theoretical models. A forward-looking, well-informed, rational agent should not change her mind just because time has progressed. Time consistency is less relevant in applied policy analysis. Decisions are necessarily made with imperfect foresight and incomplete knowledge. Over time, new information arrives and decisions need to be revised anyway.

In the empirical literature there is no agreement yet on the way in which a discount rate should be chosen. Studies differ in the size of the discount rate as well as in the form of the discount function. While most studies apply a (constant) rate of pure time preference of between 1 and 3 percent, Stern et al. (2006) take an extreme position by applying a pure rate of time preference of

[8]Consider the following example. After one year, the average of a 1% and a 10% discount rate is $1 - \left(\frac{(1.01^{-1}+1.10^{-1})}{2}\right)^{1/1} = 5.0\%$ (and not 5.0%). After 100 years, $1 - \left(\frac{(1.01^{-100}+1.10^{-100})}{2}\right)^{1/100} = 1.7\%$. That is, the average approaches the minimum as time progresses.

only 0.1 percent[9], which is justified by their estimate of the annual probability of the extinction of the human race. The cost of inaction in the Stern report is therefore higher than in most other studies. Recent studies indicate that a declining rate over time might be a promising way to appropriately address short-term and long-term decisions and related equity considerations. Guo et al. (2006) estimate the marginal damage costs of carbon dioxide emissions for constant and declining discount rates. Not surprisingly, the marginal damage costs increases as the discount rate declines faster. For constant discount rates, they report estimates up to $58/tC. For declining discount rates, the estimate may be as high as $185/tC.

Temporal aggregation is a difficult ethical issue, and the results clearly differ for different assumptions. Analysts can only highlight the sensitivity of the conclusions to the alternative ethical choices, and measure the preferences revealed by past decisions. However, climate change is unique problem in many ways, including in its long-term impacts. Past decisions may therefore be a bad guide. The choice of the discount rate is a political one.

3.6 Aggregation: Spatial

Climate change is a global problem. Carbon dioxide and other greenhouse gases mix uniformly in the atmosphere. This implies most of the impacts of one country's emissions fall on other countries. The same is true for the benefits of emission reduction. The impacts on different countries need to be aggregated somehow.

Two methods dominate the literature. In the first and oldest method, regional impacts are quantified in local currencies, converted to dollars, say, and added up (Fankhauser, 1995; Tol, 1995). This is simple, but the disadvantage is that similar impacts are treated differently. Most disturbingly, climate-change-induced deaths in rich countries receive a greater weight than climate-change-induced deaths in poor countries. The second method, known as equity weighing, corrects for this (Azar & Sterner, 1996; Fankhauser et al., 1997, 1998; Azar, 1999). Rather than simply adding regional estimates, the regional utility-equivalents are added and then converted back to money according to an assumed global welfare function. A big disadvantage of this method is that climate-change-induced deaths are treated differently than deaths by other, national causes. The reason for this discrepancy is that equity weighing, as practiced in the literature, explicitly assumes a global decision maker. Nonetheless, national governments use equity weighting too. The UK government, for instance, uses equity-weighed marginal damage costs of carbon dioxide emissions—as if it were a global decision maker[10].

[9] This is one of the two most common complaints about the Stern Review. The other complaint is that the report is so badly written that it is impossible to reconstruct (Dasgupta, 2007; Mendelsohn, 2006; Nordhaus, forthcoming; Tol & Yohe, 2006; Weitzman, forthcoming).

[10] According to an anonymous referee, the UK government was aware that it adopted the position of a global planner. Some of the authors of this paper prefer to be ruled by their own government rather than the British one. It should also be noted that the typical equity-weight

In the meta-analysis of Tol (2005*a*), the median estimate of the marginal damage costs of carbon dioxide is \$10/tC without equity weights, and \$54/tC with equity weights. So, equity weighing is obviously important. The reason is simple. Poor countries are more vulnerable to climate change. Poor countries have little economic weight. Equity weights correct for this.

Morally, this may be the right thing to do. However, national governments also have a certain obligation to defend the interests of their citizens—and equity weights are typically below unity for countries that are richer than average. A narrow interpretation of self-interest would suggest that impacts abroad be ignored (unless they spill over, e.g., through international migration). Then, climate change policy would be very limited, as most impacts will be abroad. However, the principle of good neighborliness is well established, both morally and legally. This entails that one should avoid doing harm to others; and should pay compensation if harm is done nonetheless (e.g., Tol & Verheyen, 2004).

A rational actor would avoid doing harm if that is cheaper than the compensation paid, and in the optimum the marginal harm would equal the marginal compensation. From a national perspective, the relevant damages are then the impacts on the own country plus the compensation paid to other countries. Schelling (1984) forcefully argues that compensation should equal the welfare loss of the victim rather than the welfare loss that the culprit would have experienced had she been the victim. If a Mercedes and a Fiat collide and both are total-loss, the insurance companies would compensate both owners for the current value of their cars. It is not the case that, if the collision is caused by the Mercedes driver, the Fiat driver would be bought a Mercedes. This scenario is attractive (if one disregards moral hazard), but the logical implication is that if the collision is the fault of the Fiat driver, the Mercedes driver would be bought a Fiat. That is, compensation should be done on the basis of the preferences of the victim. This argues for aggregation of monetized impact estimates without equity weighing. Note that the distinction between WTP and WTA (see above) may make a difference here.

Compensation would need to be paid only once—the impacts of sea level rise on the Maldives would be the collective liability of the rich countries, not of each country separately. Furthermore, a country would also reasonably expect to be compensated itself. This implies that the damage to a country equals the global damage times its share in causing the problem. Defining the latter is a thorny issue, as the cause-effect chain is long, complex, and uncertain. One would need to make arbitrary decisions on cause, effect and their connection.

For instance, according to the Brazilian Proposal, a country's responsibility for climate change equals its share in the cumulative carbon dioxide emissions from fossil fuel combustion since 1750 in its current territory. Table 1 shows the implications. Compensation redistributes the marginal costs between the regions of the world, but it does not affect the world total. Regional marginal costs are obviously lower than the aggregate. However, one may also argue

for the UK is less than one—that is, the UK government places less value on climate change damage in the UK than on equivalent air-pollution damage. See Anthoff & Tol (2007) for further discussion.

Table 1: Regional marginal damage costs (in $/tC) in 2005 and 2055 for a 1% pure rate of time preference—the table contrasts the regional marginal damage costs and the regional marginal liability. Source: Tol (2006)

	2005		2055	
	Damage	Liability	Damage	Liability
USA	2.20	2.61	1.15	1.80
Canada	0.09	0.20	0.08	0.14
Western Europe	3.16	1.29	2.08	0.84
Japan and South Korea	-1.42	0.86	0.21	0.63
Australia and New Zealand	-0.05	0.13	0.08	0.09
Eastern Europe	0.10	0.31	0.09	0.27
Former Soviet Union	1.27	1.45	0.61	1.36
Middle East	0.05	0.66	0.33	0.65
Central America	0.07	0.18	0.12	0.15
South America	0.27	0.36	0.15	0.30
South Asia	0.36	0.86	0.34	0.84
Southeast Asia	0.73	0.52	0.45	0.54
China	4.36	3.39	4.88	3.40
North Africa	0.97	0.16	0.42	0.13
Sub-Saharan Africa	1.07	0.24	0.33	0.19
Small Island States	0.06	0.06	0.07	0.06
World	13.27	13.27	11.40	11.40

that countries cannot be held responsible for emissions from before 1988, when climate change first emerged on the political agenda. This would shift liability away from the OECD towards India and China.

As with aggregation over time, aggregation of climate change impacts is fraught with difficult ethical questions. However, the global marginal damage cost, and hence the intensity of emission reduction, is not affected by the question of compensation. That is a matter of equity, not efficiency. The marginal damage cost estimates does change if one adopts the position of a global planner rather than a collection of sovereign nations. Global planners are only in the minds of academics, however.

3.7 Uncertainty and irreversibility

Climate change is plagued by uncertainty. Partly, this is because our understanding of climate change and its impacts is incomplete. For the larger part, however, this is because climate change will take place in the future, driven by future emissions, and impacting a future world. Future research and observations may reduce the uncertainty, although surprises may increase the uncertainty just as well, but uncertainty will never disappear. Learning and irreversibility play a crucial role in how to deal with uncertainty. Events that may or may not occur in some distant future, but whose consequences can be alleviated once it becomes clear if they would occur, should not worry us too much. On the other hand, if an effect is irreversible (e.g., species extinction), we may want to prevent it regardless of how uncertain it is and regardless of what future research will show (according to the "precautionary principle"). Another crucial part of dealing with uncertainty is risk aversion. Essentially, this determines how much weight we place on negative surprises. A risk neutral decision maker would cancel negative surprises against positive ones, but a risk adverse decision maker would not. Recent work has shown that the marginal damage costs of carbon dioxide are indeed very sensitive to the assumed degree of risk aversion. Indeed, although uncertainty and risk are often emphasized—often in a casual way—only few studies seek to quantify its implications.

Up to now, research studies primarily discuss the importance of uncertainty and risk in the context of climate change, but they rarely quantify their implications. One of the exceptions is Newell & Pizer (2004) who include statistical uncertainty in their cost calculations by analyzing the effect of uncertain future discount rates on the valuation of future benefits. They find that the effect of uncertainty is larger for higher discount rates, implying that the valuation of benefits occurring in the future is less sensitive to the choice of the current discount rate when the effect of uncertainty is taken into account. This study demonstrates the importance of coping with uncertainty when assessing climate change impacts. The dimension of uncertainty which characterizes this literature should therefore gain an explanatory role in the modeling exercises in the sense that uncertainty can have important implications on climate effects, shedding thereby more light on their driving forces.

Ceronsky et al. (2005) estimate that large-scale methane releases from melting permafrost would increase the social cost of carbon from \$11/tC to \$12–21/tC (for a 1% pure rate of time preference). For a thermohaline circulation shutdown, the estimates would range from \$10–13/tC. However, they also find the impact of these low-probability/high-impact scenarios is dominated by the impact of high-climate-sensitivity scenarios. In the base case, the climate sensitivity is 2.5°C equilibrium warming per doubling of the atmospheric concentration of carbon dioxide. The marginal damage costs is \$11/tC. If the climate sensitivity is 4.5°C, 7.7°C or 9.3°C, marginal costs are \$89/tC, \$360/tC, or \$580/tC. The reason is that high climate sensitivity would have impacts in the near future too.

Deep or fundamental uncertainty on the probability and extend of climate change's potentially catastrophic impacts has led some analysts to critically examine the appropriateness of expected utility theory on which current damage assessments are based (Chichilnisky, 1998). There are alternative frameworks for decision-making under fundamental uncertainty (see, e.g., Perrings, 2003; Intergovernmental Panel on Climate Change, 2007), but we are still far from practical solutions to this issue.

The IA model underlying the analysis of Stern et al. (2006) is in essence a sensitivity analysis tool. The Page2002 model (Hope, 2006) can compute the sensitivity of climate change impact variables on changes in a large number of physical and economic parameter values. It is regrettable that Stern et al.

(2006) did not make full use of this particular strength of the model. Dietz et al. (2007) do publish limited sensitivity analyses, but as this was kept out of the public eye, Tol & Yohe (forthcoming) call this "too little, too late".

4 Conclusions

In this paper we have discussed some key methodological issues in the assessing the damage costs of climate change. We have shown schematically how recent (post-2000) studies have dealt with these methodological issues. Recent studies have taken alternative approaches. Some studies use dynamic economy and climate scenarios, but that it is not yet commonplace. The valuation method for non-market goods is predominantly a rough version of benefit transfer and there is little attention for the complexities of this method. Adaptation costs are rarely disentangled from residual damage. Equity concerns are not taken into account, and if so only by equity weighting of regional impacts. Uncertainty and risk are dealt with by sensitivity analysis, but not many studies use (fully) stochastic models. Studies deal with one or a limited number of aspects of climate change, but never with all of them.

There is a clear need for more original work on the damage cost of climate change. As new scientific evidence on physical climate change impacts becomes available, and as climate change will start affecting our present-day economies, the quality of the damage estimates will undoubtedly improve and the uncertainty of the estimates will diminish. As another potential source of improvement, this paper suggested a number of methodological issues that could and should be addressed by future research. These issues include: (i) dynamic representations of climate and economic scenarios in integrated assessment frameworks, (ii) more original valuation studies on non-market goods in the context of climate change, (iii) estimation of indirect, geographic-specific macroeconomic impacts of climate changes including extreme events, (iv) better representation of adaptation in integrated assessment models, (v) issues of temporal and regional aggregation from different political and ethical perspectives, and (vi) a better representation of 'deep' uncertainty and irreversibility, including fundamental considerations on the appropriate decision-making framework.

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