Estimating socio-economic impacts of climate change

Richard S.J. Tol

Institute for Environmental Studies, Vrije Universiteit, De Boelelaan 1115,
1081 HV Amsterdam, The Netherlands

1. INTRODUCTION

The potential impacts of a possible climate change are many and diverse (cf. also Watson *et al.*, 1996). In this talk, I will address the issue from an economic point of view, in fact, from a decision-analytic point of view. Decision analysis helps a careful, systematic and consistent balancing of the pros and cons of policy strategies towards a problem, climate change and greenhouse gas emission reduction in this case. To that end, different types of impact need to be made comparable, by expressing them in a single indicator. Money is a suitable metric, because of its central importance in almost all exchanges and the long experience of economists in monetary valuation. I will thus try and express the impact of climate change in money. This allows us to interpret the seriousness of climate change (and its regional differences), compared to other problems and compared to the costs of emission reduction. I will even go a step further to present the marginal damages of carbon dioxide, that is, the additional impact that would accrue should we emit one additional ton of carbon. Straightforward mathematics shows that it justified to reduce emissions only up to the point that marginal costs and benefits are equal. Justified, that is, if we want to maximize welfare.

The paper is structured as follows. Section 2 reviews the economic assessments of climate change impacts, following the Second Assessment Report (SAR) of the

Intergovernmental Panel on Climate Change (IPCC). Section 3 discusses more in-depth the contentious issue of valuing non-market impact. Section 4 presents estimates of the marginal damage of carbon dioxide emissions. Section 5 concludes.

2. CLIMATE CHANGE DAMAGE COSTS

The scientific research on global warming impacts has focused predominantly on the $2\times CO_2$ benchmark, that is, a scenario with an atmospheric CO_2 equivalent concentration of twice the preindustrial level. Despite the fact that this scenario is arbitrary, counterfactual and of limited policy relevance, a large part of the social cost chapter in IPCC SAR (Pearce *et al.*, 1996) is consequently also devoted to "$2\times CO_2$ damage". A climate change associated with a doubling of the atmospheric concentration of carbon dioxide equivalents is expected to occur in the second half of the next century if no substantial emission reductions are realized.

Information on the impacts of global warming is available for several regions and countries. The best studied regions are developed countries, in particular the United States, where climate change impacts have been analyzed in a series of studies, following initial work by Smith and Tirpak (1989). The most prominent US studies are made comparable by Smith (1996). The most recent, comprehensive US study is by Mendelsohn and Neumann (forthcoming). Other OECD regional studies include CRU/ERL (1992) for the European Union (updated by Plambeck and Hope, 1996); Parry and Duncan (1995) for the United Kingdom); and Nishioka *et al.* (1993) for Japan. In the context of an Asian Development Bank (ADB, 1992) project on climate change in Asia, global warming impacts have also been analyzed for a number of Asian countries. Stzrepek and Smith (1995) contains case studies for Africa, Latin America and Asia. Under the various country study programs brought about by the Framework Convention on Climate Change, most developing countries and countries with economies in transition are now being studied. If these studies go well, the most significant white spot on the climate impact knowledge map will be continental Western Europe.

Studies usually deal with only a subset of damages, and are often restricted to a description of impacts in physical terms. Estimates generally combine, but do not neatly separate the costs of adaptation (such as sea level rise protection) and the costs of residual damages (such as the inundation of unprotected areas).

By far the best studied impact categories are agricultural impacts (e.g., Rosenzweig and Parry, 1994; Adams *et al.*, 1994; Darwin *et al.*, 1995; Schimmelpfennig *et al.*, 1996; Reilly *et al.*, 1996) and the costs of sea level rise (e.g., Fankhauser, 1995b; Turner *et al.*, 1995; Yohe *et al.*, 1995, 1996; Bijlsma *et al.*, 1996). Several types of impacts have largely been ignored so far, because they could not be sufficiently quantified. Other damages were estimated on the back of an envelope.

Attempts at a comprehensive monetary quantification of all impacts are relatively rare, and usually restricted to the United States (Cline, 1992a; Titus, 1992; Mendelsohn and Neumann, forthcoming; Nordhaus, 1991). Preliminary estimates of monetary damage in different world regions are provided by Fankhauser (1995a), Tol (1995), and, subsequent to the finalization of the SAR, Mendelsohn *et al.* (forthcoming).

The impacts of climate change fall apart in two broad categories: impact on marketed and non-marketed goods and services. For market goods, deriving an income change is relatively straightforward. For non-market goods, valuation techniques have to be employed. Four major techniques are available to estimate the 'price' of goods and services which are not traded on markets: the travel cost method, hedonic pricing, household production, or contingent valuation.

In the travel cost method, one analyzes the effort (in time and money) people are willing to spend to visit a particular site with desirable attributes. This effort, expressed in money, is a measure for the monetary worth of the desirable attributes. Advantages of the travel cost method are that it is simple in concept and application, and does not require strong assumptions on the real world. A major disadvantage is that only direct use values can be measured with the travel cost method. Using the travel cost method, one could, for instance, estimate in monetary terms the pleasure people derive from visiting a forest or a beach. People spend time and money to go there, which can be measured and used to derive a demand curve. The value to the average visitor times the number of visitors is an indication of the worth of that forest or beach.

In hedonic pricing, one analyzes price differentials of traded goods and services which have different bundles of non-tradeable attributes. These price differentials are measures for the monetary values of the non-tradeables. Advantages of hedonic pricing are that it is conceptually simple and that it can be used to value a wide range of non-traded goods and services. Disadvantages are that hedonic pricing may involve strong assumptions on information and rationality of economic actors, that it may require complicated statistical techniques, and that only direct use values can be measured. Using the hedonic pricing method, one could, for instance, estimate in monetary terms the pleasure people derive from living in a particular place. A house at a beautiful place is more expensive than the same house at an unattractive location. Measuring the difference -- and controlling for other factors -- one can estimate a demand curve, and thereby obtain an indication of the value of the surroundings of that place.

The household production function approach is similar to, yet more ad than hedonic pricing. In lieu of price differentials in trade goods and services, one analyzes differences in consumption bundles as to the influence of non-tradeables. Demand curves are then derived through an assumed preference structure of the economic agent.

In contingent valuation, one interviews people so as to simulate a hypothetical market on which in reality non-tradeable goods and markets are traded for money. The main advantage of contingent valuation is that it can be used on any good or service, and that it can measure direct and indirect use values as well as option, existence and bequest values. Disadvantages are that contingent valuation assumes that people have well expressed preferences, and that contingent valuation is expensive and elaborate. Using the contingent valuation method, one could, for instance, interview people whether they would be willing to pay amount X to preserve forest Y. Based on the interview results, a demand curve can be derived.

The comprehensive studies mentioned above are based on a mix of these techniques and various approximations. The Fankhauser and Tol figures, which were at the core of the IPCC assessment (Pearce *et al.*, 1996), are reproduced in Table 1. Fankhauser and Tol (1997) have recalculated the initial set of estimates consistently correcting for purchasing power parity and using the same benefit transfer methodology throughout. These results are reproduced in Table 1.

Figures vary between 0 and 7 percent of real (purchasing power parity corrected) GDP.

Table 1 highlights the substantial differences between regions. For the former Soviet Union, for example, damage could be as low as 0.4 percent of GDP, or even negative (climate change is potentially beneficial). Asia and Africa, on the other hand, could face extremely high damages, mainly due to the severe life/morbidity impacts. Developing countries generally tend to be more vulnerable (in relative terms) to climate change than developed countries, because of the greater importance of agriculture, lower health standards and the stricter financial, institutional, and knowledge constraints on adaptation.

Pearce *et al.* (1996) stress the preliminary and incomplete character of these estimates. The estimates do not fully reflect the current state of knowledge, since it takes many years for new insights in climatology and agronomy to trickle down to quantative economic estimates. It should be noted that the above figures are *best guess* estimates. The range does not reflect a confidence interval, but the variation of estimates found in the literature. There is a considerable range of error which has not been quantified. Pearce *et al.* also note that figures on developing countries in particular are largely based on approximation and extrapolation, and are clearly less reliable than those for developed regions. Further, as best-guess estimates, the figures neglect the possibility of impact surprises (such social and political unrest), and of low probability/high impact events (such as a shut down of the ocean conveyor belt). To avoid long-term predictions, damage figures measure the impact of $2{\times}CO_2$ on a society with today's structure. Vulnerability is likely to change as regions develop and population grows.

Despite these shortcomings, available figures give a rough indication of the possible order of magnitude of $2{\times}CO_2$ damages and the relative vulnerability of various regions.

Table 1
Annual monetized $2\times CO_2$ damage in different world regions

	Fankhauser		Tol	
	bn$	%rGDP[a]	bn$	%rGDP[a]
· European Union	63.6	1.4		
· United States	61.0	1.3		
· Other OECD	55.9	1.2		
· OECD America			74.5	1.5
· OECD Europe			57.4	1.6
· OECD Pacific			60.7	3.8
Total OECD	*180.5*	*1.3*	*192.7*	*1.9*
· E. Europe / Former USSR	29.8[b]	0.4[b]	-14.8	-0.4
· Centrally Planned Asia	50.7[c]	2.9[c]	-4.0	-0.1
· South and South East Asia			92.2	5.3
· Africa			46.4	6.9
· Latin America			40.3	3.1
· Middle East			11.5	5.5
Total Non-OECD	*141.6*	*0.9*	*172.8*	*1.7*
World	*322.0*	*1.1*	*364.4*	*1.8*

[a] purchasing power parity corrected GDP; note that the GDP base may differ between the studies.

[b] Former Soviet Union only

[c] China only

Source: Fankhauser and Tol (1997), based on Fankhauser (1995a) and Tol (1995).

3. VALUATION ISSUES

As the previous section makes clear, greenhouse damage estimates still have a number of limitations. A number of important issues concern valuation. A first one is the choice between the two concepts of willingness to pay (WTP) and willingness to accept compensation (WTA), which is essentially an issue of property rights. A second issue is the question of benefit transfer, which asks how estimates for one region or one problem area can be extrapolated to another. A third issue concerns the incorporation of equity issues into comparison and aggregation of estimates. This section deals with each of these in turn.

3.1. Willingness to pay vs willingness to accept

It is a well known empirical fact that economic values derived under a WTP framework tend to differ from estimates that measure the same damage using WTA. The latter can be several times higher. Bateman and Turner (1992), for example, report ratios of WTA over WTP ranging from 1.6 up to 6.5. Climate change damages, too, can therefore be expected to be sensitive to the choice of valuation concept. For practical reasons however, Arrow *et al.* (1993) have recommended the use of WTP for contingent valuation studies, since they tend to produce more reliable results.

Various reasons for this discrepancy between WTP and WTA have been advanced. Firstly, some authors have suggested that the valuation experiments showing the discrepancy have failed to replicate near-market contexts. When respondents are asked to repeat bids, for example, WTP and WTA eventually converge (Coursey *et al.*, 1987). This suggests that lack of time and familiarity with the good might explain the divergence, and that as goods and the context of valuation become more familiar, WTP and WTA values converge. Secondly, respondents may be rejecting the implied property right. WTA implies that the sufferer does not 'own' the environment, or that the sufferer is bereft from an environmental property. If the respondent feels that is incorrect or immoral in some sense, large WTA values may result, including high 'protest' values. Thirdly, psychological prospect theory suggests that respondents are anchored to a reference point, generally defined by the prevailing bundle of goods and assets in their possession. The context of taking some of these goods away is then treated very differently to the context of adding to the set of goods. Increments therefore attract lower values than decrements. This concavity is reinforced if respondents see the good in question as part of their 'identity', i.e., integral to their lifestyle or psychological make-up. The resulting value function is concave or even kinked, contrary to the normal assumption of demand theory (Kahneman and Tversky, 1979). Fourthly, Hanemann (1991) has argued that the discrepancy between WTP and WTA is least where the substitution possibilities for goods are highest. Unique assets, often the context of contingent valuation studies, will tend to have high WTP/WTA discrepancies.

The choice between WTP and WTA constitutes an implicit statement about prevailing property rights, and this is sometimes used as a guideline for the choice of concept. By using WTP -- i.e. asking people how much they would pay to avoid adverse impacts -- a changing climate is implicitly chosen as the reference scenario. People do not have a 'right' to the climate currently observed, but have to pay to obtain it. Conversely, by using WTA, the assumption is that people are entitled to the preindustrial climate or the current climate. They have to be compensated for any damage arising from alterations to it.

However, the appropriate allocation of property rights (and thus the choice between WTP and WTA) in the case of climate change is unclear. On the one hand, the right of future generations to a functioning environment seems hard to question, and is at the core of such notions as sustainable development. This would point toward the use of WTA (assuming, as current evidence suggests, that climate change is predominantly harmful - see Budyko, 1996, and Mendelsohn and Neumann, forthcoming, for a different position): future generations are to be compensated for a climate change induced deterioration in living standards. On the other hand, an equally strong case can be made for the right of developing countries to increase their standard of living, which would imply at least a certain degree of baseline warming, and hence the use of WTP.

In practice, WTP and WTA are often mixed up in actual valuation. This is particularly the case for climate change damages, where the limited number of original studies make it necessary to use whatever information is available, often resorting to benefit transfer. Consequently, estimates tend to be a blend of various approaches, although WTP is perhaps more frequently used. Most estimates in the literature were derived with the benefits of emission reductions in mind, and consequently took business-as-usual climate change as the starting point, asking people about their WTP to obtain a deviation. WTA has also been used, however, as have been a number of second-best measures that were used as approximations in the absence of primary studies. Estimates for the value of a statistical life (VOSL), for example, were derived from a series of predominantly WTA studies (wage-risk studies).

At least as far as the current generation of damage estimates is concerned, the distinction between WTP and WTA is thus blurred. Nevertheless the issue is important conceptually, and it is likely to become increasingly relevant as refinements in damage analysis take place and additional studies are undertaken.

3.2. Benefit transfer and scaling by income

Since primary WTP/WTA data for climate change impacts are still scarce, the damage cost literature relies heavily on what is called benefit transfer. The term refers to an often used short-cut in valuation, in which WTP/WTA results ('environmental benefits') obtained in one study are transferred to a new problem and another site. For the assessment of climate change-induced mortality risk, for example, per-unit values were 'transferred' from a wide range of VOSL studies in various developed countries, most of them using wage differentials (a WTA procedure called the hedonic approach, see e.g. Viscusi, 1993).

Benefit transfer is not without problems. Estimates are often site or problem specific and hence difficult to transfer. In the case of climate change-induced mortality, for example, the cause of the mortality risk in the underlying studies (occupational hazard) is different from that in the new application (climate change related deaths). If people have a different WTP/WTA depending on the type of hazard, the transferred per-unit value would be biased. For example, it is conceivable that the WTP/WTA of the elderly, who will be most at risk from climate-change related heat stress, is different from that of workers in the prime of their life. For other climate change related risks (e.g., malaria, or extreme events), the WTP/WTA may be different again.

To take such effects into account, the values from the underlying study should ideally be corrected for differences in site and socio-economic conditions. Even so, the accuracy of benefit transfer remains open to question. In a direct test of the method, Bergland *et al.* (1995), for example, found a statistically significant difference between estimates based on benefit transfer and the results from a primary study. Alberini *et al.* (1995), on the other hand, secure a consistent set of results for contingent valuation and income-adjusted benefit transfer in a study on morbidity in Taiwan.

Bearing these problems in mind, transferred estimates can provide useful ballpark figures, and the method is often used in situations where the accuracy sought does not justify the costs of a primary study. As for climate change, the use of benefit transfer is primarily necessitated by the absence of primary studies for a large number of countries and damage categories.

In most climate change damage studies, per-unit value estimates were more or less directly transferred from the study site. The only major adjustment made concerned income, which is one of the main explanatory variables for both WTP and WTA. A standard assumption is that WTP/WTA is an increasing function of income.[***] A rich person would normally be willing (and able) to make a higher payment, in absolute terms, than a poor person. By the same token, a compensation of, say $1,000 will appear less attractive to a rich person than to a poor individual. The damage studies reviewed in Pearce *et al.* (1996) therefore usually scale per-unit values according to income, i.e., they use lower values in low income countries. A possible benefit transfer function is

$$V_j = V_i \left[\frac{Y_j}{Y_i}\right]^{\beta} \tag{1}$$

where subscript *j* denotes the new application where the value is 'transferred' to, and *i* the original study site. *V* denotes the WTP/WTA estimate, *Y* is per capita income, and β is a scaling parameter, e.g., the income elasticity of marginal utility.

Although there is clear empirical evidence for an income effect, little is known about its magnitude, and scaling is correspondingly controversial. Most of the studies surveyed in

*** Although the theoretical work of Flores and Carson (1995) does not exclude the possibility of a negative correlation.

Pearce *et al.* (1996) assume an income elasticity of WTP/WTA of 1, or slightly higher, following an early study by Pearce (1980). That is, WTP/WTA as proportions of income are identical across individuals. If a rich person is willing to pay, say, 5% of his income for an environmental good, a poor person would equally be willing to spend 5% of his.

Recent results cast doubt on the assumption of a unitary income elasticity of WTP/WTA, suggesting an income elasticity of less than one (Flores and Carson, 1995; Kristrom and Riera, 1996; see also Krupnick *et al.*, 1996). Given the logic of scaling, a lower income elasticity would imply that damages in developing countries were underestimated initially. (The estimates for developed countries are not affected, since these are the subject of the original study). The evidence is not yet conclusive, though. The few available studies that directly estimate the VOSL in developing countries all came up with substantially lower values than would be obtained through benefit transfer. Thus, Parikh *et al.* (1994) found VOSLs in Bombay of $25,000 using the human capital approach; $20,000 using the wage differential approach and $15,000 based on the Indian Workman's Compensation Act. Da Motta *et al.* (1993) find a VOSL of $15,000 using the human capital approach in Brazil. For comparison, the lowest VOSL assumed in the IPCC social cost chapter is $150,000. The IPCC value is based on an elasticity of WTP/WTA of about one. The Brazilian and Indian evidence would thus imply an elasticity much greater than one. It is worth noting, though, that the human capital approach is largely discredited as an approach to estimate VOSLs. It is also well known that WTP/WTA is likely to exceed the expected value of forgone earnings. It is therefore likely that the Indian and Brazilian studies have underestimated the true VOSL.

Better information is clearly needed in this area. At the same time, it should be recalled that the question of the income elasticity of WTP/WTA has arisen only due to the absence of original damage research which necessitated the use of benefit transfer. Although benefit transfer is likely to continue to be important, primary studies directly concerned with the valuation of climate change damages are therefore at least as important as refinements in benefit transfer. With an increasing number of such studies, issues of benefit transfer will automatically become less relevant. In the meantime, and until clear empirical evidence becomes available, it will be important for subsequent damage assessments to explore the sensitivity of estimates to crucial parameters such as the income elasticity of WTP/WTA.

3.3. Equity weighing

One of the key features of WTP/WTA estimates is that they are a mixture of descriptive and prescriptive concepts. The value of goods is set according to people's own appreciation of them (description) and it is assumed that people's preferences should count (prescription). At the same time, the socio-economic situation from which people make their assessment is taken as given. This can lead to problems if the currently observed situation (say, the distribution of income) is considered to be unfair. WTP/WTA estimates, because they are a function of socio-economic characteristics, will automatically reflect this unfairness. The issue is well known, though, and has a long history in cost-benefit analysis (see, e.g., Pearce, 1986). The solution offered by welfare economics is not to use uniform per-unit values (as some have called for -- Meyer and Cooper, 1995; Hohmeyer and Gaertner, 1992; Ayers and Walter, 1991), but to weight individual estimates by a corrective factor that adjusts values for inequalities in the income distribution. These 'equity weights' are usually derived from a social welfare function. Consequently they strongly depend on the analyst's or policy makers' value judgment and on the welfare function they endorse.

None of the estimates in Pearce *et al.* (1996) had been corrected initially, although the chapter did show how such equity weighing could be carried out. (In addition, equity was the subject of two separate chapters in the SAR: Banuri *et al.*, 1996, and Arrow *et al.*, 1996). Fankhauser *et al.* (1997) fill this gap and calculate equity weights and the corresponding damage figures for a variety of possible welfare and utility functions. In that paper, we show that total, worldwide damage can be expressed as

$$D^{world} = \left[\frac{W_1 \cdot u_Y^1}{W_M}\right] D^1 + \ldots + \left[\frac{W_n \cdot u_Y^n}{W_M}\right] D^n \tag{2}$$

where the terms in brackets denote the equity weights. Equity weights consist of three parts. Firstly, u_Y is a measure how much regional welfare changes as a consequence of damage D. Secondly, W_i is a measure how much global welfare changes as a consequence of a change in regional welfare. Thirdly, W_M is a scaling factor which ensures that equity weights are zero if the underlying income distribution or the distribution of damages is considered just.

Three debatable assumptions underlie (2). Firstly, meaningful welfare functions do exist. Secondly, economic and environmental goods and services are substitutable, at least within the stress imposed by climate change. Thirdly, climate change impacts are small enough to allow for linearization.

A selection of results is reproduced in Table 2. A conventional iso-elastic utility function:

$$u = \frac{a}{(1-e)} \cdot Y^{(1-e)} \tag{3}$$

is used. Different values for parameter e (the income elasticity of marginal utility, or risk aversion) will be used below.

The specification for the welfare function is

$$W = \frac{\sum_{i=1}^{n} u^i(\cdot)^{(1-\gamma)}}{1-\gamma} \tag{4}$$

where γ is a parameter of inequality aversion. The larger is γ, the larger is the concern about equality. For $\gamma = 0$, equation (4) reduces to a utilitarian welfare function, letting γ approach 1 gives a Bernoulli-Nash function, $\gamma \rightarrow \infty$ represents the maximin (Rawlsian) case, and $\gamma \rightarrow -\infty$ is the maximax (Nietzschean) welfare function.

As Table 2 makes clear, estimates are highly sensitive to the assumed welfare concept. World damages are generally (but not necessarily) higher than originally reported in Pearce *et al.* (1996), particularly for high values of risk or inequality aversion. This exercise makes also clear that the original studies (with implicit equity weights of one), implicitly assumed either a just distribution of welfare, or a linear, utilitarian welfare function.

4. MARGINAL DAMAGE ESTIMATES

The analysis so far was confined to comparative statics. All figures in Table 1 are estimates of the impact of one specific change of the climate (2×CO_2) on the current economy. This is clearly insufficient. Not only will we, for the larger part of the future, be confronted with climate change substantially different from 2×CO_2, but socio-economic vulnerability to climate change will also shift as a consequence of economic development.

Table 2
Aggregate damages corrected for inequality (in bn$)

	Fankhauser (1995a)	Tol (1995)
Uncorrected damages[a]	322.0	364.4
Utilitarian Welfare Function		
e = 0.0[b]	322.0	364.4
e = 0.5	315.6	411.4
e = 1.0	405.2	614.3
e = 1.5	621.9	1057.6
e = 2.0	1041.7	1930.0
Bernoulli-Nash Welfare Function[c]	405.2	614.3
Maximin Welfare Function		
e = 0.0	50.7	46.4
e = 0.5	95.8	89.4
e = 1.0	181.0	172.2
e = 1.5	342.7	331.8
e = 2.0	646.5	639.3

[a] as in Table 1

[b] e denotes the income elasticity of marginal utility (parameter of the utility function)

[c] Bernoulli-Nash weights are independent of e, and correspond to the case e = 1 of the utilitarian welfare function.

Source: Fankhauser *et al.* (1997), based on indicated sources.

What would be relevant to know from a policy point of view are marginal figures, ie, estimates of the extra damage done by one extra ton of carbon emitted. Unfortunately, the requirements for marginal damage calculations go far beyond the information available from $2xCO_2$ studies. Greenhouse gases are stock pollutants. That is, a ton of gas emitted will affect climate over several decades, as fractions of the gas remain long in the atmosphere. Calculating marginal costs therefore requires the comparison of two present value terms: The discounted sum of future damages associated with a certain emission scenario is compared to the sum of damages in an alternative scenario with marginally different emissions in the base period (in estimates based on optimal control models, the marginal cost is calculated as the shadow price of carbon, i.e., the carbon tax necessary to keep emissions on the socially optimal trajectory; Nordhaus, 1994; Peck and Teisberg, 1993).

The current generation of models deals with this challenge in a rather ad hoc manner, using very simplistic representations of the complex dynamic processes involved. In older studies damage costs were typically specified as a power (usually linear to cubic) function of global mean temperature, calibrated around the $2\times CO_2$ estimates. Damage is usually fully reversible and typically assumed to grow with GNP. Only recently, studies have started to emerge which explicitly incorporate regionally diversified temperatures and sea levels, model individual damage categories (e.g., agriculture) separately, or at least distinguish between damages related to absolute temperature level and those related to the rate of change (Dowlatabadi and Morgan, 1993; Hope *et al.*, 1993; Tol, 1995).

Table 3 provides a list of estimates of the marginal damages obtained from polynomial damage models. Estimates range from about \$5 to \$125 per ton of carbon, with most estimates at the lower end of this range. The wide range reflects variations in model assumptions, as well as the high sensitivity of figures to the choice of the discount rate (Pearce *et al.*, 1996). Estimates are expected to rise over time as a consequence of economic growth and increasing concentration levels.

Using a model called DICE, Nordhaus (1994) finds that the shadow price begins at only about \$5 per ton of carbon in 1995, rises to about \$10 by 2025, and reaches \$21 by 2095 (at 1990 prices). Peck and Teisberg (1993) find values of a similar order of magnitude. Tol's (1994) alternative specification of DICE yields shadow prices of \$13 for 1995, rising to $89 for 2095. These model runs all assume that parameter values are known with certainty. In the case of DICE, expected shadow prices more than double, once uncertainty is added to the model. This result arises because of the skewedness in the damage distribution, which allows for low probability - high impact events (Nordhaus, 1994); risk aversion and concave damage functions further enhance this effect (Tol, 1995). All three authors assume a pure rate of time preference (or utility discount rate) of 3% (for a discussion on discounting see Arrow *et al.*, 1996; Nordhaus, 1994). In contrast, Cline (1993, 1992b) finds significantly higher shadow prices by using a zero utility discount rate. His reproduction of the DICE model generates a path of shadow prices beginning at about $45 per ton, reaching about $243 by 2100. Other parameter specifications provide even higher values.

Fankhauser (1995a) identifies a lower and flatter trajectory for the shadow price of carbon, rising from $20 per ton by 1991-2000 to $28 per ton by 2021-2030, with confidence intervals of $6-45 and $9-64, respectively. Fankhauser uses a probabilistic approach to the range of discount rates, in which low and high discount rates are given different weights. His sensitivity analysis with the discount rate suggest that moving from high (3%) to low (0%) discounting could increase marginal costs by about a factor 9, from $5.5 to $49 per ton of carbon emitted now.

5. CONCLUSIONS

Economic impact estimates of climate change are still in a very early stage of scientific analysis. Some insights can be gained, however. According to current knowledge, the impact of climate change associated with a doubling of atmospheric concentrations of greenhouse gases would be around 1.5% of world income per year, with equally strong arguments that this would be too high as well as too low. Although 1.5% sounds low, it is quite a considerable amount of money. In rich economies, the impact would be a little lower, in poor economies, substantially higher than the world average.

Table 3
The marginal social costs of CO_2 emissions (current value (1990)$/tC)

Study	Type	1991-2000	2001-2010	2011-2020	2021-2030
Nordhaus	MC		7.3		
			(0.3-65.9)		
Ayres and Walter	MC		30 - 35		
Nordhaus, DICE	CBA				
- best guess		5.3	6.8	8.6	10.0
- expected value		12.0	18.0	26.5	n.a.
Cline	CBA	5.8 - 124	7.6 - 154	9.8 - 186	11.8 - 221
Peck and Teisberg	CBA	10 - 12	12 - 14	14 - 18	18 - 22
Fankhauser	MC	20.3	22.8	25.3	27.8
		(6.2-45.2)	(7.4-52.9)	(8.3-58.4)	(9.2-64.2)
Maddison	CBA -MC	5.9-6.1	8.1 - 8.4	11.1-11.5	14.7-15.2

MC = marginal social cost study, CBA = shadow value in a cost-benefit study.
Figures in brackets denote 90% confidence intervals.

Sources: Pearce *et al.* (1996); see also Ayres and Walter (1991), Nordhaus (1994), Cline (1992b, 1993), Peck and Teisberg (1993), Fankhauser (1995a) and Maddison (1994).

These estimates reflect the world as it is, not as we would like to see it. This distinction may be blurred if it comes to valuation of non-market goods and services and to aggregation of impact estimates over countries with widely different living standards. Impact estimates are shown to be quite sensitive to such issues.

Estimates of the marginal impact of carbon dioxide emissions show that there is a clear case to go beyond no-regret emission reduction. How far is open to debate. The minimally justified carbon tax is $5 per ton of carbon, while the best guess is $20/tC.

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