IS THE UNCERTAINTY ABOUT CLIMATE CHANGE TOO LARGE FOR EXPECTED COST-BENEFIT ANALYSIS?

RICHARD S. J. TOL

Center for Marine and Climate Research, Hamburg University, Hamburg, Germany
Institute for Environmental Studies, Vrije Universiteit, De Boelelaan 1115,
1081 HV Amsterdam, the Netherlands
Center for Integrated Study of the Human Dimensions of Global Change,
Carnegie Mellon University, Pittsburgh, PA, U.S.A.

Abstract. Cost-benefit analysis is only applicable if the variances of both costs and benefits are finite. In the case of climate change, the variances of the net present marginal costs and benefits of greenhouse gas emission reduction need to be finite. Finiteness is hard, if not impossible to prove. The opposite is easier to establish as one only needs to show that there is one, not impossible representation of the climate change with infinite variance. The paper shows that all relevant current variables of the *FUND* model have finite variances. However, there is a small chance that climate change reverses economic growth in some regions. In that case, the discount rate becomes negative and the net present marginal benefits of greenhouse gas emission reduction becomes very large. So large, that its variance is unbounded. One could interpret this as an indication that cost-benefit analysis is invalid. Alternatively, one could argue that the infinity is present in both the base case and the policy scenario, and therefore irrelevant; in that interpretation, cost-benefit analysis is a valid tool.

1. Introduction

Uncertainty abounds in climate change. Uncertainty also abounds in the literature about climate change. Some papers try to describe and classify the uncertainties (Hammitt, 1995; Harvey, 1996a,b; Paté-Cornell, 1996; Schimmelpfennig, 1996), others try to quantify it (Morgan and Keith, 1995; Nordhaus, 1994). A number of papers try to place uncertainties in a decision analytic framework (see Kann and Weyant, 1999, for an overview). This paper places the decision analytic framework in the context of uncertainty.

Decision analysis is a subdiscipline of economics. Decision analysts develop tools that support public and private decision makers in structuring problems and finding and picking solutions. Raiffa (1970) and Schlaifer (1978) are excellent introductions to the field. Different tools have been developed for different situations. The nature of the uncertainty about a problem is an important criterion for choosing between tools. This paper investigates the nature of the uncertainty about climate change, and draws some preliminary conclusions about the applicability of cost-benefit analysis to greenhouse gas emission reduction.

Climatic Change **56:** 265–289, 2003.
© 2003 *Kluwer Academic Publishers. Printed in the Netherlands.*

Cost-benefit analysis (CBA) is a prominent decision analytic framework. In CBA, emissions are reduced so as to maximise welfare. Maddison (1995), Manne et al. (1995), Nordhaus (1991, 1992, 1993, 1994), Nordhaus and Yang (1996) and Peck and Teisberg (1992, 1994) apply CBA to the emission abatement, largely ignoring uncertainty. Eismont and Welch (1996), Kolstad, (1994, 1996), Leimbach (1996), Nordhaus and Popp (1997), Peck and Teisberg (1993, 1995), Ulph and Maddison (1997), Welsch (1995) apply various techniques of uncertainty analysis to (elements of) CBA. None of these authors wonders whether this is appropriate.

The main challenger of CBA is the safe minimum standard (SMS) approach (e.g., Pearce et al., 1996).[1] With SMS, emissions are reduced so that concentrations meet certain 'safe' standards, whilst emission abatement costs are not excessive. SMS is better known in climate change contexts as the safe corridor/landing approach (Alcamo and Kreileman, 1996a,b) or the tolerable windows approach (Dowlatabadi, 1999; Petschel-Held et al., 1999; Toth et al., 1997; Yohe, 1999).[2]

The current author is squarely in the CBA camp (Tol, 1997, 1999a–e). The main advantage of CBA is that it is internally consistent, founded on axioms of rational behaviour. Although policy makers are not always rational, I think policy advisors should be, and should seek the greatest good for the greatest number.

In practice, SMS are arbitrary.[3] They are typically set by a small group of researchers and policy makers, only a minority of whom are democratically elected. SMS are not based on polling people's preferences, as CBA is. Yet, SMS are the dominant decision analytic paradigm in climate change policy making.

In principle (though not as practiced in a climate change context), SMS have counterparts in formal decision analysis, such as 'minimax regret' and similar decision rules. Such rules are applicable in cases of large uncertainties and incomplete information. Indeed, the axioms underlying (expected) CBA fall apart if the uncertainties about either costs or benefits are infinite.[4] CBA is a practical form of welfare or utility theory. Uncertainty is an integral part of this theory. If the variance goes to infinity, alternatives can no longer be compared (as infinity minus infinity is indeterminate). On a more practical note, according to CBA, the carbon tax should be set equal to the certainty equivalent of the marginal costs of climate change. The certainty equivalent is some increasing function of the standard deviation of the marginal costs. Thus, if the variance is infinite, the optimal carbon tax is infinite too.

This paper tests whether the uncertainties about climate change are infinite, and thus whether CBA is an appropriate approach to climatic change. This is done by calculating the expectation and variance of the marginal costs of carbon dioxide emissions. This is one approach of a number of alternatives. Starrett (1988) suggests the use of risk-adjusted discount rates, while Lind (1992) advocates the use of certainty equivalents. Like the approach used here, these are approximate shortcuts to a full-blown welfare analysis under uncertainty; like the approach used here, they fall apart if the uncertainty is too large.

Testing for infinities looks like an impossible task. It is rather easy to build a model that has crucial variables with infinite variances. It is also rather easy to build a model with only finite variances. As climate change is a thing of the future, it is currently impossible to invalidate either type of model.

This paper follows a different route. I first review the conditions for finite uncertainties and their consequences for CBA (Section 2). After that, the paper takes a more empirical turn. I use a model that is constructed to be very regular (cf. Section 3). I use a model that was constructed to have finite variances (cf. Section 4). But, it has not. The reason is technical and model-dependent (cf. Section 5). This reason suggests a narrative (cf. Section 6), which I leave for the reader to judge whether it is credible or not (cf. Section 7).

The analysis is largely based on an approximation to a welfare analysis under uncertainty. However, Section 5 also presents some results of an analysis with lesser approximations. This suggests that other approximations of CBA under uncertainty – such as risk-adjusted discount rates and certainty-equivalent net benefits – would have run into similar problems. This analysis also shows that the question ‘is the uncertainty about climate change too large for expected cost-benefit analysis?’ is not answered with an unambiguous no. A more cynical interpretation would be that the found infinities are irrelevant. Again, I leave judgement to the reader (cf. Section 7).

2. Analytical Representation

Collard (1988) distinguishes between weak and strong catastrophes. An environmental problem is catastrophic if its impact I becomes infinitely large at some state of nature s

$$\lim_{s \to \infty} I(s) = \infty\,, \tag{1}$$

where the possible states of nature are ordered as to the size of the impact. A catastrophe is strong if the expected value of its impact, $\mathrm{E}I$, is infinite

$$\mathrm{E}I = \int_0^\infty f(s)I(s)\mathrm{d}s > M; \forall M < \infty\,, \tag{2}$$

where $f(s)$ denote the probability density function of s. For strong catastrophes, diminishing chances do not cancel growing impacts. A catastrophe is weak if the expected value of its impact, $\mathrm{E}I$, is finite

$$\mathrm{E}I = \int_0^\infty f(s)I(s)\mathrm{d}s < \infty\,. \tag{3}$$

Of course, catastrophes are either weak of strong. Condition (3) implies

$$\lim_{s \to \infty} f(s)I(s) = 0\,. \tag{4}$$

That is, a catastrophe is weak if the chance decreases faster than the associated impact increases. In the limit, probability times effect is zero. However, (4) does not imply (3), because (4) does not only need to converge to zero but it also needs to do so at a fast enough rate.

For cost-benefit analysis to be applicable, it is necessary that an uncertain outcome can be expressed as its certainty equivalent. This is only possible if the variance of the outcome is finite. Thus, a catastrophe needs not be weak, but very weak. A catastrophe is very weak if the variance of its impact, $\mathrm{Var}I$, is finite

$$\mathrm{Var}I = \int_0^\infty f(s)(I(s) - \mathrm{E}I)^2 \mathrm{d}s < \infty\,. \tag{5}$$

If the mean is infinite, then so is the variance; but not the other way around. Therefore, the set of weak catastrophes is a subset of the set of very weak catastrophes.

For weak catastrophes, condition (5) implies

$$\lim_{s\to\infty} f(s)I^2(s) = 0\,. \tag{6}$$

Again, (6) does not imply (5). In other words, (6) implies that the probability should decrease faster than the increase of the impact *squared*, a strong demand.

The impact of climate change is not instantaneous. Instead, we are interested in the expected value of the net present value, discounted at rate δ, of the impact over time t

$$\mathrm{ENPV}I = \int_0^\infty \int_0^\infty f(s)I(t,s)\mathrm{e}^{-\delta_s t}\mathrm{d}t\mathrm{d}s\,. \tag{7}$$

Arguably, larger impacts are more remote in time and less probable than smaller impacts. Thus, catastrophes are discounted in two ways, in time and in probability. The function I has to increase rapidly in either t or s to offset both time and probability discounting.[5]

However, the discount rate δ_s is a function of impact $I(t,s)$. The standard neoclassical formulation is

$$\delta_t = \rho + \eta g_t\,. \tag{8}$$

That is, the (time-dependent) discount rate δ is the pure rate of time preference ρ plus the growth rate of consumption g_t times the marginal elasticity of utility η. Large impacts negatively affect growth, and if this effect is large enough, the discount rate becomes negative.

If the discount rate becomes negative for a long time, the integral of Equation (7) diverges and the net present value of the impact becomes infinite. In that case, the catastrophe is strong. Recall that for cost-benefit analysis to be applicable, the catastrophe needs to be very weak.

Cost-benefit analysis assumes a single decision maker. In public policy, that decision maker is typically interpreted as a benevolent dictator, or a philosopher-king in Plato's sense. The decision maker aggregates the impact suffered by his subjects

$$\mathrm{ENPV}I^W = \int_0^\infty \int_0^\infty \sum_n w_{n,s} f_n(s) I_n(t,s) \mathrm{e}^{-\delta_{t,n,s} t} \mathrm{d}t \mathrm{d}s \, , \tag{9}$$

where w_n is the 'equity weight' attached to person n. One can also interpret social cost-benefit analysis as a search for potential Pareto improvements.

Fankhauser et al. (1997) show that, if impact I is expressed in monetary terms,[6] appropriate[7] equity weights may be

$$w_n = \frac{\bar{y}}{y_n} \, , \tag{10}$$

where y_n is per capita income and $\bar{y}$ is the average per capita income. So, should there be a positive chance that climate change drives per capita income to subsistence levels, then this is amplified by both the discount rate and the equity weight.[8]

Equation (10) rests on a number of assumptions. Two crucial ones are the shape of the regional welfare function, and the shape of the global welfare function (which has regional welfare as its attributes). In (10), the assumption is that regional welfare is the natural logarithm of per capita income, and that global welfare is the sum of regional welfare. Alternatively, if global welfare is the product of regional welfare, and regional welfare is given by a function with constant relative risk aversion, then (10) would also result. Higher risk aversion, or a greater emphasis on the plight of the poor would result in higher equity weights for the poor than given by (10) – and more rapid divergence of (9). See Fankhauser et al. (1997, 1998) for derivations and results.

To sum up the above, CBA is applicable to problems that are not catastrophic or very weakly catastrophic. This condition is violated if 'impact times probability times weight' does not fall fast enough. High impact scenarios may have a low probability, but they do get a high weight – both through the discount rate and the equity weight.

The final step in the analysis is this. Suppose there are a finite number of models, each with a plausible representation of reality. Each model has an expected value of the (net present value of the equity weighted) impact and a variance. The true expectation and variance (assuming independence between the models) are:

$$\mathrm{E}I = \sum_m p_m \mathrm{E}I_m ; \mathrm{Var}I = \sum_m p_m^2 \mathrm{Var}I_m \, , \tag{11}$$

where p_m is the chance of model m being true. If only one model has an infinite variance (mean), then the true variance (mean) is also infinite.[9]

In the next sections, the net present, equity weighted impact is calculated for one particular model. Its variance is very large, probably infinite. If this model has some chance of being realistic, then the real variance is infinite too, and expected cost-benefit analysis cannot be applied to climate change (according to the rules of CBA). The next sections also argue at length that the model used is not implausible.

3. The Model

The *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*) serves various purposes. It was primarily developed to analyse efficient emission reduction strategies for various groups of countries (Tol et al., 1995; Tol, 1997, 1999a,b). Following the political agenda, *FUND* is now regularly used for cost-effectiveness analysis as well (Tol, 1999b,c), including multiple greenhouse gases (Tol et al., in press). Uncertainty (Tol, 1995, 1999d) and impacts (Tol, 1995, 1996, 1998a, 1999e) have also been important considerations. This paper returns to the question about the uncertainty of impacts, using version 2.0 of *FUND*. Version 2.0 is the same as versions 1.6 to 1.9, which were used in the above papers, except for its impacts module, which is completely different (see Tol, 2001a,b).

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations, specified for nine major world-regions, namely OECD-America, OECD-Europe, OECD-Pacific, Central and Eastern Europe and the former Soviet Union, Middle East, Latin America, South and South-East Asia, Centrally Planned Asia, and Africa.

The model runs from 1950 to 2200, in time steps of a year. The prime reason for extending the simulation period into the past is the necessity to initialise the climate change impact module. In *FUND*, some climate change impacts are assumed to depend on the impact of the year before, so as to reflect the process of adaptation to climate change. Without a proper initialisation, climate change impacts are thus misrepresented in the first decades. Scenarios for the period 1950–1990 are based on historical observation, viz. the *IMAGE* 100-year database (Battjes and Goldewijk, 1994). The period 1990–2100 is based on the FUND scenario, which lies somewhere in between the IS92a and IS92f scenarios (Leggett et al., 1992). Note that the original IPCC scenarios had to be adjusted to fit *FUND*'s nine regions and yearly time-step. The period 2100–2200 is based on extrapolation of the population, economic and technological trends in 2050–2100, that is, a gradual shift to a steady state of population, economy and technology. The model and scenarios are so far extrapolated that the results for the period 2100–2200 are not to be relied upon. This period is only used to provide the forward-looking agents in *FUND* with a proper perspective.

The exogenous scenarios concern economic growth, population growth, urban population, autonomous energy efficiency improvements, decarbonisation of the energy use, nitrous oxide emissions, and methane emissions.

Table I

Parameters of Equation (11)

Gas	α [a]	β [b]	Pre-industrial concentration
Methane (CH_4)	0.3597	1/8.6	790 ppb
Nitrous oxide (N_2O)	0.2079	1/120	285 ppb

[a] The parameter α translates emissions (in million metric tonnes of CH_4 or N_2O) into concentrations (in parts per billion by volume).

[b] The parameter β determines how fast concentrations return to their pre-industrial (and assumedly equilibrium) concentrations; $1/\beta$ is the atmospheric life-time (in years) of the gases.

Incomes and population are perturbed by the impact of climate change. Population falls with climate change deaths, resulting from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to affect only the elderly, non-reproductive population; heat stress only affects urban population. Population also changes with climate-induced migration between the regions. Economic impacts of climate change are modelled as deadweight losses to disposable income. Scenarios are only slightly perturbed by climate change impacts, however, so that income and population are largely exogenous.

The endogenous parts of *FUND* consist of carbon dioxide emissions, the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, and the impact of climate change on coastal zones, agriculture, extreme weather, natural ecosystems and malaria.

Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted:

$$C_t = C_{t-1} + \alpha E_t - \beta \left(C_{t-1} - C_{pre}\right) , \tag{12}$$

where C denotes concentration, E emissions, t year, and *pre* pre-industrial. Table I displays the parameters for both gases. Equation (14) is a simplified representation of the relevant atmospheric chemistry. Particularly, the atmospheric life-time is not constant, but depends on the concentrations and emissions of other chemical species.

The carbon cycle is a five-box model:

$$Box_{i,t} = \rho_i Box_{i,t-1} + 0.000471 \alpha_i E_t \tag{13a}$$

with

$$C_t = \sum_{i=1}^{5} \alpha_i Box_{i,t} , \tag{13b}$$

where α_i denotes the fraction of emissions E (in million metric tonnes of carbon) that is allocated to box i (0.13, 0.20, 0.32, 0.25 and 0.10, respectively) and ρ the decay-rate of the boxes ($\rho = \exp(-1/\text{lifetime})$, with life-times infinity, 363, 74, 17 and 2 years, respectively). Thus, 13% of total emissions remains forever in the atmospheric, while 10% is – on average – removed in two years. The model is due to Maier-Reimer and Hasselmann (1987), its parameters to Hammitt et al. (1992). It assumes, incorrectly, that the carbon cycle is independent of climate change. Carbon dioxide concentrations are measured in parts per million by volume.

Radiative forcing for carbon dioxide, methane and nitrous oxide are based on Shine et al. (1990). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by radiative forcing *RF*), with a life-time of 50 years. In the base case, global mean temperature rises in equilibrium by 2.5 °C for a doubling of carbon dioxide equivalents, so:

$$T_t = \left(1 - \frac{1}{50}\right) T_{t-1} + \frac{1}{50}\frac{2.5}{6.3 \cdot \ln(2)} RF_t \ . \tag{14}$$

Global mean sea level is also geometric, with its equilibrium determined by the temperature and a life-time of 50 years. These life-times result from a calibration to the best guess temperature and sea level for the IS92a scenario of Kattenberg et al. (1996). The climate impact module is fully described in Tol (1999f,g). The impact module has two units of measurement: people and money. People can die prematurely and migrate. These effects, like all other impacts, are monetised. Damage can be due to either the rate of change or the level of change. Benchmark estimates can be found in Table II; more underlying assumptions are given in the Appendix. Impacts of climate change on energy consumption, agriculture and cardiovascular and respiratory diseases explicitly recognise that there is a climate optimum. A mix of factors, including physiology and behaviour, determines the climate optimum. Impacts are positive or negative depending on whether climate is moving to or away from that optimum climate. Impacts are larger if the initial climate is further away from the optimum climate. The optimum climate concerns the potential impacts. Actual impacts lag behind potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to the new climate are always negative.

Other impacts of climate change, on coastal zones, forestry, unmanaged ecosystems, water resources, malaria, dengue fever and schistosomiasis, are modelled as simple power functions. Impacts are either negative or positive, but do not change sign.

Vulnerability changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanisation) and ecosystems and health (with higher values from higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector-borne diseases (with improved health care).

Table II

Estimated impacts of a 1 °C increase in the global mean temperature. Standard deviations are given in brackets

	Billion dollar		Percent of GDP	
OECD-A	175	(107)	3.4	(2.1)
OECD-E	203	(118)	3.7	(2.2)
OECD-P	32	(35)	1.0	(1.1)
CEE and fSU	57	(108)	2.0	(3.8)
ME	4	(8)	1.1	(2.2)
LA	–1	(5)	–0.1	(0.6)
S and SEA	–14	(9)	–1.7	(1.1)
CPA	9	(22)	2.1	(5.0)
AFR	–17	(9)	–4.1	(2.2)

Source: Tol (2001a).

All parameters in *FUND* are uncertain, and to each of them a probability density function was assigned. Table III shows the assumptions, which are more based on my judgement than on anything else.

4. The Variance of Variables in the Long Run

The main question of this paper is whether or not the variance of the impact of climate change is finite. This is a tricky question. We do not observe the impacts. Most impacts will occur in the future. We do not have a systematic observation programme for current and past impacts. So, we have to rely on imperfect models. The second problem is that we have only a finite sample size, whether our observations are from reality or from models. Finite samples have finite variances. However, if the true variance is infinite, then the sample variance should grow with sample size.

That is the test I use in this paper. *FUND* is used in a Monte Carlo analysis with a large sample size (1000 runs). The variance of crucial variables is plotted for small but growing subsamples. If the variance grows with sample size, we suspect the true variance to be infinite. If not, we accept that it is finite.

Figure 1 shows the results for world average per capita income in the years 2050, 2100, 2150 and 2200, for sample sizes ranging from 100 to 1000. The uncertainty is growing over time, but there are no clear upward trends. It would be surprising if there was an upward trend, because per capita income is bounded from below (at zero) while there are no positive feedback mechanisms in the model (and probably in reality) that would propel income to infinity.

Figure 2 shows the standard deviations of the global mean temperature as a function of the sample size. The uncertainty is large and growing over time, but

Table III
Assumptions in the Monte Carlo analysis

Parameter	Distribution	Mean	Standard deviation
Scenarios			
Population growth	Normal	Scenario	Grows over time
Economic growth	Normal	Scenario	Grows over time
AEEI	Normal	Scenario	Grows over time
ACEI	Normal	Scenario	Grows over time
Urban population	Normal	Scenario	Grows over time
Methane emissions	Normal	Scenario	Grows over time
Nitrous oxide emissions	Normal	Scenario	Grows over time
Climate change			
Life-time carbon dioxide	Normal	363; 74; 17; 2	182; 37; 9; 1
Life-time methane	Triangular	10.2	1.3
Life-time nitrous oxide	Triangular	130	15
Climate sensitivity	Gamma	2.85	1.00
Sea level sensitivity	Gamma	0.36	0.15
Climate response time	Triangular	58	16
Sea level response time	Triangular	58	16
Impacts			
Sensitivity to level of climate change	Normal	See appendix	See appendix
Sensitivity to rate of climate change	Normal[a]	See appendix	See appendix
Sensitivity to sea level	Normal[a]	See appendix	See appendix
Non-linearity			
Agriculture	Normal[a]	2.0	0.5
Forestry	Normal[a]	1.0	0.5
Water	Normal[a]	1.0	0.5
Space heating	Normal[a]	1.0	0.5
Space cooling	Normal[a]	1.0	0.5
Vector-borne diseases	Normal[a]	1.0	0.5
Vector-borne diseases (income)	Normal[a]	1.0	0.5
Adaptation time			
Agriculture	Normal[a]	10	2.5
Immigration	Normal[a]	3	1
Adaptation speed			
Dryland loss	Exponential	0.1	0.1
Wetland loss	Exponential	0.1	0.1
Emigration	Exponential	0.1	0.1
Income elasticity			
Agriculture	Normal[a]	0.31	0.15
Forestry	Normal[a]	0.31	0.20
Water	Normal[a]	0.85	0.15

Table III

(Continued)

Parameter	Distribution	Mean	Standard deviation
Space heating	Normal[a]	0.80	0.20
Space cooling	Normal[a]	0.80	0.20
Population over 65	Normal[a]	0.25	0.08
Valuation			
Value of a statistical life	Normal a	200	100
Value of ecosystem change	Normal[a]	50	50
Standard income	Normal[a]	20,000	10,000
Miscellaneous			
Income threshold vector borne disease	Normal	3100	100 in 2000 plus 10 each year
Emigration costs	Normal[a]	3.0	1.5
Immigration costs	Normal[a]	0.4	0.2
Immigration intake	Stand. normal		
Cardiovascular limit	Normal[a]	0.05	0.02
Elasticity base cardiovascular disease to p.c. income	Normal[a]	0.000259	0.000096
Elasticity base respiratory disease to p.c. income	Normal[a]	0.000016	0.000005

[a] Knotted at zero.

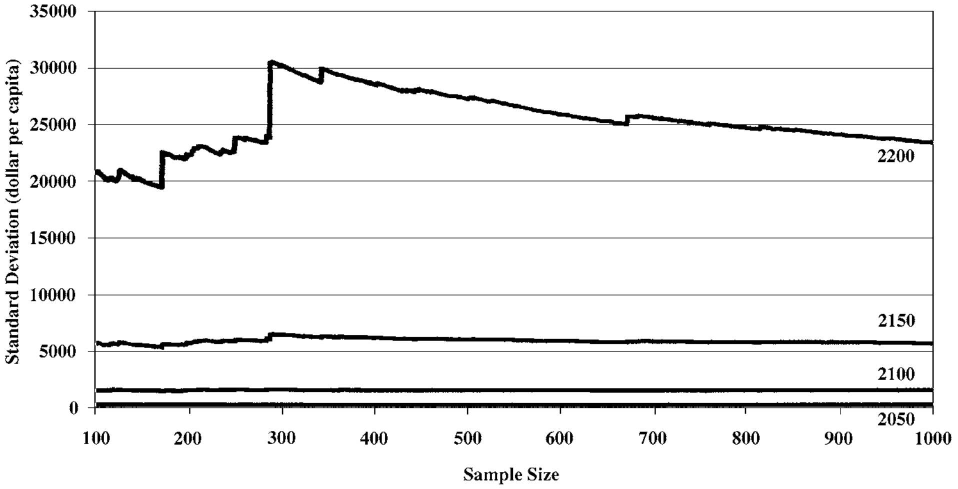

Figure 1. The standard deviation of the average world per capita income in the years 2050, 2100, 2150 and 2200 as a function of the sample size of the Monte Carlo analysis.

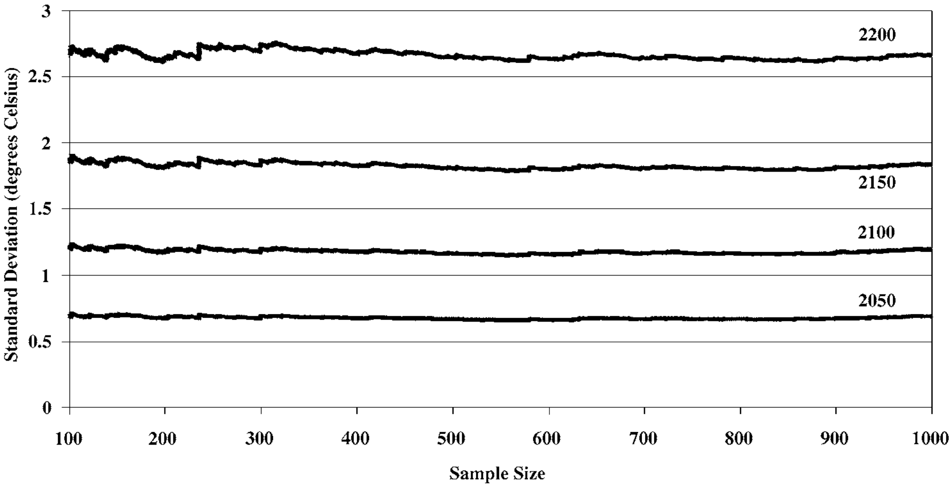

Figure 2. The standard deviation of the global mean temperature in the years 2050, 2100, 2150 and 2200 as a function of the sample size of the Monte Carlo analysis.

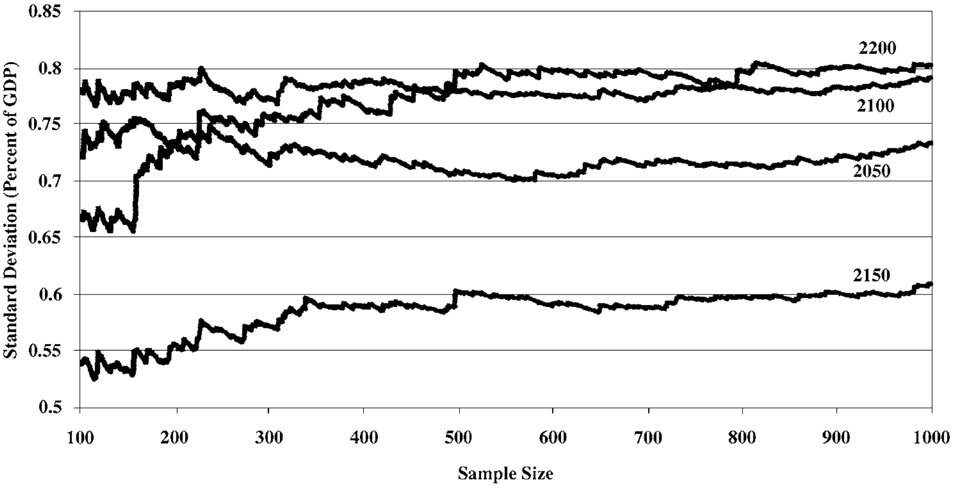

Figure 3. The standard deviation of the global monetized impact of climate change, as a percentage of world GDP, in the years 2050, 2100, 2150 and 2200 as a function of the sample size of the Monte Carlo analysis.

the uncertainty is remarkable independent of sample size. According to *FUND*, the uncertainty about the global mean temperature is finite.

Figure 3 shows the standard deviation of climate change impacts, normalised with GDP, as a function of sample size. For sample sizes up to 1000, there may be a small upward trend in the standard deviation. However, it appears that it just takes a lot of observations to estimate the standard deviation with some reliability. For sample sizes between 8000 and 10,000, the standard deviation is constant.

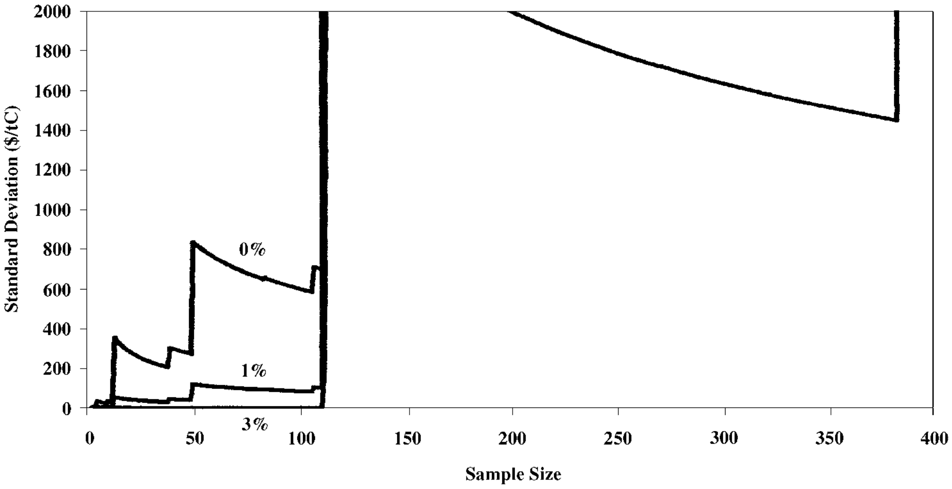

Figure 4. The standard deviation of the marginal costs of carbon dioxide emissions, in dollars per tonne of carbon, for pure rates of time preference of 0, 1, and 3% as a function of the sample size of the Monte Carlo analysis.

The conclusion of this section is not surprising. Although the uncertainties in *FUND* are large, they are finite. That is because the model was constructed that way.

5. The Variance of the Net Present Marginal Impact of Climate Change

In a cost-benefit analysis, the total impacts of climate change matter less than the marginal net present costs. The marginal net present costs are the incremental costs of a small increase in emissions, discounted to the time the decision about emission reduction is made. Here, marginal costs are approximated by contrasting the impacts of the base scenario and the perturbed scenario, in which the perturbed scenario has slightly higher emissions in the period 2000–2009. The difference in impacts is normalised by the difference in emissions, and discounted to 2000 (Tol, 1999; Tol and Downing, 2000).

Figure 4 displays the uncertainty about the marginal costs of carbon dioxide emissions. Recall that the uncertainty about the total costs of climate change is finite. The uncertainty about the marginal costs is not, however. The standard deviation increases, with discrete jumps, with the sample size. This is not because of the uncertainty about the impact, which is finite, but because of the uncertainty about per capita income. The marginal costs are calculated by taking the difference between two almost identical impact scenarios. The uncertainty about the difference of two finite uncertainties is finite.

The uncertainty about the marginal costs explodes because of the per capita growth rate. The uncertainty about per capita income is finite. If per capita income

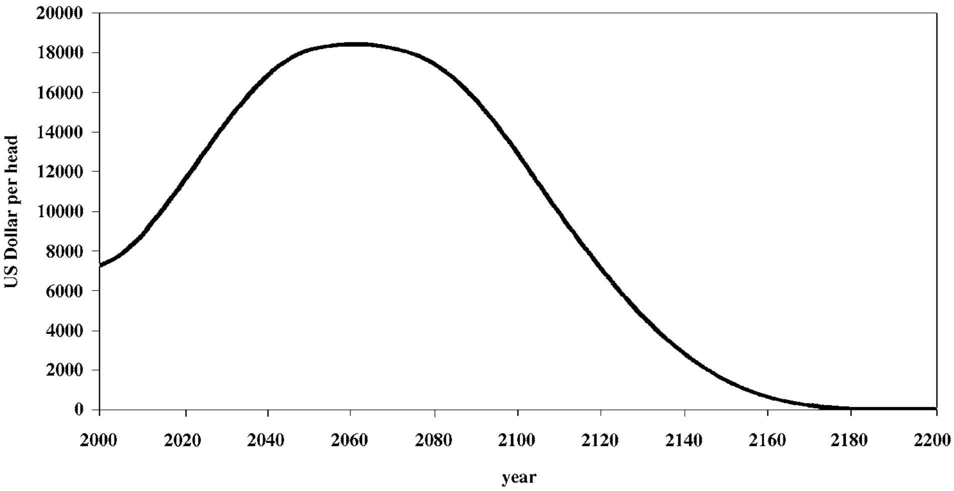

Figure 5. Per capita income in Central and Eastern Europe and the former Soviet Union in run 383 of the Monte Carlo analysis.

falls rapidly in a small number of scenarios, the uncertainty is still finite, because per capita income is bounded from below at zero. However, if income falls to subsistence levels, the discount factor goes to infinity, taking the marginal costs with it.

This is what happens in run 383 of the Monte Carlo analysis. Figure 5 displays, for that particular run, the per capita income in Central and Eastern Europe and the former Soviet Union. Figure 6 displays the per capita income growth rate, and the resulting discount factor. In this run, water gets so scarce in this region that the economy collapses.[10]

There is another factor at play. If a region's economy collapses, but not the world economy, that region's impacts would hardly count in the global aggregate impact, if that aggregate is calculated by summing the regional impacts dollar per dollar. I use a different aggregation method, however. Instead of adding dollars, I add the utility equivalent of dollars. In this specific form of equity weighting, regional impacts are first multiplied by the ratio of world and regional per capita income before they are added (Fankhauser et al., 1997, 1998). Figure 6 also displays the regional weight factor. This grows even faster than the discount factor.

The above argument is about the uncertainty about the marginal costs of carbon dioxide emissions. An infinite variance is sufficient to render CBA inapplicable. However, not only the variance, but also the mean is infinite, for the same reasons. See Table IV.

The above argument is all about the marginal net present costs of climate change. This is one of the crucial variables in a cost-benefit analysis. However, the monetary value of something is nothing more than the first derivative of the utility function to that something, normalised to money. Essentially, this is a local

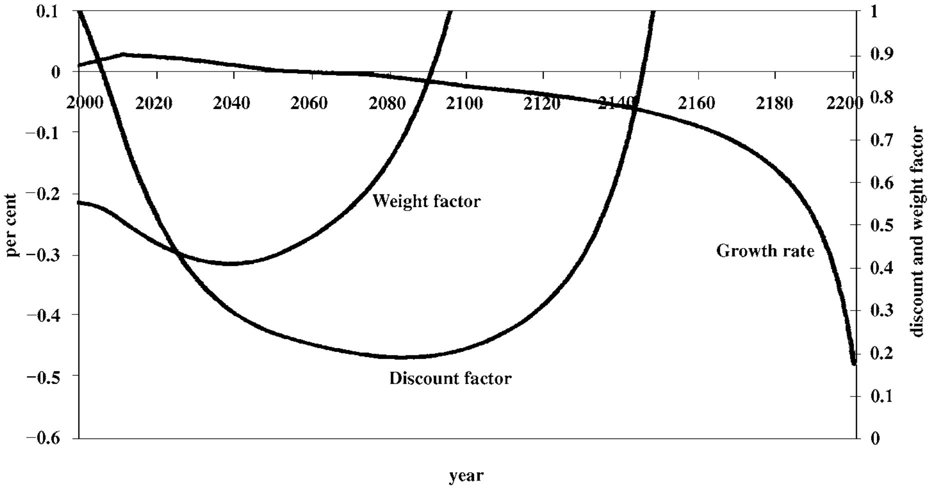

Figure 6. The growth rate, discount factor, and weight factor in Central and Eastern Europe and the former Soviet Union in run 383 of the Monte Carlo analysis.

Table IV

The marginal costs of carbon dioxide emissions (in $/tC), for four time horizons (2050, 2100, 2150 and 2200), three rates of pure time preference (0, 1 and 3%) and two ways of aggregation (SS: simple sum and EW: equity-weighted)

	0%		1%		3%	
	SS	EW	SS	EW	SS	EW
2050	3.2	3.2	2.6	2.4	1.8	1.4
	(5.2)	(1.5)	(4.0)	(1.1)	(2.5)	(0.6)
2100	5.9	8.8	3.9	5.1	2.1	2.1
	(3.9)	(5.8)	(3.0)	(3.1)	(2.2)	(1.0)
2150	11.4	24.9	5.5	9.4	2.2	2.4
	(7.0)	(96.3)	(3.1)	(24.2)	(2.1)	(2.2)
2200	25.0	∞	7.7	∞	2.3	∞
	(57.9)	(∞)	(9.1)	(∞)	(2.1)	(∞)

approximation, and local approximations should be interpreted with care if taken to extremes. In *FUND*, utility is logarithmic, so we value a small change in consumption with inverse of consumption in the base case. The equity weights – Equation (10) – do the same thing. Is it the approximation that drives the result to infinity?

Figure 7 displays the standard deviation of the net present welfare differences due to a small change in emissions; the welfare of Central and Eastern Europe and the former Soviet Union and the world is shown as a function of the Monte Carlo

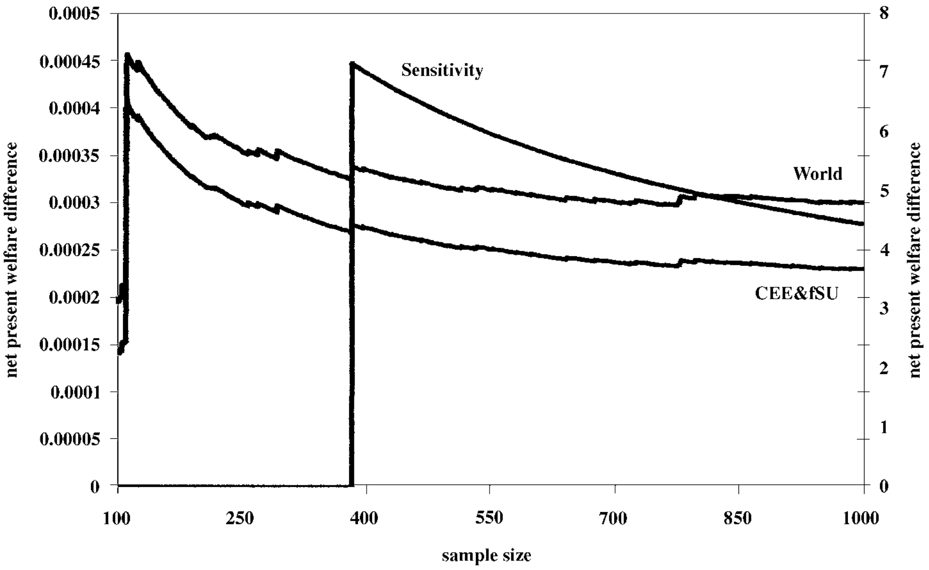

Figure 7. The standard deviation of the marginal net present welfare losses of carbon dioxide emissions, in dollars per tonne of carbon for a pure rates of time preference of 1% as a function of the sample size of the Monte Carlo analysis; displayed are the marginal welfare losses of Central and Eastern Europe and the former Soviet Union (CEE and fSU) and the world; also displayed, on the right axis, is a sensitivity analysis assuming that the economic collapse in the perturbed scenario occurs one year earlier.

sample size. Figure 7 suggests that the uncertainty about the marginal welfare is finite, even though the uncertainty about its approximation, marginal costs, is not. The reason lies in yet another approximation. In run 383, the economies of Central and Eastern Europe and the former Soviet Union hit subsistence levels in the year 2163 in both the base scenario and the perturbed scenario. From then on, welfare is set to the numerical minimum in both scenarios, and the difference is zero. Had subsistence levels been hit a year earlier in the perturbed scenario than in the base scenario, the standard deviation would have sky-rocketed; Figure 7 illustrates this.

One can have various views on this. On the one hand, a little bit of emission reduction will not help to avoid the disaster from happening, it only postpones it a bit. This is a small gain, and should be counted as such. The infinite variance of the marginal net present cost should be dismissed as an approximation error, and the analysis should proceed with welfare differences directly, and at a course resolution. On the other hand, the infinite variance of the marginal costs warns that something is dramatically wrong in the baseline, and one should pursue greenhouse gas emission reduction at least up to the point that that wrong is corrected.

6. Could the Variance Be Infinite?

Suppose that climate change is worse than expected. Suppose that the impacts of climate change are worse than expected. Suppose that vulnerability is larger than expected. Suppose that a lot of money needs to be spent on building sea walls and curing malaria. Suppose that agricultural yields are disappointing and storms and floods damage roads and houses. In a fragile economy, this means that economic growth is halted. It means that investment and past savings are diverted from enhancing productivity and preventing further havoc to restoring damage. It means that the economy grows more fragile. It means that climate change can do even more damage, making the economy yet more fragile.

Can climate change cause a poverty trap? Recurring natural disasters can definitely contribute to poverty traps (Burton et al., 1993). Estimates of the impact of climate change suggest that they can be worth a couple of percent of GDP, particularly in poor regions. Climate change seems likely to cause poverty traps in some places, and with some non-negligible change at a regional scale.

If economic growth becomes negative, then the discount rate becomes small. If economic growth is substantially negative, then the discount rate becomes negative as well. If the discount rate is negative, the discount factor begins to grow, placing relatively more weight on the bad years. If the discount factor grows large enough, the net present value may diverge.

If globally aggregate impacts correct in some way for disparate per capita incomes across the globe, e.g., via the equity weighting proposed by Fankhauser et al. (1997, 1998), the net present value diverges even faster, because higher weights are placed on poorer countries.

7. Discussion and Conclusion

This paper is concerned with the question whether the uncertainty about climate change is too large to apply cost-benefit analysis to the question of emission reduction.

CBA can be applied to individual scenarios provided that critical variables (e.g., marginal benefits) are finite. Low, perhaps negative discount rates (a possible consequence of climate change) emphasize large negative consequences of climate change.

Expected CBA can be applied only if the probabilities of catastrophic scenarios are so low that the *variance* of the expected outcome is finite.

One can test whether or not the variance is infinite by plotting the variance as a function of a growing sample size in a Monte Carlo experiment.

The numerical results in Section 5 show that the uncertainty about the net present marginal costs of climate change is infinite in the case in *FUND*. Sections 3 and 4 show that *FUND* is a standard model, not set up to yield extreme results.

However, even in this model, there are circumstances in which climate change impacts become very large. Section 6 argues that such circumstances are not beyond imagination. The effects of very large, negative impacts on the net present value are amplified by the discount rate and perhaps by equity weighting. If, instead, one were to use a discount rate that is not sensitive to economic shrink or large risks, or if one were to ignore climate change impacts to the worst off, then the uncertainty about the marginal net present damage is finite.

One cannot dismiss this result as the outcome of an extreme scenario in a maverick model. Per Section 2, what matters is whether there is a non-zero chance that the model and scenario reflect reality. If this is the case, then *FUND* dominates all other models.

The bottom line of all this is that it seems as if the uncertainty about climate change is too large to apply cost-benefit analysis.

One can also interpret the results differently. The infinite uncertainty arises from very large impacts that are present in both base and policy scenarios. Therefore, one could argue that this should not influence our evaluation of the policy intervention. In that case, expected cost-benefit analysis is still a valid tool, provided that the uncertainty about the difference between the base and policy scenarios is finite. Section 6 shows that it is very hard to test whether this is the case; particularly, the result depends on the resolution of the model.

Policy implications cannot be drawn from this result. Although climate change may have dramatic impacts, the analysis in this paper does not include what it takes to avoid this. The implications of greenhouse gas emission reduction may be unacceptable too (cf. Tol, 1999d).

By the same token, the methodological implications are unclear as well. If the uncertainty about the costs of emission abatement is finite, regardless of how ambitious the emission reduction programme might need to be, then one would want to cut emissions at least to that point at which the variance of the climate change impact becomes finite. A cost-benefit analysis can then be applied to see if emissions need to be cut any further.[11]

If there are also infinitely large uncertainties at the emission reduction side, then decision analysis could resort to techniques such as minimax regret, safe minimum standards and tolerable windows.

It is clear, however, that climate change tests decision analytic tools to the extreme. The results in this paper show that economic analyses of climate policy should be interpreted with more than the usual care.

Acknowledgements

An early version of this paper was delivered as the HMA Jansen Lecture at the Institute for Environmental Studies, Amsterdam; the paper was also presented at the Workshop Uncertainty and Normativity, University of Stuttgart, February 21–22,

2002. Gary Yohe and three anonymous referees gave excellent feedback to previous versions. The EU DG Research Environment and Climate Programme through the European Forum on Integrated Environmental Assessment (ENV4-CT97-045), the U.S. National Science Foundation through the Center for Integrated Study of the Human Dimensions of Global Change (SBR-9521914) and the Michael Otto Foundation for Environmental Protection provided welcome financial support. All errors and opinions are mine.

Appendix. Assumptions in the Climate Change Impact Module

Table A.I
Impacts of climate change on agriculture (from Tol, 1999b)

Region	Rate of change (%GAP/0.04 °C)		Level of change (%GAP/1 °C)		Optimal temperature (Δ °C wrt 1990)	
OECD-A	–0.021	(0.031)	0.398	(0.530)	2.29	(1.32)
OECD-E	–0.026	(0.025)	0.838	(0.450)	0.45	(0.50)
OECD-P	–0.016	(0.038)	0.321	(0.648)	2.71	(0.33)
CEE and fSU	–0.028	(0.027)	1.060	(0.452)	2.96	(0.43)
ME	–0.017	(0.011)	0.233	(0.193)	3.08	(0.49)
LA	–0.022	(0.015)	0.221	(0.280)	2.14	(0.26)
S and SEA	–0.022	(0.007)	0.253	(0.132)	2.16	(0.33)
CPA	–0.023	(0.023)	1.239	(0.403)	3.41	(1.01)
AFR	–0.012	(0.006)	0.189	(0.111)	3.00	(0.48)

Table A.II
Impact of a 1 °C warming on current day forestry, water, heating, and cooling, in millions of U.S. dollars (from Tol, 1999b)

Region	Forestry		Water		Heating		Cooling	
OECD-A	218	(24)	–3	(3)	22	(22)	–11	(11)
OECD-E	134	(16)	–2	(2)	13	(13)	–20	(20)
OECD-P	93	(20)	–0	(0)	7	(7)	–1	(1)
CEE and fSU	–136	(17)	–76	(76)	46	(46)	–19	(19)
ME	0	(0)	–1	(1)	8	(8)	–1	(1)
LA	–10	(2)	–1	(1)	3	(3)	–2	(2)
S and SEA	140	(34)	–2	(2)	4	(4)	–4	(4)
CPA	0	(0)	2	(2)	17	(17)	–12	(12)
AFR	0	(0)	–2	(2)	0	(0)	–5	(5)

Table A.III

Additional deaths due to vector-borne diseases for a 1 °C global warming (from Tol, 1999b)

Region	Malaria		Schistosomiasis		Dengue fever	
OECD-A	0	(0)	0	(0)	0	(0)
OECD-E	0	(0)	0	(0)	0	(0)
OECD-P	0	(0)	0	(0)	0	(0)
CEE and fSU	0	(0)	0	(0)	0	(0)
ME	155	(112)	–64	(13)	0	(0)
LA	1,101	(797)	–114	(22)	0	(0)
S and SEA	8,218	(5949)	–116	(3)	6,745	(1,171)
CPA	0	(0)	–128	(25)	393	(68)
AFR	56,527	(40,919)	–503	(99)	343	(60)

Table A.IV

Additional deaths (in thousands) due to cardiovascular and respiratory diseases for a 1 °C global warming (from Tol, 1999b)

Region	Cardiovascular – cold		Cardiovascular – heat		Respiratory	
OECD-A	–64.4	(4.4)	11.4	(5.9)	3.0	(9.7)
OECD-E	–99.8	(2.6)	11.7	(4.0)	–2.8	(5.7)
OECD-P	–13.1	(2.2)	3.5	(2.8)	1.0	(4.8)
CEE and fSU	–87.5	(5.2)	10.7	(4.4)	4.5	(11.0)
ME	–8.9	(1.3)	2.5	(0.4)	9.9	(2.6)
LA	–20.0	(3.5)	8.1	(1.8)	11.1	(7.0)
S and SEA	–63.8	(16.9)	17.5	(2.9)	141.2	(34.1)
CPA	–103.4	(21.7)	24.3	(4.6)	62.8	(44.4)
AFR	–18.2	(3.0)	4.7	(0.5)	24.8	(6.0)

Table A.V

Impact of a one metre sea level rise (from Tol, 1999b)

	Level prot. %	Dryland loss 10^3 km^2		Dryland value 10^6 \$/km^2		Wetland loss 10^3 km^2		Wetland value 10^6 \$/km^2		Protection costs 10^9 \$		Emigrants 10^6	
OECD-A	0.77	4.8	(2.4)	1.3	(0.6)	12.0	(8.6)	5.4	(2.7)	83	(74)	0.13	(0.07)
OECD-E	0.86	0.7	(0.4)	13.1	(6.6)	4.0	(2.3)	4.3	(2.2)	136	(45)	0.22	(0.10)
OECD-P	0.95	0.3	(0.4)	13.7	(6.7)	1.0	(1.1)	5.9	(2.9)	63	(38)	0.04	(0.02)
CEE and fSU	0.93	1.2	(2.7)	0.9	(0.5)	0.0	(0.0)	2.9	(1.5)	53	(50)	0.03	(0.03)
ME	0.30	0.6	(1.2)	0.5	(0.3)	0.0	(0.0)	1.3	(0.7)	5	(3)	0.05	(0.08)
LA	0.86	7.8	(7.1)	0.3	(0.2)	50.2	(36.4)	0.9	(0.5)	147	(74)	0.71	(1.27)
S and SEA	0.93	9.3	(9.6)	0.5	(0.3)	54.9	(48.0)	0.3	(0.2)	305	(158)	2.30	(1.40)
CPA	0.93	8.4	(15.1)	0.3	(0.2)	15.6	(17.1)	0.2	(0.1)	171	(126)	2.39	(3.06)
AFR	0.89	15.4	(18.4)	0.4	(0.2)	30.8	(14.8)	0.4	(0.2)	92	(35)	2.74	(2.85)

Notes

[1] See Lempert et al. (1996) for a further alternative.

[2] SMS are often combined with cost-effectiveness analysis (Manne and Richels, 1996, 1998; Peck and Teisberg, 1996), also under uncertainty (Manne and Richels, 1995; Yohe, 1997; Yohe and Wallace, 1996).

[3] As noted above, SMS may result from formal welfare analysis. See, for example, Woodward and Bishop (1997).

[4] Besides expected cost-benefit analysis, there is also scenario-based cost-benefit analysis. In expected cost-benefit analysis, the assumed decision maker is uncertain about future developments. She attaches probabilities to each possible future, evaluates the costs and benefits, and optimises the probability-weighted cost-benefit balance. In scenario-based cost-benefit analysis, the assumed decision maker knows the future. Given this single future, she assesses costs and benefits, and optimises their balance. The analyst, however, is uncertain about what the decision maker knows or assumes. The analyst therefore studies the decision maker under various scenarios of her knowledge. The analyst may even attach probabilities to these scenarios, and calculate the expected behaviour. (This is not the same as expected cost-benefit analysis – exp max $\neq$ max exp – as both operators are non-linear.) Expected cost-benefit analysis is the usual approach in decision analysis, and seems the more appropriate for climate change policy analysis. Throughout the paper, cost-benefit analysis is meant as expected cost-benefit analysis.

[5] Equation (7) should be extended to the variance as in (5) and (6). This implies an unnecessary complication of the notation, however, without adding much insight.

[6] Recall that our argument for the discount rate also assumes that the impact is measured in money.

[7] That is, consistent with welfare theory – see below.

[8] Note that, if the decision maker adds monetary impacts rather than welfare impacts, the catastrophic impact on a small part of the population is essentially disregarded. Monetary impacts are to a large extent determined by ability to pay.

[9] If there are an infinite number of models, then a non-negligible fraction of all models would have to have an infinite variance (mean).

[10] I also ran the Monte Carlo analysis without climate change so as to verify that the economic collapse is indeed climate-change induced.

[11] This implicitly assumes that mitigation is the only way to avoid large climate change impacts. Adaptation may be an alternative. *FUND* does not allow for international assistance to alleviate climate change damages.

References

Alcamo, J. and Kreileman, G. J. J.: 1996a, ‘Emission Scenarios and Global Climate Protection’, *Global Environ. Change* **6** (4), 305–334.

Alcamo, J. and Kreileman, G. J. J.: 1996b, *The Global Climate System: Near Term Action for Long Term Protection*, 481508001, RIVM, Bilthoven, pp. 1–17.

Batjes, J. J. and Goldewijk, C. G. M.: 1994, *The IMAGE 2 Hundred Year (1890–1990) Database of the Global Environment (HYDE)*, 410100082, RIVM, Bilthoven.

Burton, I., Kates, R. W., and White, G. F.: 1993, *The Environment as Hazard*, 2nd edn., The Guilford Press, New York.

Collard, D.: 1988, ‘Catastrophic Risk, or: The Economics of Being Scared’, in Collard, D., Pearce, D. W., and Ulph, D. (eds.), *Economics, Growth and Sustainable Environments: Essays in Memory of Richard Lecomber*, MacMillan, New York.

Dowlatabadi, H.: 1999, ‘Climate Change Thresholds and Guardrails for Emissions’, *Clim. Change* **41** (3–4), 297–301.

Eismont, O. and Welsch, H.: 1996, ‘Optimal Greenhouse Gas Emissions under Various Assessments of Climate Change Ambiguity’, *Environ. Resour. Econ.*

Fankhauser, S., Tol, R. S. J., and Pearce, D. W.: 1997, ‘The Aggregation of Climate Change Damages: A Welfare Theoretic Approach’, *Environ. Resour. Econ.* **10**, 249–266.

Fankhauser, S., Tol, R. S. J., and Pearce, D. W.: 1998, ‘Extensions and Alternatives to Climate Change Impact Valuation: On the Critique of IPCC Working Group III’s Impact Estimates’, *Environment and Development Economics* **3**, 59–81.

Hammitt, J. K.: 1995, ‘Outcome and Value Uncertainty in Global-Change Policy’, *Clim. Change* **30**, 125–145.

Hammitt, J. K., Lempert, R. J., and Schlesinger, M. E.: 1992, ‘A Sequential-Decision Strategy for Abating Climate Change’, *Nature* **357**, 315–318.

Harvey, L. D. D.: 1996a, ‘Development of a Risk-Hedging CO_2-Emission Policy, Part I: Risks of Unrestrained Emissions’, *Clim. Change* **34**, 1–40.

Harvey, L. D. D.: 1996b, ‘Development of a Risk-Hedging CO_2-Emission Policy, Part II: Risks Associated with Measures to Limit Emissions, Synthesis, and Conclusions’, *Clim. Change* **34**, 41–71.

Kattenberg, A., Giorgi, F., Grassl, H., Meehl, G. A., Mitchell, J. F. B., Stouffer, R. J., Tokioka, T., Weaver, A. J., and Wigley, T. M. L.: 1996, ‘Climate Models – Projections of Future Climate’, in Houghton, J. T., Meiro Filho, L.G., Callander, B. A., Harris, N., Kattenberg, A., and Maskell, K. (eds.), *Climate Change 1995: The Science of Climate Change – Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, 1st edn., Cambridge University Press, Cambridge, pp. 285–357.

Kolstad, C. D.: 1994, ‘George Bush versus Al Gore - Irreversibilities in Greenhouse Gas Accumulation and Emission Control Investment’, *Energy Policy* **22** (9), 772–778.

Kolstad, C. D.: 1996, ‘Learning and Stock Effects in Environmental Regulations: The Case of Greenhouse Gas Emissions’, *J. Environ. Econ. Manage.* **31**, 1–18.

Leggett, J., Pepper, W. J., and Swart, R. J.: 1992, ‘Emissions Scenarios for the IPCC: An Update’, in Houghton, J. T., Callander, B. A., and Varney, S. K. (eds.), *Climate Change 1992 – The Supplementary Report to the IPCC Scientific Assessment*, 1st edn., Cambridge University Press, Cambridge, pp. 71–95.

Leimbach, M.: 1996,‘Development of a Fuzzy Optimization Model, Supporting Global Warming Decision-Making’, *Environ. Resour. Econ.* **7** 163–192.

Lempert, R. J., Schlesinger, M. E., and Bankes, S. C.: 1996, ‘When We Don’t Know the Costs or the Benefits: Adaptive Strategies for Abating Climate Change’, *Clim. Change* **33**, 235–274.

Lind, R. C. (ed.): 1982, *Discounting for Time and Risk in Energy Policy*, Resources for the Future, Washington, D.C.

Maddison, D. J.: 1995, ‘A Cost-Benefit Analysis of Slowing Climate Change’, *Energy Policy* **23** (4/5), 337–346.

Maier-Reimer, E. and Hasselmann, K.: 1987, ‘Transport and Storage of Carbon Dioxide in the Ocean: An Inorganic Ocean Circulation Carbon Cycle Model’, *Clim. Dyn.* **2**, 63–90.

Manne, A. S., Mendelsohn, R. O., and Richels, R. G.: 1995, ‘MERGE - A Model for Evaluating Regional and Global Effects of GHG Reduction Policies’, *Energy Policy* **23** (1), 17–34.

Manne, A. S. and Richels, R. G.: 1995, ‘The Greenhouse Debate: Economic Efficiency, Burden Sharing and Hedging Strategies’, *Energy J.* **16** (4), 1–37.

Manne, A. S. and Richels, R. G.: 1996, ‘The Berlin Mandate: The Costs of Meeting Post-2000 Targets and Timetables’, *Energy Policy* **24** (3), 205–210.

Manne, A. S. and Richels, R. G.: 1998, ‘On Stabilizing CO_2 Concentrations – Cost-Effective Emission Reduction Strategies’, *Environ. Model. Assess.* **2**, 251–265.

Morgan, M. G. and Keith, D. W.: 1995, 'Subjective Judgments by Climate Experts', *Environmental Science and Technology* **29** (10), 468A–476A.

Nordhaus, W. D.: 1991, 'To Slow or Not to Slow: The Economics of the Greenhouse Effect', *Economic Journal* **101**, 920–937.

Nordhaus, W. D.: 1992, 'An Optimal Transition Path for Controlling Greenhouse Gases', *Science* **258**, 1315–1319.

Nordhaus, W. D.: 1993, 'Rolling the "DICE": An Optimal Transition Path for Controlling Greenhouse Gases', *Resource and Energy Economics* **15**, 27–50.

Nordhaus, W. D.: 1994a, 'Expert Opinion on Climate Change', *American Scientist*, 45–51.

Nordhaus, W. D.: 1994b, *Managing the Global Commons: The Economics of Climate Change*, The MIT Press, Cambridge.

Nordhaus, W. D. and Popp, D.: 1997, 'What is the Value of Scientific Knowledge? An Application to Global Warming Using the PRICE Model', *Energy J.* **18** (1), 1–45.

Nordhaus, W. D. and Yang, Z.: 1996, 'RICE: A Regional Dynamic General Equilibrium Model of Optimal Climate-Change Policy', *American Economic Review* **86** (4), 741–765.

Pate-Cornell, E.: 1996, 'Uncertainties in Global Climate Change Estimates', *Clim. Change* **33**, 145–149.

Pearce, D. W., Achanta, A. N., Cline, W. R., Fankhauser, S., Pachauri, R., Tol, R. S. J., and Vellinga P.: 1996, 'The Social Costs of Climate Change: Greenhouse Damage and the Benefits of Control', in Bruce, J. P., Lee, H., and Haites, E. F. (eds.), *Climate Change 1995: Economic and Social Dimensions of Climate Change – Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*, Chapter 6, Cambridge University Press, Cambridge, pp. 179–224.

Peck, S. C. and Teisberg, T. J.: 1992, 'CETA: A Model for Carbon Emissions Trajectory Assessment', *Energy J.* **13** (1), 55–77.

Peck, S. C. and Teisberg, T. J.: 1993, 'Global Warming Uncertainties and the Value of Information: An Analysis using CETA', *Resource and Energy Economics* **15**, 71–97.

Peck, S. C. and Teisberg, T. J.: 1994, 'Optimal Carbon Emissions Trajectories When Damages Depend on the Rate or Level of Global Warming', *Clim. Change* **28**, 289–314.

Peck, S. C. and Teisberg, T. J.: 1995, 'Optimal CO_2 Control Policy with Stochastic Losses from Temperature Rise', *Clim. Change* **31**, 19–34.

Peck, S. C. and Teisberg, T. J.: 1996, 'International CO_2 Emissions Targets and Timetables: An Analysis of the AOSIS Proposal', *Environ. Model. Assess.* **1** (4), 219–227.

Petschel-Held, G., Schellnhuber, H.-J., Bruckner, T., Toth, F. L., and Hasselmann, K.: 1999, 'The Tolerable Windows Approach: Theoretical and Methodological Foundations', *Clim. Change* **41**, (3–4), 303–331.

Raiffa, H.: 1970, *Decision Analysis: Introductory Lectures on Choices under Uncertainty*, Addison-Wesley, Reading.

Schimmelpfennig, D.: 1996, 'Uncertainty in Economic Models of Climate Change Impacts', *Clim. Change* **33**, 213–234.

Schlaifer, R.: 1978, *Analysis of Decisions under Uncertainty*, Robert E. Krieger Publishing, Huntington.

Shine, K. P., Derwent, R. G., Wuebbles, D. J., and Morcrette, J.-J.: 1990, 'Radiative Forcing of Climate', in Houghton, J. T., Jenkins, G. J., and Ephraums, J. J. (eds.), *Climate Change - The IPCC Scientific Assessment*, 1st edn., Cambridge University Press, Cambridge, pp. 41–68.

Starrett, D.: 1988, *Foundations of Public Economics*, Cambridge University Press, Cambridge.

Tol, R. S. J.: 1995, 'The Damage Costs of Climate Change Toward more Comprehensive Calculations', *Environ. Resour. Econ.* **5**, 353–374.

Tol, R. S. J.: 1996, 'The Damage Costs of Climate Change Towards a Dynamic Representation', *Ecological Economics* **19**, 67–90.

Tol, R. S. J.: 1997, 'On the Optimal Control of Carbon Dioxide Emissions: An Application of *FUND*', *Environ. Model. Assess.* **2**, 151–163.

Tol, R. S. J.: 1998a, 'Kyoto Mistakes', *International Journal of Environment and Pollution* **10** (3/4), 503–507.

Tol, R. S. J.: 1998b, 'On the Difference in Impact of Two Almost Identical Climate Change Scenarios', *Energy Policy* **26** (1), 13–20.

Tol, R. S. J.: 1999a, 'Time Discounting and Optimal Control of Climate Change – An Application of *FUND*', *Clim. Change* **41** (3–4), 351–362.

Tol, R. S. J.: 1999b, 'Spatial and Temporal Efficiency in Climate Change: Applications of FUND', *Environ. Resour. Econ.* **14** (1), 33–49.

Tol, R. S. J.: 1999c, 'Kyoto, Efficiency, and Cost-Effectiveness: Applications of FUND', *Energy Journal Special Issue on the Costs of the Kyoto Protocol: A Multi-Model Evaluation*, 130–156.

Tol, R. S. J.: 1999d, 'Safe Policies in an Uncertain Climate: An Application of FUND', *Global Environ. Change* **9**, 221–232.

Tol, R. S. J.: 1999e, 'The Marginal Costs of Greenhouse Gas Emissions', *Energy J.* **20** (1), 61–81.

Tol, R. S. J.: 2002a, 'Estimates of the Damage Costs of Climate Change, Part I: Benchmark Estimates', *Environ. Resour. Econ.* **21** (1), 47–73.

Tol, R. S. J.: 2002b, 'Estimates of the Damage Costs of Climate Change, Part II: Dynamic Estimates', *Environ. Resour. Econ.* **21** (1), 135–160.

Tol, R. S. J., van der Burg, T., Jansen, H. M. A., and Verbruggen, H.: 1995, *The Climate Fund – Some Notions on the Socio-Economic Impacts of Greenhouse Gas Emissions and Emission Reductions in an International Context*, Institute for Environmental Studies **R95/03**, Vrije Universiteit, Amsterdam.

Tol, R. S. J. and Downing, T. E.: 2000, *The Marginal Costs of Climate Changing Gases*, Institute for Environmental Studies D00/08, Vrije Universiteit, Amsterdam.

Tol, R. S. J., Heintz, R. J., and Lammers, P. E. M.: in press, 'Methane Emission Reduction: An Application of *FUND*', *Clim. Change*, in press.

Toth, F. L., Bruckner, T., Fussel, H.-M., Leimbach, M., Petschel-Held, G., and Schellnhuber, H.-J.: 1997, 'The Tolerable Windows Approach to Integrated Assessments', in Cameron, O. K., Fukuwatari, K., and Morita, T. (eds.), *Climate Change and Integrated Assessment Models: Bridging the Gaps – Proceedings of the IPCC Asia-Pacific Workshop on Integrated Assessment Models, United Nations University, Tokyo, Japan, March 10–12, 1997*, Center for Global Environmental Research, National, Institute for Environmental Studies, Tsukuba, pp. 403–430.

Ulph, A. and Maddison, D. J.: 1997, 'Uncertainty, Learning and International Environmental Policy Coordination', *Environ. Resour. Econ.* **9** 451–466.

Welsch, H.: 1995, 'Greenhouse Gas Abatement under Ambiguity', *Energy Economics* **17** (2), 91–100.

Woodward, R.T and Bishop, R. C.: 1997, 'How to Decide if Experts Disagree: Uncertainty Based Choice Rules in Environmental Policy', *Land Economics* **73** (4), 492–507.

Yohe, G. W.: 1999, 'The Tolerable Windows Approach: Lessons and Limitations', *Clim. Change* **41** (3–4), 283–295.

Yohe, G. W. and Wallace, R.: 1996, 'Near Term Mitigation Policy for Global Change under Uncertainty: Minimizing the Expected Cost of Meeting Unknown Concentration Thresholds', *Environ. Model. Assess.* **1** (1–2), 47–58.

Yohe, G. W.: 1997, 'Uncertainty, Short Term Hedging and the Tolerable Window Approach', *Global Environ. Change* **7** (4), 303–315.

(Received 2 April 2001; in revised form 6 May 2002)