How Large is the Uncertainty about Climate Change?

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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 needs to shows 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.

Keywords
Climate change; cost-benefit analysis; uncertainty

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1. Introduction

Uncertainty abounds in climate change. Uncertainty also abounds in the literature about climate change. Some papers try to describe the uncertainties (Hammitt, 1995; Harvey, 1996a,b; Pate-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 (Kann and Weyant, 1999). A prominent decision analytic framework is cost-benefit analysis (CBA), or rather welfare-maximisation (see Maddison, 1995; Manne *et al.*, 1995; Nordhaus, 1991, 1992, 1993, 1994; Nordhaus and Yang, 1996; Peck and Teisberg, 1992, 1994; see Eismont and Welch, 1996; Kolstad, 1994, 1996; Leimbach, 1996; Nordhaus and Popp, 1997; Peck and Teisberg, 1993, 1995; Ulph and Maddison, 1997; Welsch, 1995 for applications of CBA under uncertainty). The main challenger of CBA is the safe minimum standard (SMS) approach (but see Lempert *et al.*, 1996, 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). 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).

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.

SMS are arbitrary. They are 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.

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 CBA fall apart if the uncertainties about either costs or benefits are infinite.

This paper tests whether the uncertainties about climate change are infinite, and thus whether CBA is an appropriate approach to climatic change.

This 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 (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).

2. Analytical representation

Collard (1988) distinguishes between weak and strong catastrophes. The set of environmental problems is denoted by P. An environmental problem $p \in P$ is catastrophic ($p \in C$) if its impacts become infinitely large at the extreme. That is, if we denote impact of problem p by I_p indexed on state of nature s

$$C = \left\{ I_p \mid \lim_{s \to \infty} I_p(s) = \infty \right\}; s \in \mathbb{R}^+; I_p \in \mathbb{R} \tag{1}$$

Of course, $C \subset P$.

A catastrophe is strong ($p \in SC$) if the expected value of its impact, $\mathrm{E}I_p$, is infinite

$$SC = \left\{ I_p \in C \mid \mathrm{E}I_p = \int_0^\infty f(s) I_p(s) \mathrm{d}s > M; \forall M < \infty \right\} \tag{2}$$

where $f(s)$ denote the probability density function of s. For strong catastrophes, diminishing chances do not cancel growing impacts.

A catastrophe is weak ($p \in WC$) if the expected value of its impact, $\mathrm{E}I_p$, is finite

$$WC = \left\{ I_p \in C \mid \int_0^\infty f(s) I_p(s) \mathrm{d}s \le M; \exists M < \infty \right\} \tag{3}$$

Of course, $C = SC \cup WC$.

Obviously, (3) implies

$$\lim_{s \to \infty} f(s) I_p(s) = 0 \tag{4}$$

That is, a catastrophe is weak if the chance decreases faster than the impact increases. However, (4) does not imply (3).

For cost-benefit analysis to be applicable, a catastrophe needs not be weak, but very weak ($p \in VWC$). A catastrophe is very weak if the variance of its impact, $\mathrm{E}I$, is finite

$$VWC = \left\{ I_p \in WC \mid \mathrm{Var}I_p = \int_0^\infty f(s)(I_p(s) - \mathrm{E}I_p)^2 \mathrm{d}s \le M; \exists M < \infty \right\} \tag{5}$$

Obviously, $WC \subset VWC$.

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

$$I_p = \int_0^\infty I_p(t) \mathrm{e}^{-\delta t} \mathrm{d}t; t \in \mathbb{R} \tag{6}$$

or rather its expected value

$$\mathrm{E}I_p = \int_0^\infty \int_0^\infty f(s) I_p(t,s) \mathrm{e}^{-\delta t} \mathrm{d}t \mathrm{d}s \tag{7}$$

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

However, the discount rate δ is a function of impact I. The standard neo-classical 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 (6) diverges and the net present value of the impact becomes infinite. If this happens with a positive chance, the integral of equation (7) diverges as well. In that case, the catastrophe is strong. Recall that for cost-benefit analysis to be applicable, the catastrophe needs to be very weak.

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; Tol, 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.*, 2000). 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, 1999f,g).

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.

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:

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

where C denotes concentration, E emissions, t year, and *pre* pre-industrial. Table 1 displays the parameters for both gases. Equation (1) 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.

Table 1. Parameters of Equation (1).

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.

The carbon cycle is a five-box model:

$$Box_{i,t} = \rho_i \, Box_{i,t-1} + 0.000471 \alpha_i E_t \tag{2a}$$

with

$$C_t = \sum_{i=1}^{5} \alpha_i Box_{i,t} \qquad (2b)$$

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 ρthe decay-rate of the boxes (ρ = exp(-1/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:

$$T_t = \left(1 - \frac{1}{50}\right) T_{t-1} + \frac{1}{50} \frac{2.5}{6.3 \ln(2)} RF_t \qquad (3)$$

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 2; more underlying assumptions are given in the Appendix.

Table 2. 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&fSU	57	(108)	2.0	(3.8)
ME	4	(8)	1.1	(2.2)
LA	-1	(5)	-0.1	(0.6)
S&SEA	-14	(9)	-1.7	(1.1)
CPA	9	(22)	2.1	(5.0)
AFR	-17	(9)	-4.1	(2.2)

Source: Tol (1999f).

Impacts of climate change on energy consumption, agriculture and cardiovascular and respiratory diseases explicitly recognise that there is a climate optimum. The climate optimum is determined by a mix of factors, including physiology and behaviour. 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).

All parameters in *FUND* are uncertain, and to each of them a probability density function was assigned. Table 4 shows the assumptions, which are more based on my judgement than on anything else.

Table 4. 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*	see appendix	see appendix
Sensitivity to sea level	Normal*	see appendix	see appendix
Non-linearity			
Agriculture	Normal*	2.0	0.5
Forestry	Normal*	1.0	0.5
Water	Normal*	1.0	0.5
Space heating	Normal*	1.0	0.5
Space cooling	Normal*	1.0	0.5
Vector-borne diseases	Normal*	1.0	0.5
Vector-borne diseases (income)	Normal*	1.0	0.5

Adaptation time			
Agriculture	Normal*	10	2.5
Immigration	Normal*	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*	0.31	0.15
Forestry	Normal*	0.31	0.20
Water	Normal*	0.85	0.15
Space heating	Normal*	0.80	0.20
Space cooling	Normal*	0.80	0.20
Population over 65	Normal*	0.25	0.08
Valuation			
Value of a statistical life	Normal*	200	100
Value of ecosystem change	Normal*	50	50
Standard income	Normal*	20,000	10,000
Miscellaneous			
Income threshold vector borne disease	Normal	3100	100 in 2000 plus 10 each year
Emigration costs	Normal*	3.0	1.5
Immigration costs	Normal*	0.4	0.2
Immigration intake	Stand. normal		
Cardiovascular limit	Normal*	0.05	0.02
Elasticity base cardiovascular disease to p.c. income	Normal*	0.000259	0.000096
Elasticity base respiratory disease to p.c. income	Normal*	0.000016	0.000005

* Knotted at zero.

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 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.

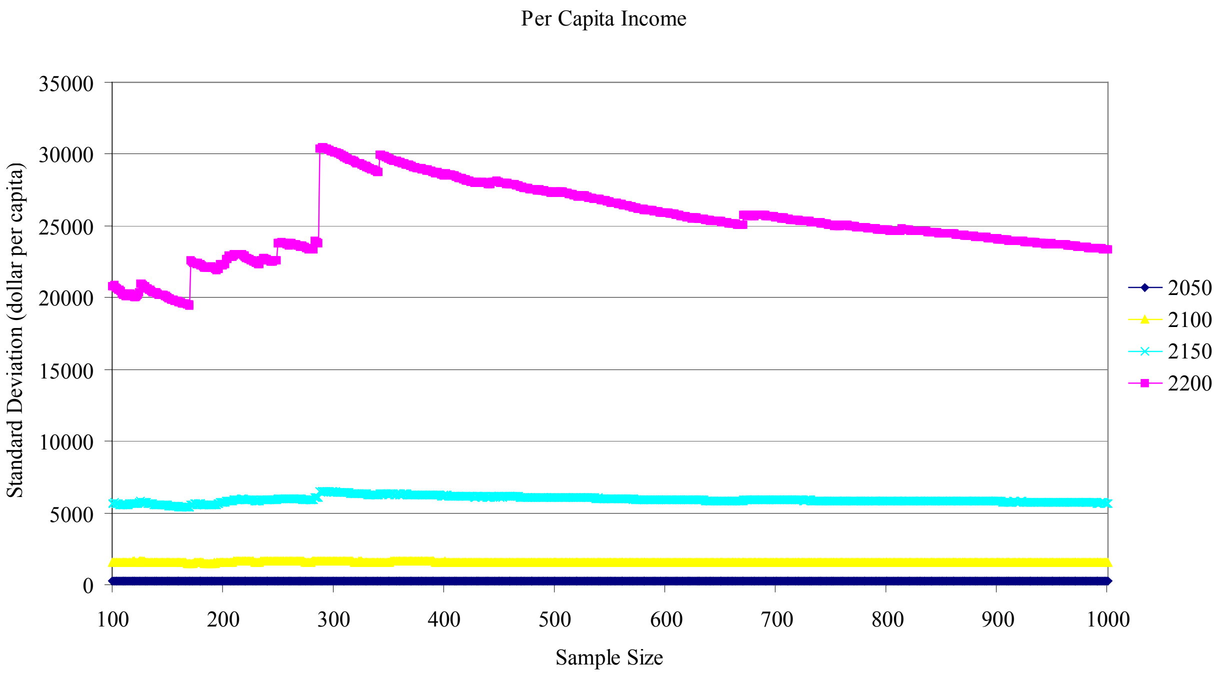

Figure 1. The standard deviation of the average world per capita income in the years 2050, 2100, 2150 and 2200 as a function of the sample size of the Monte Carlo analysis.

Figure 2 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 the uncertainty is remarkable independent of sample size. According to *FUND*, the uncertainty about the global mean temperature is finite.

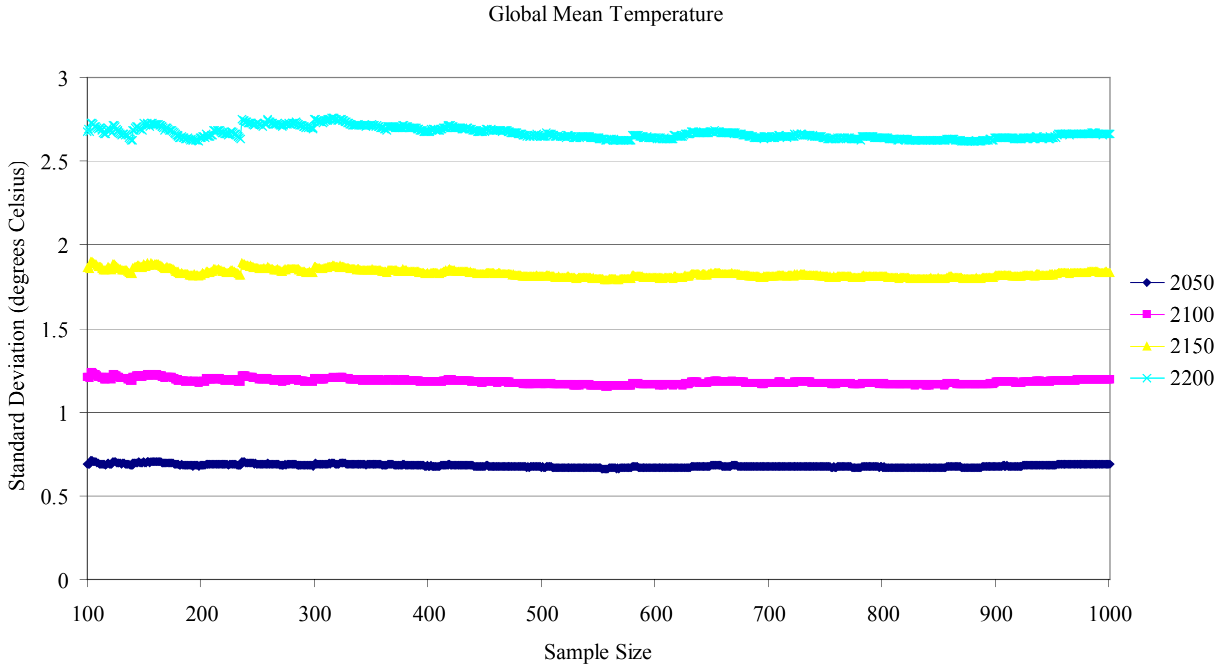

Figure 2. The standard deviation of the global mean temperature in the years 2050, 2100, 2150 and 2200 as a function of the sample size of the Monte Carlo analysis.

Figure 3 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.

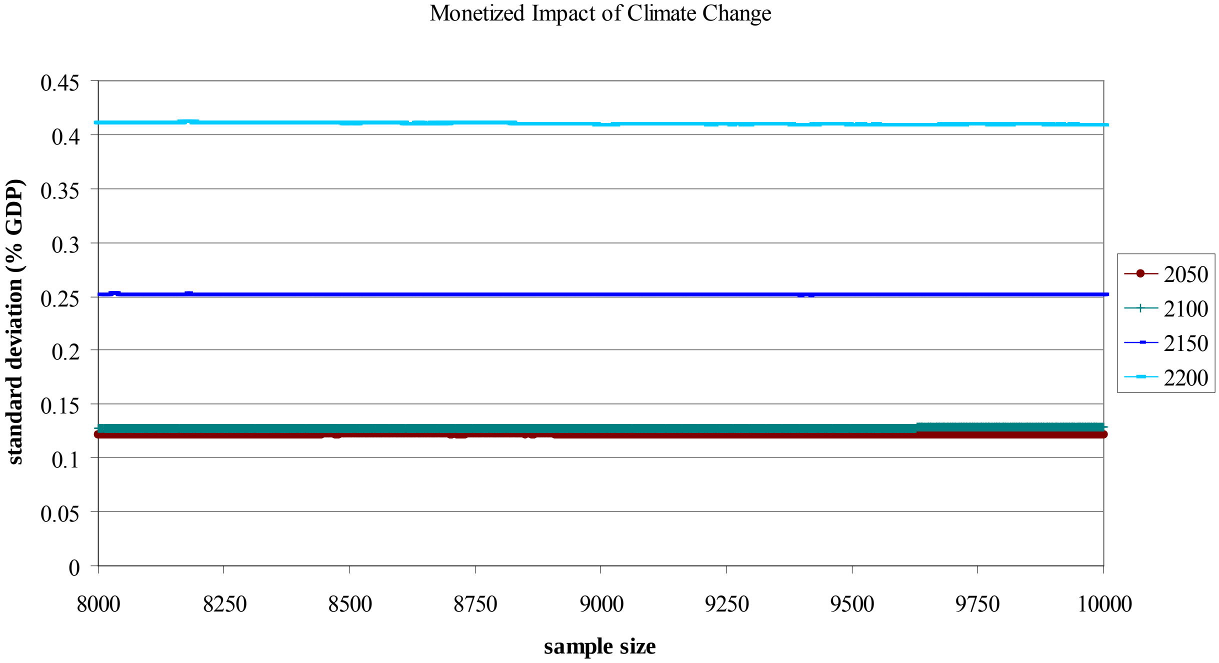

Figure 3. The standard deviation of the global monetized impact of climate change, as a percentage of world GDP, in the years 2050, 2100, 2150 and 2200 as a function of the sample size of the Monte Carlo analysis.

The 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

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 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 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 zero, the discount factor goes to infinity, taking the marginal costs with it.

This 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.

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.

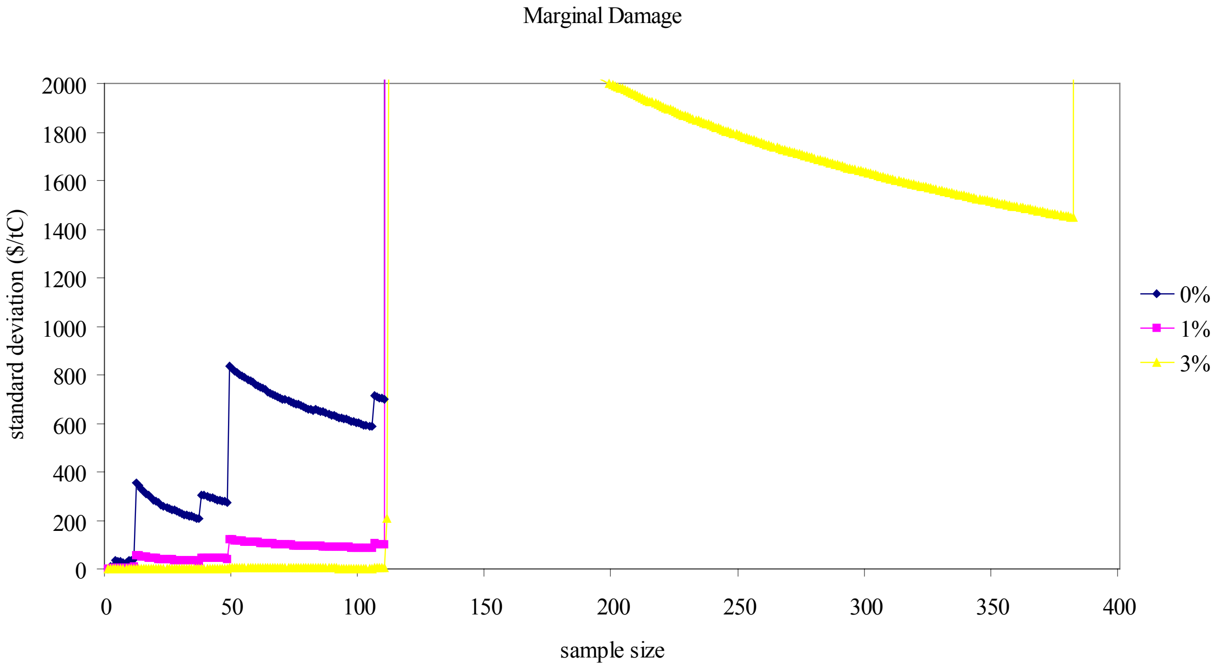

Figure 4. The standard deviation of the marginal costs of carbon dioxide emissions, in dollars per tonne of carbon, for pure rates of time preference of 0, 1, and 3% as a function of the sample size of the Monte Carlo analysis.

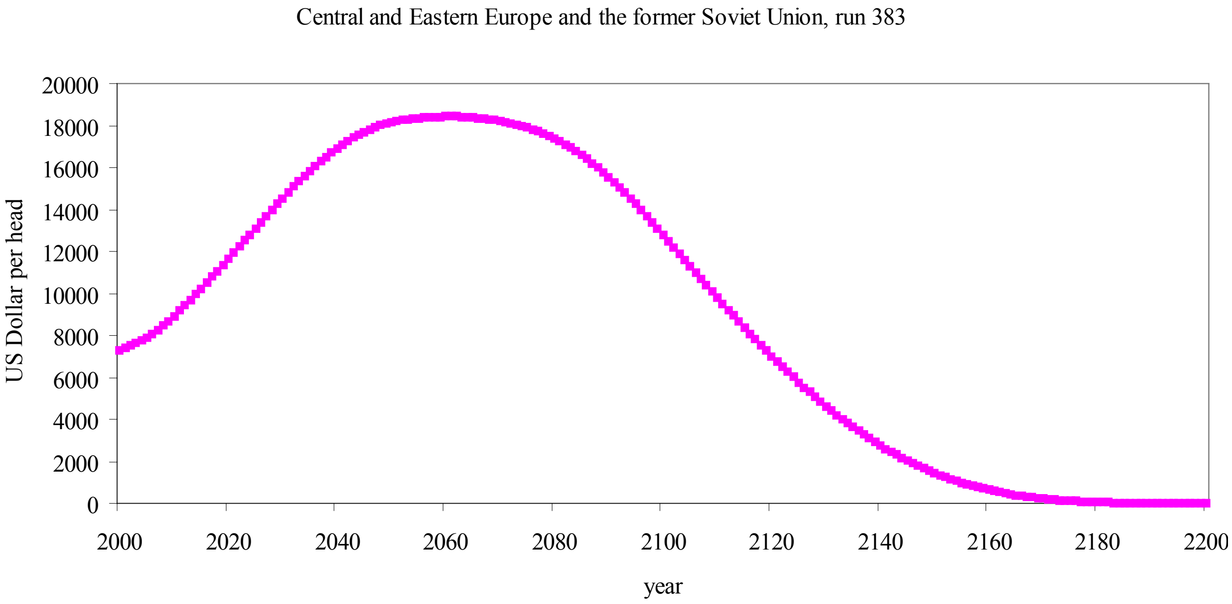

Figure 5. Per capita income in Central and Eastern Europe and the former Soviet Union in run 383 of the Monte Carlo analysis.

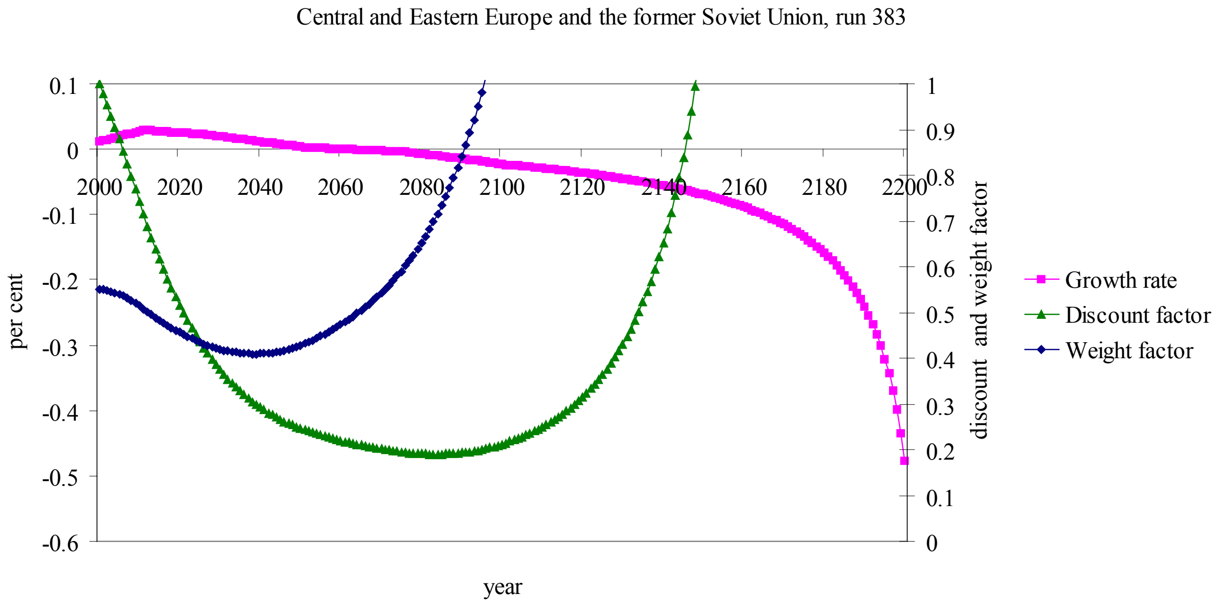

Figure 6. The growth rate, discount factor, and weight factor in Central and Eastern Europe and the former Soviet Union in run 383 of the Monte Carlo analysis.

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 5.

Table 5. 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)	(∞)

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 the net present value of the impact of climate change can be infinite. The analysis of Section 2 shows that the variance of the net present value becomes infinitely large if there is a set of parameters, with non-zero chance, under which the net present value becomes infinitely large. The numerical results in Section 5 show that this is the case in *FUND*. Section 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. 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.

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.

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References

Alcamo, J. and Kreileman, G.J.J. (1996a) Emission Scenarios and Global Climate Protection. *Global Environmental 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, pp.1-17. Bilthoven: RIVM.

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

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

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*, New York: MacMillan]

Dowlatabadi, H. (1999) Climate Change Thresholds and Guardrails for Emissions. *Climatic Change* **41** (3-4):297-301.

Eismont, O. and Welsch, H. (1996) Optimal Greenhouse Gas Emissions under Various Assessments of Climate Change Ambiguity. *Environmental and Resource Economics*

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.

Fankhauser, S., Tol, R.S.J. and Pearce, D.W. (1997) The Aggregation of Climate Change Damages: A Welfare Theoretic Approach. *Environmental and Resource Economics* **10** 249-266.

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

Hammitt, J.K. (1995) Outcome and Value Uncertainty in Global-Change Policy. *Climatic Change* **30** 125-145.

Harvey, L.D.D. (1996a) Development of a Risk-Hedging CO_2-Emission Policy, Part I: Risks of Unrestrained Emissions. *Climatic 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. *Climatic 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*, 1 edn. pp. 285-357. Cambridge: Cambridge University Press]

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. *Journal of Environmental Economics and Management* **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*, 1 edn. pp. 71-95. Cambridge: Cambridge University Press]

Leimbach, M. (1996) Development of a Fuzzy Optimization Model, Supporting Global Warming Decision-Making. *Environmental and Resource Economics* **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. *Climatic Change* **33** 235-274.

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. *Climate Dynamics* **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. (1998) On Stabilizing CO_2 Concentrations -- Cost-Effective Emission Reduction Strategies. *Environmental Modeling and Assessment* **2** 251-265.

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. (1995) The Greenhouse Debate: Economic Efficiency, Burden Sharing and Hedging Strategies. *Energy Journal* **16** (4):1-37.

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

Nordhaus, W.D. (1992) An Optimal Transition Path for Controlling Greenhouse Gases. *Science* **258** 1315-1319.

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*, Cambridge: The MIT Press.

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.

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. (1991) To Slow or Not to Slow: The Economics of the Greenhouse Effect. *Economic Journal* **101** 920-937.

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

Pate-Cornell, E. (1996) Uncertainties in Global Climate Change Estimates. *Climatic Change* **33** 145-149.

Peck, S.C. and Teisberg, T.J. (1992) CETA: A Model for Carbon Emissions Trajectory Assessment. *Energy Journal* **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. (1996) International CO_2 Emissions Targets and Timetables: An Analysis of the AOSIS Proposal. *Environmental Modeling and Assessment* **1** (4):219-227.

Peck, S.C. and Teisberg, T.J. (1994) Optimal Carbon Emissions Trajectories When Damages Depend on the Rate or Level of Global Warming. *Climatic Change* **28** 289-314.

Peck, S.C. and Teisberg, T.J. (1995) Optimal CO_2 Control Policy with Stochastic Losses from Temperature Rise. *Climatic Change* **31** 19-34.

Petschel-Held, G., Schellnhuber, H.-J., Bruckner, T., Toth, F.L. and Hasselmann, K. (1999) The Tolerable Windows Approach: Theoretical and Methodological Foundations. *Climatic Change* **41** (3-4):303-331.

Schimmelpfennig, D. (1996) Uncertainty in Economic Models of Climate Change Impacts. *Climatic Change* **33** 213-234.

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*, 1 edn. pp. 41-68. Cambridge: Cambridge University Press]

Tol, R.S.J. (1995) The Damage Costs of Climate Change Toward More Comprehensive Calculations. *Environmental and Resource Economics* **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*. *Environmental Modeling and Assessment* **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*. *Climatic Change* **41** (3-4):351-362.

Tol, R.S.J. (1999b) Spatial and Temporal Efficiency in Climate Change: Applications of FUND. *Environmental and Resource Economics* **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 Environmental Change* **9** 221-232.

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

Tol, R.S.J. (1999f) New Estimates of the Damage Costs of Climate Change, Part II: Dynamic Estimates. D99/02, pp.1-31. Amsterdam: Institute for Environmental Studies, Vrije Universiteit.

Tol, R.S.J. (1999g) New Estimates of the Damage Costs of Climate Change, Part I: Benchmark Estimates. D99/01, pp.1-32. Amsterdam: Institute for Environmental Studies, Vrije Universiteit.

Tol, R.S.J., R.J. Heintz and P.E.M. Lammers (2000) Methane Emission Reduction: An Application of *FUND. Climatic Change* (submitted).

Tol, R.S.J., T. van der Burg, H.M.A. Jansen and H. Verbruggen, *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.

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*, pp. 403-430. Tsukuba: Center for Global Environmental Research, National Institute for Environmental Studies]

Ulph, A. and Maddison, D.J. (1997) Uncertainty, Learning and International Environmental Policy Coordination. *Environmental and Resource Economics* **9** 451-466.

Welsch, H. (1995) Greenhouse Gas Abatement under Ambiguity. *Energy Economics* **17** (2):91-100. 0140-9883(95)00010-0.

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. *Environmental Modeling and Assessment* **1** (1-2):47-58.

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

Yohe, G.W. (1997) Uncertainty, Short Term Hedging and the Tolerable Window Approach. *Global Environmental Change* (forthcoming).

Appendix. Assumptions in the climate change impact module.

Table A1. 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&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&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 A2. Impact of a 1°C warming on current day forestry, water, heating, and cooling, in million US dollar (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&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&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 A3. Additional deaths due to vector-borne diseases for a 1ºC 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&fSU	0	(0)	0	(0)	0	(0)
ME	155	(112)	-64	(13)	0	(0)
LA	1,101	(797)	-114	(22)	0	(0)
S&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 A4. 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&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&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 A5. 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&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&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)