INFINITE UNCERTAINTY, FORGOTTEN FEEDBACKS, AND COST-BENEFIT ANALYSIS OF CLIMATE POLICY

Richard S.J. Tol[a,b,c] *and Gary W. Yohe*[d]

August 29, 2005

[a] *Research unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science, Hamburg, Germany*

[b] *Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands*

[c] *Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA*

[d] *John E. Andrus Professor of Economics, Wesleyan University, Middletown, CT, USA*

Working Paper FNU-83

Abstract

Tol (2003) found evidence that the uncertainty that surrounds estimates of the marginal damage of climate change may be infinite even if total damages are finite and questioned the applicability of expected cost-benefit analysis to global mitigation policy. Yohe (2003) suggested that this problem could be alleviated if international development aid were directed at eliminating the source of the problem – climate induced negative growth rates in a few regions along a handful of troublesome scenarios. The hypothesis about adding a second policy lever to the climate policy calculus is shown to hold, but not as robustly as perhaps expected. Infinite uncertainty and its implications for global mitigation policy can be avoided for a reasonable price in the relatively unlikely event that climate change can cause negative economic growth in a region or two when the portfolio of international policies includes at least two tools.

Keywords: climate policy, development aid, equity weighting, expected cost-benefit analysis

1. Introduction

The determination of appropriate climate policy is controversial because it is driven, in part, by the choice of the decision-making framework. This choice, in turn, depends on alternative views not only of how the world works, but also of how the world should work. Two alternative approaches dominate the discussion. The first is based on (expected) cost-benefit analysis (Nordhaus and Boyer, 2000) which, broadly defined, can include risk management (Yohe *et al.*, 2004). The second defines tolerable windows of climate change (Petschel-Held *et al.*, 1999) and is a variant of safe minimum standards. According to the axioms of cost-benefit analysis, uncertainty about the net benefit of any policy must be finite. If not this is not the case, then cost-benefit analysis is invalid and should be replaced by a perspective designed to minimize the maximum regret assigned across a wide range of plausible futures (i.e., safe minimum standards or tolerable windows). It follows, therefore, that the discussion on how to approach the climate policy debate turns in large measure on the size of the uncertainty.

Tol (2003) used the *FUND* integrated assessment model to estimate the uncertainty about the marginal damage costs of carbon dioxide emissions, a crucial input into an expected cost-benefit analysis of greenhouse gas emissions control. He found evidence that the uncertainty that surrounds our estimates of marginal damages may be infinite even if total damages are, themselves, finite. His reasoning contemplated a philosopher-queen who would take into account climate change impacts on all people. Indeed, she would aggregate monetised impacts using equity-weights that correct for the fact that a dollar to a poor man is not the same as a dollar to a rich man. She would, as well, recognize that climate change may reverse economic growth in some countries under some, not-implausible specifications of climate change and associated damages so that these countries would be assigned a negative consumption discount rate and a high equity-weight. As a result, these extreme scenarios would overwhelm the expected value of the marginal damage costs, its standard deviation, and the calculation of the optimal policy. Without equity weights, the low dollar value of the climate change impact on the poorest would be ignored in the global calculus; but with equity weights, negative economic growth rates would define impacts thresholds that would serve, for all intents and purposes, as binding boundaries of tolerable climate change. See Azar and Lindgren (2003) and Howarth (2003) for further commentary.

Yohe (2003) responded to Tol's reasoning by arguing that global policy makers would not be confined to implementing only climate policy in these circumstances. He hypothesized, in fact, that the global community would find it in its own best interest to offer economic aid that would prevent negative economic growth in some countries because they could then impose less stringent climate policy upon themselves. The problem highlighted by Tol was, in short, simply a problem of trying to confront two policy objectives (optimal intervention into anthropogenic forcing of the climate system and maintaining positive economic growth worldwide) with only one policy tool (climate policy). Alternatively, Tol's result may be due to a missing, policy-driven negative feedback in the *FUND* model. In this short paper, we test this hypothesis by including an economic aid feedback mechanism that would be triggered by catastrophic climate impacts and thus insure that the variance of marginal damages is finite.

Section 2 describes some of the details in the modelling environment, which has evolved since Tol (2003). Section 3 shows the results of a Monte Carlo analysis of the marginal damage costs of carbon dioxide, and Section 4 offers some concluding remarks.

2. The model

This paper uses version 2.8 of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*). Version 2.8 of *FUND* corresponds to version 1.6, described and applied by Tol (1999, 2001, 2002a), except for the impact module, which is described by Tol (2002b,c) and updated by Link and Tol (2004). A further difference is that the current version of the model distinguishes 16 instead of 9 regions. Finally, the model considers emission reduction of methane and nitrous oxide as well as carbon dioxide, as described by Tol (forthcoming).[1]

[1] A full list of papers and the source code of the model can be found at http://www.uni-hamburg.de/Wiss/FB/15/Sustainability/fund.html.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. The model runs from 1950 to 2300 in time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, the impacts of climate change are assumed to depend on the impact of the previous year, this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be misrepresented in the first few decades of the model runs. The 22^{nd} and 23^{rd} centuries are included to account for the fact that key impacts of a weakening or a shutdown of the thermohaline circulation would be disregarded if the time horizon of the simulations were shorter. Previous versions of the model stopped at 2200.

The period of 1950-1990 is used for the calibration of the model, which is based on the *IMAGE* 100-year database (Batjes & Goldewijk, 1994). The period 1990-2000 is based on observations (WRI, 2000). The climate scenarios for the period 2010-2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett *et al.*, 1992). The 2000-2010 period is interpolated from the immediate past, and the period 2100-2300 extrapolated.

The scenarios are defined by the rates of population growth, economic growth, autonomous energy efficiency improvements as well as the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide. The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (WRI, 2000). It is extrapolated based on the statistical relationship between urbanization and per-capita income, which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The tangible impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. As a result, climate change reduces long-term economic growth, although consumption is particularly affected in the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies, an option not considered in this paper.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt *et al.* (1992). The model also contains sulphur emissions (Tol, forthcoming)

The radiative forcing of carbon dioxide, methane, nitrous oxide and sulphur aerosols is determined based on Shine *et al*. (1990). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by the radiative forcing RF), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. Regional temperature follows from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn *et al*., 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996).

The climate impact module, based on Tol (2002b,c) includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol, 2002c).

People can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set to be 3 times the per capita income (Tol, 1995, 1996), the value of immigration is 40 per cent of the per capita income in the host region (Cline, 1992). Losses of dryland and wetlands due to sea level rise are modelled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 (cf. Fankhauser, 1994). The wetland value is assumed to have logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their 'natural' units (cf. Tol, 2002b). Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol, 2002c).

The impacts of climate change on coastal zones, forestry, unmanaged ecosystems, water resources, diarrhoea malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (cf. Tol, 2002c).

Vulnerability to climate change 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 urbanization), and ecosystems and health (with 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- and water-borne diseases (with improved health care) (cf. Tol, 2002c).

FUND also includes instruments for and costs of reducing the emissions of carbon dioxide, methane, and nitrous oxide. It can perform cost-benefit analysis, cost-effectiveness analysis, and equity analysis. These parts of the model are not used in this paper.

3. Results

FUND was exercised to explore the distributions of marginal damages with and without an aid policy that would transfer up to 1% or 2% of the combined GDP of the OECD as necessary to sustain economic activity in regions who experience the unlikely event that climate impacts would otherwise drive them subsistence levels (i.e., the marginal damage of climate change would become unbounded for these regions). Such transfers are triggered as soon as per capita income starts to fall in any region that is currently not in the OECD. These transfers are assumed to exactly offset the income fall, unless the total transfers exceed 1% (or 2%) of the total GDP of the OECD regions. (Note that OECD countries aim to give 0.7% of their GDP in official development aid, and that few countries meet this target.) OECD regions are assumed to contribute to the transfers proportional to their GDP.

Two different regional weighting schemes in the global objective function were also considered. In the first, individuals' utilities around the world were simply summed in the calculation of a Benthamite metric of global welfare. In the second, individuals' utilities were assigned "equity weights" according to Fankhauser *et al.* (1997). In all cases, though, regional utilities were discounted according to the Ramsey rule given globally consistent pure rates of time preference but regionally specific and endogenously determined rates of growth in per-capita consumption. Slow or negative growth rates caused by particularly pernicious climate change could therefore receive abnormally high weights in the global policy analysis.

Table 1 displays results drawn from Monte Carlo analyses of 50,000 runs with and without aid. The various panels of the table reflect characteristics of the distribution of the marginal damage of carbon emissions (in dollars per tonne of carbon) across the runs for three different specifications of the pure rate of time preference and two different utility weighting schemes. Notice that adding aid to the policy calculus always lowers the mean and median estimate of marginal damage as well as its variance. These reductions are, though, always larger for the equity weighting cases and for cases in which the social discount rate is diminished by smaller pure rates of time preference. Indeed, the reductions can be several orders of magnitude in these cases. Moreover, increased aid, while it always reduces the variance of marginal damages, need not reduce the mean (or the median) for low discount rates even for the equity weighting calculations.

These trends are easily explained in terms of the relative importance associated with the occasional regionally catastrophic scenario in the expected value calculation. Equity weights give significant weight to these cases, and so the expected value calculus assigns significant (ordinary) value to economic aid that can work to reduce the severe (modest) harm caused by carbon emissions along (far away from) those critical margins. Low discount rates (i.e., those associated with low pure rates of time preference) operate in the same way but without regard to geographic differentiation. Smaller in effect, as a result, lower (higher) pure rates of time preference simply expand (contract) the weight given to damage in the distant future when regional catastrophes may occur. Finally, the effect of increasing aid from 1% to 2% can be explained in terms of the overall economic productivity of the transfer. The reduction in global economic growth associated over time with the second 1-percent increment does not reduce climate damage as effectively, and this loss counts more heavily for smaller discount rates. Besides, more aid would sustain a vulnerable economy, increasing aggregate damages.

Figures 1 through 3 offers some insight into why the variance of marginal damages does not necessarily converge as more runs are added to the analysis, though the problem is more severe for equity weighting (Figures 1 and 2). The sudden peaks that appear along the "No Aid" and "Aid, 1%" schedules in Figures 1 and 3 (read from the left-hand vertical axis and the right hand axis, respectively, in Figure 1) indicate the inclusion of a scenario for which high marginal damages are felt in some region of the world (a run just before the 15,000th and for a 1 percent pure rate of time preference, just below the 40,000th). Interestingly, 2% aid eliminates the importance of both peaks, and 1% aid seems to eliminate even the significance of the second, high peak. These regionally confined economic catastrophes are rare events in the Monte Carlo simulations, but their occurrence in a poor but populated region gives them high weight in the expected value calculus from which estimates of marginal damages emerge when aid cannot fully compensate and/or when the pure rate of time preference is low. Indeed, a little bit of aid can bring a region back from the brink of catastrophe (and nearly unbounded marginal damages) without moving the region away from the region of high and steeply rising damages. In these cases, significant amounts of aid are required to reduce significantly the distribution of marginal damages. It was to be expected, therefore, that the variance would converge more robustly for the high-aid and/or high discount rate scenarios. Notice in Figure 2, in fact, that the differences are muted by the higher discount rate associated with a pure rate of time preference of 3%. In fact, aid eliminates both peaks for the high discount rate even with equity weighting, even if aid is limited to 1% of OECD income.

Figure 3 shows that, without equity weighing, aid may increase the variance. This is because, without equity weighing, the climate change impact on a collapsed economy would hardly count; a little aid would sustain such an economy and increase the absolute impacts it suffers. Figure 3 also shows that, if aid were higher, impacts would be lower; this is because a more robust economy would be less vulnerable to climate change.

Figure 4 offers a different view of the results, expressing the difference across the various cases in terms of per-capita income for the USA and Sub-Saharan Africa, which typify a high and a low income region, respectively. One notes that aid, even at a maximum of 2% of OECD GDP, has hardly any effect on the overall probability density of per capita income in 2100.

Figure 5 shows the probability density function of the *difference* in per capita income for the same two regions. Aid affects US (African) income in only 1.01% (0.19%) of the cases; this confirms the message from Figure 4. The USA is more often affected than is Sub-Saharan Africa because other poor regions may face climate-change-induced economic collapse as well. In the 50,000 Monte Carlo runs, aid never reduces US income in 2100 by more than 10%; in this scenario, annual aid is capped at 2% of GDP, but there are economic growth effects as well. On the other hand, per capita income in Sub-Saharan Africa can be up to 60% higher due to aid; in most cases, however, income is boosted by less than 30%.

4. Discussion and conclusion

It would appear that the hypothesis about adding a second policy lever to the climate policy calculus holds, but not as robustly as one might have thought initially. The vagaries of growth discounting, compounded here by equity weighting in the global welfare calculations, are always difficult to predict. Nonetheless, adding aid to the policy portfolio does reduce expected marginal damages associated with climate change, sometimes by orders of magnitude (for equity weighting and low pure rates of time preference). Aid also reduces the variance of marginal damages, again by orders of magnitude in some cases. These improvements can, though, be muted by high discount rates derived from high pure rates of time preference. Note that, with higher discount rates, the problem with large, maybe infinite variances, is much less pronounced. It is also possible to "do too much aid" at the opposite extreme in which future effects are more significant. In short, infinite uncertainty and its implications for global mitigation policy can be avoided for a reasonable price in the relatively unlikely event that climate change can cause negative economic growth in a region or two when the portfolio of international policy includes at least two tools.

Acknowledgements

This paper benefited from the series of Climate Change Impact and Integrated Assessment Workshops at Snowmass, CO. David Anthoff and Ada Li worked hard on implementing and testing the Monte Carlo analysis in FUND2.8. The Michael Otto Foundation for Environmental Protection and the Hamburg University Innovation Fund provided welcome financial support. GY acknowledges the support offered by B. Belle. All errors and opinions are ours.

References

Azar, C. and Lindgren, K. (2003), 'Catastrophic events and stochastic cost-benefit analysis of climate change', *Climatic Change*, **56**, 245-255.

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

Cline, W. R. (1992), *The Economics of Global Warming* Institute for International Economics, Washington, D.C.

Fankhauser, S. (1994), 'Protection vs. Retreat -- The Economic Costs of Sea Level Rise', *Environment and Planning A*, **27**, 299-319.

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.

Howarth, R. B. (2003), 'Catastrophic outcomes in the economics of climate change', *Climatic Change*, **56**, 257-263.

Kattenberg, A., Giorgi, F., Grassl, H., Meehl, G. A., Mitchell, J. F. B., Stouffer, R. J., Tokioka, T., Weaver, A. J., & Wigley, T. M. L. (1996), "Climate Models - Projections of Future Climate," in *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, J. T. Houghton et al., eds. (eds.), Cambridge University Press, Cambridge, pp. 285-357.

Leggett, J., Pepper, W. J., & Swart, R. J. (1992), "Emissions Scenarios for the IPCC: An Update," in *Climate Change 1992 - The Supplementary Report to the IPCC Scientific*

Assessment, 1 edn, vol. 1 J. T. Houghton, B. A. Callander, & S. K. Varney, eds. (eds.), Cambridge University Press, Cambridge, pp. 71-95.

Link, P. M. and Tol, R. S. J. (2004), 'Possible economic impacts of a shutdown of the thermohaline circulation: an application of FUND', *Portuguese Economic Journal*, **3**, 99-114.

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.

Mendelsohn, R., Morrison, W., Schlesinger, M. E., and Andronova, N. G. (2000), 'Country-specific market impacts of climate change', *Climatic Change*, **45**, 553-569.

Nordhaus, W.D. and Boyer, J.G. (200), *Warming the World: Economic Models of Global Warming*, MIT Press, Cambridge.

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.

Shine, K. P., Derwent, R. G., Wuebbles, D. J., & Morcrette, J.-J. (1990), "Radiative Forcing of Climate," in *Climate Change - The IPCC Scientific Assessment*, 1 edn, vol. 1 J. T. Houghton, G. J. Jenkins, & J. J. Ephraums, eds. (eds.), Cambridge University Press, Cambridge, pp. 41-68.

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. (1999), ‘Spatial and Temporal Efficiency in Climate Policy: Applications of *FUND*’, *Environmental and Resource Economics*, **14** (1), 33-49.

Tol, R.S.J. (2001), ‘Equitable Cost-Benefit Analysis of Climate Change’, *Ecological Economics*, **36** (1), 71-85.

Tol, R.S.J. (2002a), ‘Welfare Specification and Optimal Control of Climate Change: An Application of *FUND*’, *Energy Economics*, **24** (4), 367-376.

Tol, R.S.J. (2002b), ‘New Estimates of the Damage Costs of Climate Change, Part I: Benchmark Estimates’, *Environmental and Resource Economics*, **21** (1), 47-73.

Tol, R.S.J. (2002c), ‘New Estimates of the Damage Costs of Climate Change, Part II: Dynamic Estimates’, *Environmental and Resource Economics*, **21** (1), 135-160.

Tol, R. S. J. (2003), 'Is the uncertainty about climate change too large for expected cost-benefit analysis?', *Climatic Change*, **56**, 265-289.

Tol, R.S.J. (forthcoming), ‘Multi-Gas Emission Reduction for Climate Change Policy: An Application of *FUND*’, *Energy Journal*.

WRI (2000) World Resources Database 2000-2001. World Resources Institute, Washington D.C..

Yohe, G. W. (2003), 'More trouble for cost-benefit analysis', *Climatic Change*, **56**, 235-244.

Yohe, G.W., Schlesinger, M.E. and Andronova, N.G. (2004), ‘To Hedge or Not Against an Uncertain Climate Future?’, *Science*, **306**, 416-417.

Table 1. Characteristics of the marginal damage costs of carbon dioxide emissions (in dollars per tonne of carbon) without and with aid (capped at 1% or 2% of OECD income) in a Monte Carlo analysis with 50,000 runs.

Pure rate of time preference:		**0%**	**0%**	**1%**	**1%**	**3%**	**3%**
		Simple Sum	**Equity Weights**	**Simple Sum**	**Equity Weights**	**Simple Sum**	**Equity Weights**
No aid	**Mean**	226.6	12523.4	36.7	790.0	1.3	8.9
	St. Dev.	3001.8	313576.8	199.3	17444.4	20.8	75.9
Percentiles:	**1%**	-214.2	-366.7	-41.8	-47.2	-21.8	-29.3
	5%	-58.1	-53.2	-27.8	-29.9	-16.8	-22.0
	50%	56.1	112.1	8.5	21.4	-4.0	-2.7
	95%	732.7	11464.3	180.4	928.5	37.0	69.8
	99%	2374.0	185468.5	403.6	12077.3	88.5	191.3
Aid, 1% max	**Mean**	94.8	192.5	28.1	48.3	1.2	5.4
	St. Dev.	8296.6	15733.7	510.0	958.6	20.7	32.3
Percentiles:	**1%**	-277.0	-302.8	-42.2	-45.8	-21.8	-29.4
	5%	-61.0	-52.4	-27.9	-29.7	-16.8	-22.0
	50%	53.0	99.6	8.1	19.4	-4.0	-2.8
	95%	551.9	978.4	163.8	239.9	36.7	59.9
	99%	1259.5	2639.9	317.0	489.1	87.7	137.8
Aid, 2% max	**Mean**	129.8	254.6	30.2	52.0	1.2	5.4
	St. Dev.	914.5	1466.5	89.1	136.9	20.6	32.1
Percentiles:	**1%**	-280.6	-303.4	-42.2	-45.8	-21.8	-29.4
	5%	-61.1	-52.2	-27.9	-29.7	-16.8	-22.0
	50%	52.9	99.6	8.1	19.4	-4.0	-2.8
	95%	548.1	968.5	163.5	239.8	36.7	59.9
	99%	1247.3	2486.4	315.9	482.1	87.7	137.7

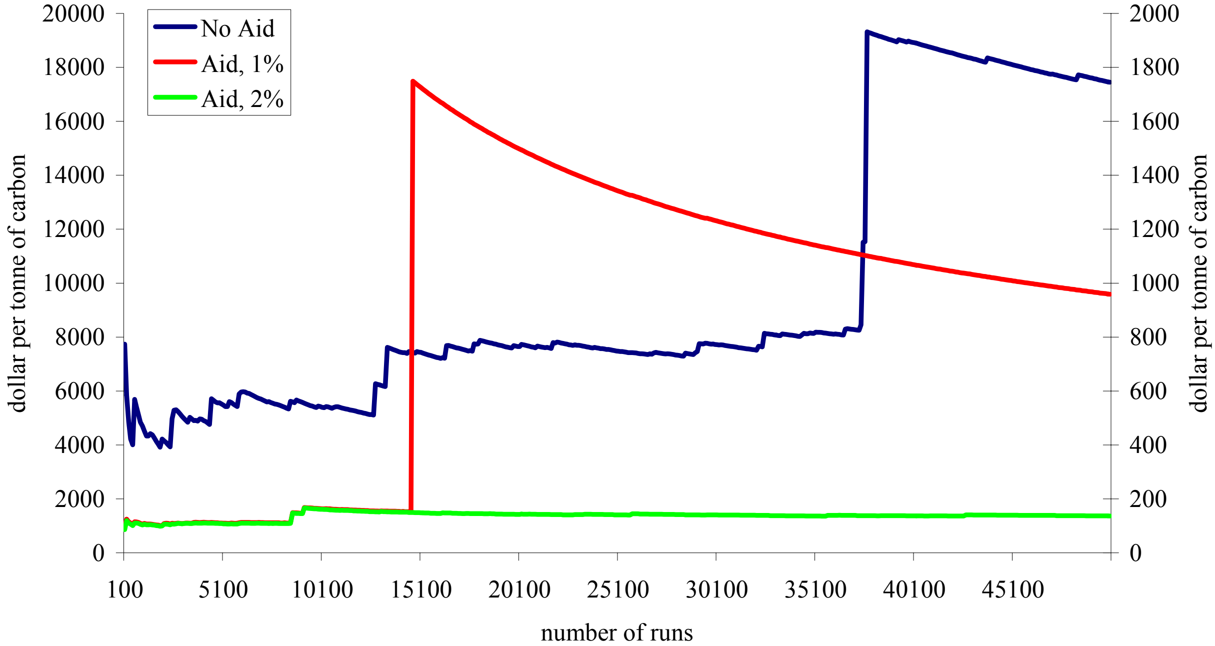

Figure 1. The standard deviation of the marginal damage costs of carbon dioxide emissions with and without aid as a function of the number of Monte Carlo runs for a 1% pure rate of time preference; impacts are equity-weighted; annual aid is limited to 1% or 2% of OECD GDP.

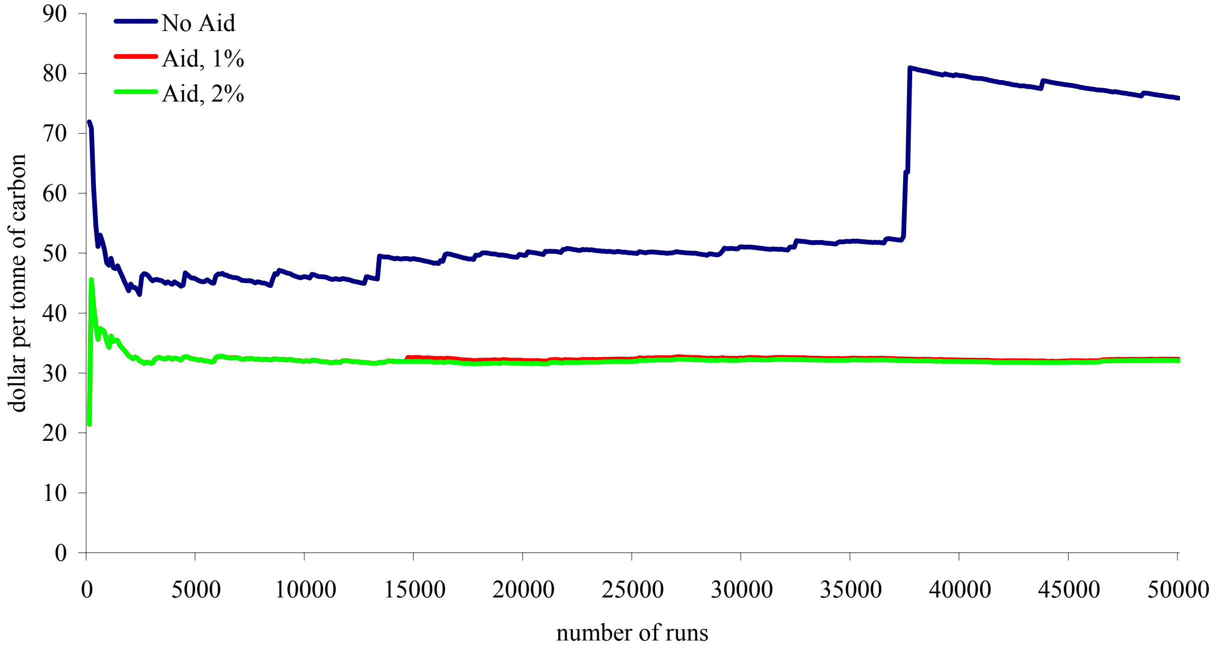

Figure 2. The standard deviation of the marginal damage costs of carbon dioxide emissions with and without aid as a function of the number of Monte Carlo runs for a 3% pure rate of time preference; impacts are equity-weighted; annual aid is limited to 1% or 2% of OECD GDP.

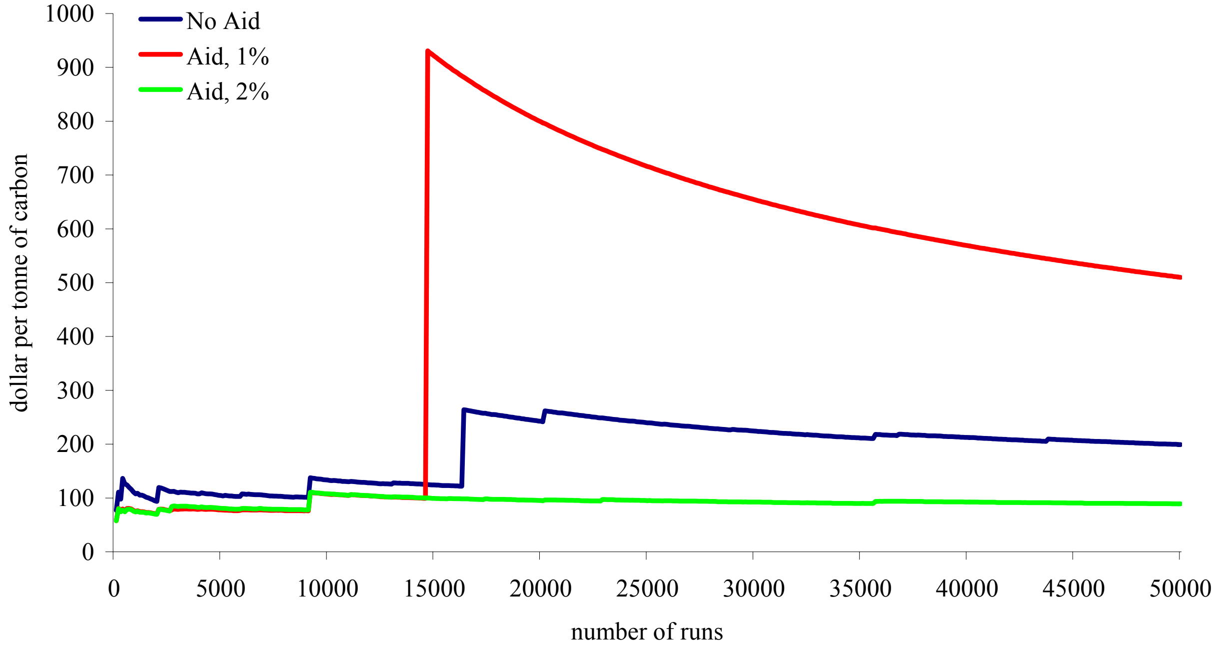

Figure 3. The standard deviation of the marginal damage costs of carbon dioxide emissions with and without aid as a function of the number of Monte Carlo runs for a 1% pure rate of time preference; impacts are not equity-weighted; annual aid is limited to 1% or 2% of OECD GDP.

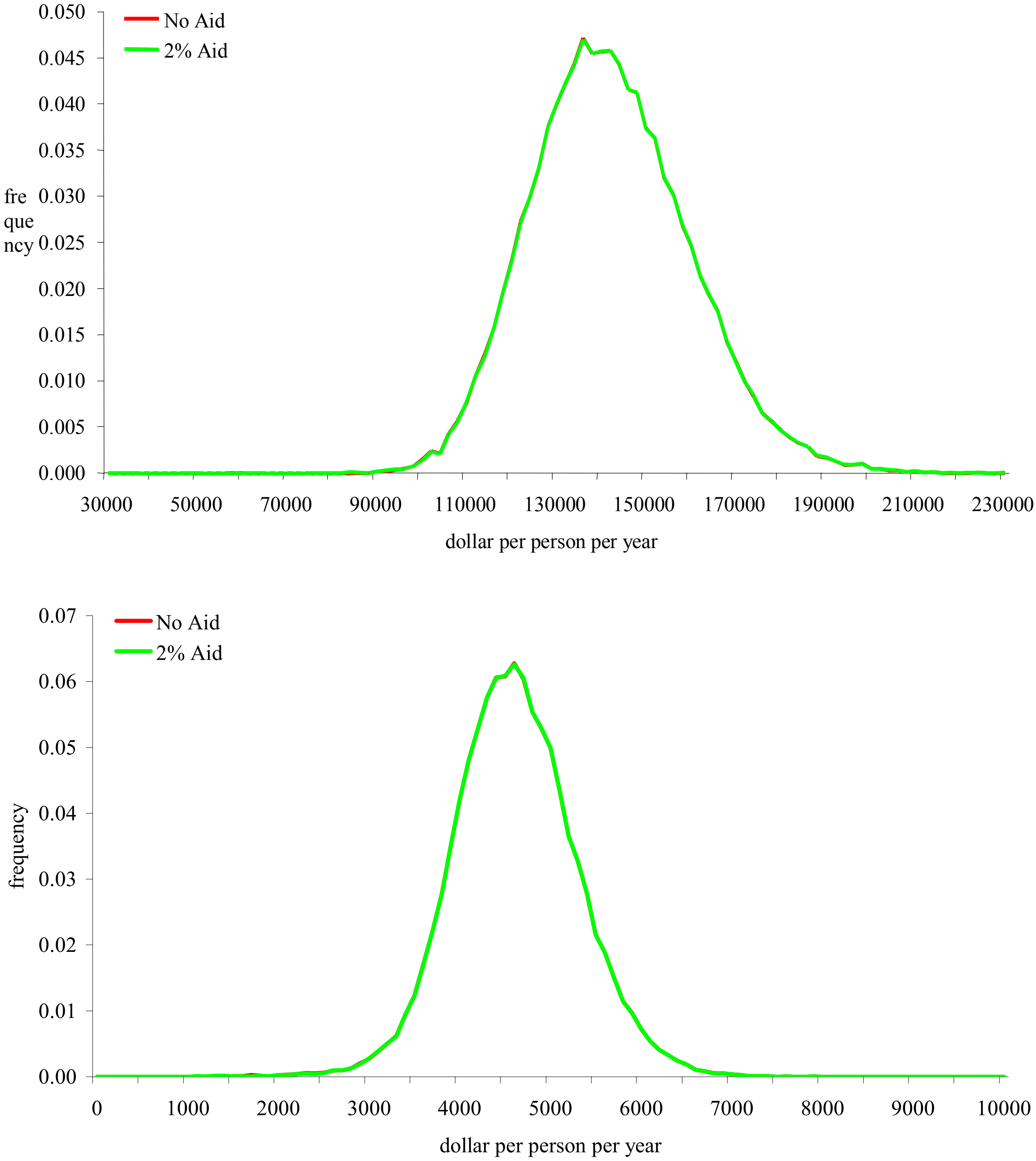

Figure 4. Probability density function of the 2100 per capita income without aid and with (capped at 2% of OECD GDP) in the USA (top panel) and in Africa (bottom panel).

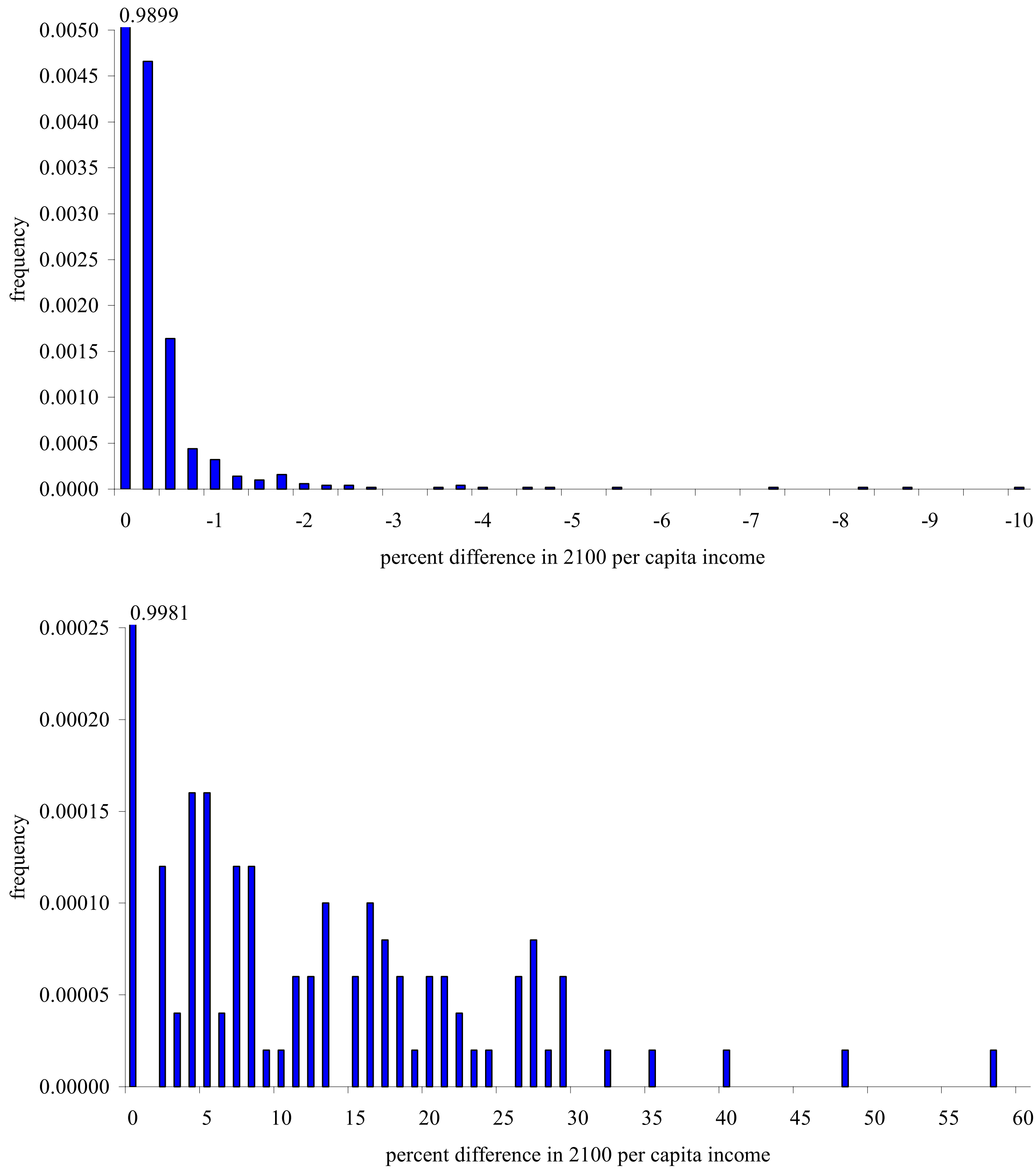

Figure 5. Probability density function of the difference in the 2100 per capita income due to aid (capped at 2% of OECD GDP), expressed as a percentage of the same income without aid, for the USA (top panel) and Africa (bottom panel).

Working Papers

Research Unit Sustainability and Global Change

Hamburg University and Centre for Marine and Atmospheric Science

Tol, R.S.J. and G.W. Yohe (2005), *Infinite uncertainty, forgotten feedbacks, and cost-benefit analysis of climate policy,* **FNU-83** (submitted)

Osmani, D. and R.S.J. Tol (2005), The case of two self-enforcing international agreements for environmental protection, **FNU-82** (submitted)

Schneider, U.A. and Bruce A. McCarl, (2005), *Appraising Agricultural Greenhouse Gas Mitigation Potentials: Effects of Alternative Assumptions*, **FNU-81** (submitted)

Zandersen, M., M. Termansen, and F.S. Jensen, (2005), *Valuing new forest sites over time: the case of afforestation and recreation in Denmark,* **FNU-80** (submitted)

Guillerminet, M.-L. and R.S.J. Tol (2005), *Decision making under catastrophic risk and learning: the case of the possible collapse of the West Antarctic Ice Sheet*, **FNU-79** (submitted)

Nicholls, R.J., R.S.J. Tol and A.T. Vafeidis (2005), *Global estimates of the impact of a collapse of the West Antarctic Ice Sheet: An application of FUND,* **FNU-78** (submitted)

Lonsdale, K., T.E. Downing, R.J. Nicholls, D. Parker, A.T. Vafeidis, R. Dawson and J.W. Hall (2005), *Plausible responses to the threat of rapid sea-level rise for the Thames Estuary,* **FNU-77** (submitted)

Poumadère, M., C. Mays, G. Pfeifle with A.T. Vafeidis (2005), *Worst Case Scenario and Stakeholder Group Decision: A 5-6 Meter Sea Level Rise in the Rhone Delta, France,* **FNU-76** (submitted)

Olsthoorn, A.A., P.E. van der Werff, L.M. Bouwer and D. Huitema (2005), *Neo-Atlantis: Dutch Responses to Five Meter Sea Level Rise,* **FNU-75** (submitted)

Toth, F.L. and E. Hizsnyik (2005), *Managing the inconceivable: Participatory assessments of impacts and responses to extreme climate change*, **FNU-74** (submitted)

Kasperson, R.E. M.T. Bohn and R. Goble (2005), *Assessing the risks of a future rapid large sea level rise: A review,* **FNU-73** (submitted)

Schleupner, C. (2005), *Evaluation of coastal squeeze and beach reduction and its consequences for the Caribbean island Martinique,* **FNU-72**

Schleupner, C. (2005), *Spatial Analysis As Tool for Sensitivity Assessment of Sea Level Rise Impacts on Martinique,* **FNU-71**

Sesabo, J.K. and R.S.J. Tol (2005), *Factor affecting Income Strategies among households in Tanzanian Coastal Villages: Implication for Development-Conservation Initiatives,* **FNU-70** (submitted)

Fisher, B.S., G. Jakeman, H.M. Pant, M. Schwoon. and R.S.J. Tol (2005), *CHIMP: A Simple Population Model for Use in Integrated Assessment of Global Environmental Change*, **FNU-69** (submitted)

Rehdanz, K. and R.S.J. Tol (2005), *A No Cap But Trade Proposal for Greenhouse Gas Emission Reduction Targets for Brazil, China and India*, **FNU-68** (submitted)

Zhou, Y. and R.S.J. Tol (2005), *Water Use in China's Domestic, Industrial and Agricultural Sectors: An Empirical Analysis*, **FNU-67** (submitted)

Rehdanz, K. (2005), *Determinants of residential space heating demand in Germany*, **FNU-66** (submitted)

Ronneberger, K., R.S.J. Tol and U.A. Schneider (2005), *KLUM: A simple model of global agricultural land use as a coupling tool of economy and vegetation,* **FNU-65** (submitted)

Tol, R.S.J. (2005), *The Benefits of Greenhouse Gas Emission Reduction: An Application of* FUND, **FNU-64** (submitted)

Röckmann, C., M.A. St.John, F.W. Köster, F.W. and R.S.J. Tol (2005), *Testing the implications of a marine reserve on the population dynamics of Eastern Baltic cod under varying environmental conditions,* **FNU-63** (submitted)

Letsoalo, A., J. Blignaut, T. de Wet, M. de Wit, S. Hess, R.S.J. Tol and J. van Heerden (2005), *Triple Dividends of Water Consumption Charges in South Africa*, **FNU-62** (submitted)

Zandersen, M., Termansen, M., Jensen,F.S. (2005), *Benefit Transfer over Time of Ecosystem Values: the Case of Forest Recreation,* **FNU-61** (submitted)

Rehdanz, K., Jung, M., Tol, R.S.J. and Wetzel, P. (2005), *Ocean Carbon Sinks and International Climate Policy*, **FNU-60** (forthcoming, *Energy Policy*)

Schwoon, M. (2005), *Simulating The Adoption of Fuel Cell Vehicles*, **FNU-59** (submitted)

Bigano, A., J.M. Hamilton and R.S.J. Tol (2005), *The Impact of Climate Change on Domestic and International Tourism: A Simulation Study*, **FNU-58** (forthcoming, *Climate Research*)

Bosello, F., R. Roson and R.S.J. Tol (2004), *Economy-wide estimates of the implications of climate change: Human health*, **FNU-57** (forthcoming, *Ecological Economics*)

Hamilton, J.M. and M.A. Lau (2004) *The role of climate information in tourist destination choice decision-making,* **FNU-56** (forthcoming, Gössling, S. and C.M. Hall (eds.), Tourism and Global Environmental Change. London: Routledge)

Bigano, A., J.M. Hamilton and R.S.J. Tol (2004), *The impact of climate on holiday destination choice*, **FNU-55** (forthcoming, *Climatic Change*)

Bigano, A., J.M. Hamilton, M. Lau, R.S.J. Tol and Y. Zhou (2004), *A global database of domestic and international tourist numbers at national and subnational level*, **FNU-54** (submitted)

Susandi, A. and R.S.J. Tol (2004), *Impact of international emission reduction on energy and forestry sector of Indonesia*, **FNU-53** (submitted)

Hamilton, J.M. and R.S.J. Tol (2004), *The Impact of Climate Change on Tourism and Recreation*, **FNU-52** (forthcoming, Schlesinger et al. (eds.), Cambridge University Press)

Schneider, U.A. (2004), *Land Use Decision Modelling with Soil Status Dependent Emission Rates*, **FNU-51** (submitted)

Link, P.M., U.A. Schneider and R.S.J. Tol (2004), *Economic impacts of changes in fish population dynamics: the role of the fishermen's harvesting strategies*, **FNU-50** (submitted)

Berritella, M., A. Bigano, R. Roson and R.S.J. Tol (2004), *A General Equilibrium Analysis of Climate Change Impacts on Tourism*, **FNU-49** (forthcoming, *Tourism Management*)

Tol, R.S.J. (2004), *The Double Trade-Off between Adaptation and Mitigation for Sea Level Rise: An Application of* FUND, **FNU-48** (submitted, *Mitigation and Adaptation Strategies for Global Change*)

Erdil, Erkan and Yetkiner, I. Hakan (2004), *A Panel Data Approach for Income-Health Causality,* **FNU-47**

Tol, R.S.J. (2004), *Multi-Gas Emission Reduction for Climate Change Policy: An Application of* FUND, **FNU-46** (forthcoming, *Energy Journal*)

Tol, R.S.J. (2004), *Exchange Rates and Climate Change: An Application of* FUND*,* **FNU-45** (forthcoming, *Climatic Change*)

Gaitan, B., Tol, R.S.J, and Yetkiner, I. Hakan (2004), *The Hotelling's Rule Revisited in a Dynamic General Equilibrium Model*, **FNU-44** (submitted)

Rehdanz, K. and Tol, R.S.J (2004), *On Multi-Period Allocation of Tradable Emission Permits*, **FNU-43** (submitted)

Link, P.M. and Tol, R.S.J. (2004), *Possible Economic Impacts of a Shutdown of the Thermohaline Circulation: An Application of* FUND, **FNU-42** (*Portuguese Economic Journal*, **3**, 99-114)

Zhou, Y. and Tol, R.S.J. (2004), *Evaluating the costs of desalination and water transport,* **FNU-41** (f*Water Resources Research,* **41** (3), W03003)

Lau, M. (2004), *Küstenzonenmanagement in der Volksrepublik China und Anpassungsstrategien an den Meeresspiegelanstieg,***FNU-40** (submitted, *Coastline Reports*)

Rehdanz, K. and Maddison, D. (2004), *The Amenity Value of Climate to German Households*, **FNU-39** (submitted)

Bosello, F., Lazzarin, M., Roson, R. and Tol, R.S.J. (2004), *Economy-wide Estimates of the Implications of Climate Change: Sea Level Rise*, **FNU-38** (submitted, *Environmental and Resource Economics*)

Schwoon, M. and Tol, R.S.J. (2004), *Optimal CO_2-abatement with socio-economic inertia and induced technological change*, **FNU-37** (submitted, *Energy Journal*)

Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2004), *The Effects of Climate Change on International Tourism,* **FNU-36** (forthcoming, *Climate Research*)

Hansen, O. and R.S.J. Tol (2003), *A Refined Inglehart Index of Materialism and Postmaterialism*, **FNU-35** (submitted)

Heinzow, T. and R.S.J. Tol (2003), *Prediction of Crop Yields across four Climate Zones in Germany: An Artificial Neural Network Approach,* **FNU-34** (submitted, *Climate Research*)

Tol, R.S.J. (2003), *Adaptation and Mitigation: Trade-offs in Substance and Methods,* **FNU-33** (forthcoming, *Environmental Science and Policy*)

Tol, R.S.J. and T. Heinzow (2003), *Estimates of the External and Sustainability Costs of Climate Change*, **FNU-32** (submitted)

Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2003), *Climate change and international tourism: a simulation study,* **FNU-31** (*Global Environmental Change,* **15** (3), 253-266)

Link, P.M. and R.S.J. Tol (2003), *Economic impacts of changes in population dynamics of fish on the fisheries in the Barents Sea*, **FNU-30** (submitted)

Link, P.M. (2003), *Auswirkungen populationsdynamischer Veränderungen in Fischbeständen auf die Fischereiwirtschaft in der Barentssee*, **FNU-29** (*Essener Geographische Arbeiten*, **35**, 179-202)

Lau, M. (2003), *Coastal Zone Management in the People's Republic of China – An Assessment of Structural Impacts on Decision-making Processes*, **FNU-28** (submitted)

Lau, M. (2003), *Coastal Zone Management in the People's Republic of China – A Unique Approach?*, **FNU-27** (*China Environment Series,* Issue 6, pp. 120-124; http://www.wilsoncenter.org/topics/pubs/7-commentaries.pdf)

Roson, R. and R.S.J. Tol (2003), *An Integrated Assessment Model of Economy-Energy-Climate – The Model Wiagem: A Comment*, **FNU-26** (forthcoming, *Integrated Assessment*)

Yetkiner, I.H. (2003), *Is There An Indispensable Role For Government During Recovery From An Earthquake? A Theoretical Elaboration*, **FNU-25**

Yetkiner, I.H. (2003), *A Short Note On The Solution Procedure Of Barro And Sala-i-Martin for Restoring Constancy Conditions*, **FNU-24**

Schneider, U.A. and B.A. McCarl (2003), *Measuring Abatement Potentials When Multiple Change is Present: The Case of Greenhouse Gas Mitigation in U.S. Agriculture and Forestry*, **FNU-23** (submitted)

Zhou, Y. and Tol, R.S.J. (2003), *The Implications of Desalination to Water Resources in China - an Economic Perspective*, **FNU-22** (*Desalination*, **163** (4), 225-240)

Yetkiner, I.H., de Vaal, A., and van Zon, A. (2003), *The Cyclical Advancement of Drastic Technologies*, **FNU-21**

Rehdanz, K. and Maddison, D. (2003) *Climate and Happiness*, **FNU-20** (*Ecological Economics,* **52** 111-125)

Tol, R.S.J., (2003), *The Marginal Costs of Carbon Dioxide Emissions: An Assessment of the Uncertainties*, **FNU-19** (*Energy Policy,* **33** (16), 2064-2074).

Lee, H.C., B.A. McCarl, U.A. Schneider, and C.C. Chen (2003), *Leakage and Comparative Advantage Implications of Agricultural Participation in Greenhouse Gas Emission Mitigation*, **FNU-18** (submitted).

Schneider, U.A. and B.A. McCarl (2003), *Implications of a Carbon Based Energy Tax for U.S. Agriculture*, **FNU-17** (submitted).

Tol, R.S.J. (2002), *Climate, Development, and Malaria: An Application of* FUND, **FNU-16** (forthcoming, *Climatic Change*).

Hamilton, J.M. (2003), *Climate and the Destination Choice of German Tourists,* **FNU-15** (revised and submitted).

Tol, R.S.J. (2002), *Technology Protocols for Climate Change: An Application of* FUND, **FNU-14** (*Climate Policy,* **4**, 269-287).

Rehdanz, K (2002), *Hedonic Pricing of Climate Change Impacts to Households in Great Britain*, **FNU-13** (forthcoming, *Climatic Change*).

Tol, R.S.J. (2002), *Emission Abatement Versus Development As Strategies To Reduce Vulnerability To Climate Change: An Application Of* FUND, **FNU-12** (forthcoming, *Environment and Development Economics*).

Rehdanz, K. and Tol, R.S.J. (2002), *On National and International Trade in Greenhouse Gas Emission Permits*, **FNU-11** (forthcoming, *Ecological Economics*).

Fankhauser, S. and Tol, R.S.J. (2001), *On Climate Change and Growth*, **FNU-10** (*Resource and Energy Economics*, **27**, 1-17).

Tol, R.S.J.and Verheyen, R. (2001), *Liability and Compensation for Climate Change Damages – A Legal and Economic Assessment*, **FNU-9** (*Energy Policy*, **32** (9), 1109-1130).

Yohe, G. and R.S.J. Tol (2001), *Indicators for Social and Economic Coping Capacity – Moving Toward a Working Definition of Adaptive Capacity*, **FNU-8** (*Global Environmental Change*, **12** (1), 25-40).

Kemfert, C., W. Lise and R.S.J. Tol (2001), *Games of Climate Change with International Trade*, **FNU-7** (*Environmental and Resource Economics*, **28**, 209-232).

Tol, R.S.J., W. Lise, B. Morel and B.C.C. van der Zwaan (2001), *Technology Development and Diffusion and Incentives to Abate Greenhouse Gas Emissions*, **FNU-6** (submitted).

Kemfert, C. and R.S.J. Tol (2001), *Equity, International Trade and Climate Policy*, **FNU-5** (*International Environmental Agreements*, **2**, 23-48).

Tol, R.S.J., Downing T.E., Fankhauser S., Richels R.G. and Smith J.B. (2001), *Progress in Estimating the Marginal Costs of Greenhouse Gas Emissions*, **FNU-4**. (*Pollution Atmosphérique – Numéro Spécial: Combien Vaut l'Air Propre?*, 155-179).

Tol, R.S.J. (2000), *How Large is the Uncertainty about Climate Change?*, **FNU-3** (*Climatic Change*, **56** (3), 265-289).

Tol, R.S.J., S. Fankhauser, R.G. Richels and J.B. Smith (2000), *How Much Damage Will Climate Change Do? Recent Estimates*, **FNU-2** (*World Economics,* **1** (4), 179-206)

Lise, W. and R.S.J. Tol (2000), *Impact of Climate on Tourism Demand*, **FNU-1** (*Climatic Change*, **55** (4), 429-449).