

Possible Economic Impacts of a Shutdown of the Thermohaline Circulation: an Application of *FUND*

Working Paper FNU-42

P. Michael Link ^{a,b} and Richard S.J. Tol ^{a,c,d}

^a Centre for Marine and Atmospheric Sciences, Hamburg University, Hamburg, Germany

^b International Max Planck Research School of Earth System Modelling, Hamburg, Germany

^c Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands

^d Center for Integrated Study of the Human Dimensions of Global Change, Carnegie Mellon University, Pittsburgh, PA, USA

Abstract

Climate change can lead to a substantial reduction of the strength of the thermohaline circulation in the world oceans. This is often thought to have severe consequences particularly on the North Atlantic region and Northern and Western Europe. The integrated assessment model *FUND* is used to estimate the extent of these impacts. The results indicate that, owing to a slower warming (rather than cooling) of the regions most affected by a thermohaline circulation collapse, climate change induced damages in these regions would be smaller in case of a shutdown of the thermohaline circulation. However, even with a thermohaline circulation collapse, the total and marginal impacts of climate change are negative.

Key words

climate change, climate change impacts, thermohaline circulation, integrated assessment

1. Introduction

In today's climate, the North Atlantic region and Northwestern Europe benefit from the heat transported northwards by the thermohaline circulation in the Atlantic Ocean. This causes this area to be much warmer than comparable regions at the same latitude, with annual mean air temperatures in Scandinavia exceeding the zonal average by more than 10°C (Rahmstorf & Ganopolski, 1999). However, the mechanism that drives the thermohaline circulation is quite sensitive to climatic conditions, and paleoclimatic records suggest that there have been significant fluctuations of the strength of the thermohaline circulation in the past (Dansgaard *et al.*, 1993). Periods of extended cooling in the North Atlantic region and Northern and Western Europe can be related to periods of inhibited heat transport to the North in the Atlantic Ocean caused by a shutdown or severe weakening of the thermohaline circulation.

A change of existing climate conditions caused by the continued emission of large amounts of carbon dioxide into the atmosphere from anthropogenic activities will lead to higher global mean temperatures which in turn can result in a weakening or even a complete shutdown of the thermohaline circulation (Manabe & Stouffer, 1993; Rahmstorf & Ganopolski, 1999; Schmittner & Stocker, 1999). The consequences of such a shutdown are manifold: The oceanic uptake of carbon may be reduced (Schmittner & Stocker, 1999), the climate of Northern and Western Europe will be severely affected (Broecker, 1997), and there may be pronounced economic and societal impacts, e.g. caused by decreased agricultural yields and

lower landings of the world's high seas fisheries (Rahmstorf, 1997; Keller *et al.*, 2000; Link & Tol, 2003).

The impacts of a possible shutdown of the thermohaline circulation can be analyzed using integrated assessment models. Using the model *DICE* (Nordhaus, 1994), Keller *et al.* (2000) determine the optimal investments and emission paths of anthropogenic carbon dioxide if the thermohaline circulation is supposed to be preserved. Results indicate that emission abatement is only of minor importance if the state of the thermohaline circulation is neglected but becomes an urgent matter if the current state of the thermohaline circulation is to be maintained. Damages related to the collapse of the thermohaline circulation are *assumed* to be slightly less than 1% of the gross world product and can be attributed to a considerable degree to a decreased uptake of carbon dioxide by the ocean and to decreased harvest yields of fisheries that result from pronounced changes in sea-surface temperatures in the world oceans.

In Mastrandrea & Schneider (2001), the DICE-model is coupled to a simple climate model that allows for analyses of climate scenarios in which abrupt changes occur endogenously (rather than requiring exogenous climate scenarios, often with only smooth transitions). In this context, the policy relevance of possible abrupt climate changes is addressed. Sensitivity studies with that coupled model show that the incorporation of the possibilities of abrupt future climate change has a profound impact on present and near-term optimal carbon taxes, increasing them by up to an order of magnitude depending on the type of discounting used in the simulation. This highlights the importance of near-term emission reduction since results indicate that it might be impossible to prevent a collapse of the thermohaline circulation despite extensive mitigation measures if they occur too late in time. Mastandrea and Schneider (2001), like Keller *et al.* (2000), *assume* economic impacts of a thermohaline circulation collapse. In this paper, we *estimate* the economic impacts. We do not do a decision analysis, however.

Climate scenarios of a shutdown of the thermohaline circulation agree that the North Atlantic region and large parts of Europe, but also to some degree the North American continent, would be affected by a considerable cooling over the North Atlantic. Thus, a thermohaline circulation collapse would impact some of the economically most potent regions of the world. Based on climate scenarios from a climate system model of intermediate complexity (*CLIMBER-2*), this study investigates the extent of the overall economic and societal impacts of a possible shutdown or weakening of the thermohaline circulation using the integrated assessment model *FUND*, with a particular focus on the North Atlantic region and the surrounding continents of Europe and North America.

The following section presents the model *FUND* and addresses the extensions of the current version of this integrated assessment model. Section 3 looks at the climate scenarios used in this analysis. Section 4 presents the results of the simulations of with *FUND*. Section 5 discusses the results and concludes the paper.

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 (1999a-e, 2001, 2002a), except for the impact module, which is described by Tol (2002b,c) and updated by Tol (2002d). A further difference is that the current version of the model distinguishes 16 instead of 9 regions. The current version of the model also includes diarrhea, not incorporated in earlier versions of *FUND*, as well as a new formulation of the relationship between vector-borne diseases and income growth.

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. Refer to Appendix 1 for a complete overview of the regions used in *FUND*. 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 22nd and 23rd 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 climate scenarios for the period 2010-2300 are as used by Rahmstorf & Ganopolski (1999), who follow the IPCC IS92e scenario (Houghton *et al.*, 1995) until 2100, causing a peak of the atmospheric carbon dioxide concentration at roughly 1200 ppm in 2150. It is further assumed that carbon dioxide emissions are zero as of 2200. Two cases are considered: one in which the thermohaline circulation of the world oceans recovers after a period of weakening and another case in which the thermohaline circulation breaks down almost entirely as a consequence of changes in climatic conditions. The smoothed regional differences between these two scenarios are added to the regional climate changes as generated by *FUND*, using the *FUND* scenario for population, technology and emissions; the *FUND* scenario is close to IS92e until 2100; following Rahmstorf & Ganopolski (1999), emissions are driven to close to zero by 2200.

The scenarios concern the rate of population growth, economic growth, autonomous energy efficiency improvements, 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 cause 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. Thus, climate change reduces the long-term economic growth, although for the short term the consumption is particularly affected. 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:

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

where C denotes the concentration, E the emissions, t the year, and pre the pre-industrial concentration. Table 1 lists the parameters for both gases.

Table 1: Parameters of equation (1) (based on Schimel *et al.*, 1996)

gas	α^a	β^b	pre-industrial concentration
methane (CH ₄)	0.3597	1/8.6	790 ppbv
nitrous oxide (N ₂ O)	0.2079	1/120	285 ppbv

^a The parameter α translates emissions in millions of metric tons of CH₄ or N₂O into concentrations in parts per billion by volume.

^b The parameter β determines how fast concentrations return to their pre-industrial (and assumed equilibrium) concentrations; the reciprocal of β is the atmospheric life time of the gases in years.

The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is derived from a five-box model:

$$(2a) \quad Box_{i,t} = \rho_i Box_{i,t} + 0.000471 \alpha_i E_t$$

where

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

Here α_i denotes the fraction of emissions E (in million metric tons of carbon) that is allocated to box i (0.13, 0.20, 0.32, 0.25 and 0.10 respectively) and ρ the rate of decay of the boxes ($\rho = \exp(-1 / \text{life time})$). The life times in the boxes are ∞ , 363, 74, 17, and 2 years respectively. This model is based on Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt *et al.* (1992). According to this model, 13 per cent of total emissions remain in the atmosphere indefinitely, while 10 per cent are removed within an average time period of two years.

The radiative forcing of carbon dioxide, methane and nitrous oxide 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, so:

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

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 is based on Tol (2002b,c). The following impact categories of climate change are considered: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhea, energy consumption, water resources, and unmanaged ecosystems.

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 modeled explicitly. The monetary value of a loss of one square kilometer 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 kilometer. Wetland losses are valued at \$2 million per square kilometer 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).

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).

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 behavior 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, malaria, dengue fever, and schistosomiasis are modeled as simple power functions. Impacts are either negative or positive, and do not change sign (cf. Tol, 2002c). Diarrhea follows a similar logic. The number of additional diarrhea deaths D^d is given by

$$(4) \quad D_{r,t}^d = \mu_r^d P_{r,t} \left(\frac{y_{r,t}}{y_{r,0}} \right)^\varepsilon (T_{r,t}^\eta - T_{r,0}^\eta)$$

where P denotes population, y per capita income, and T regional temperature; μ is the baseline mortality, ε (see below) and $\eta=1.14$ (with a standard deviation of 0.51) are parameters; r indexes region, and t time. Equation (4) was estimated based on the WHO Global Burden of Diseases data (http://www.who.int/health_topics/

global_burden_of_disease/en/). Diarrhea morbidity has the same equation as mortality, but with $\eta=0.70$ (0.26).

Table 2: Diarrhea mortality and morbidity due to a 2.5°C global warming.

Region	Population ^a	Mortality ^b	Morbidity ^c	ΔT^d	Additional Mortality ^e			Additional Morbidity ^f		
USA	278357	0.041	1.704	3.0	40	(23	70)	1019	(767	1354)
CAN	31147	0.041	1.704	3.7	6	(3	11)	132	(94	185)
WEU	388581	0.015	0.632	2.8	18	(11	31)	506	(387	662)
JPK	173558	0.009	0.166	2.6	5	(3	8)	57	(44	73)
ANZ	22748	0.001	0.083	2.4	0	(0	0)	3	(3	4)
EEU	121191	0.018	0.847	2.9	7	(4	13)	217	(164	287)
FSU	291538	0.122	6.735	3.2	135	(74	244)	4443	(3279	6020)
MDE	237590	0.030	0.166	2.9	24	(14	41)	83	(63	109)
CAM	135222	0.162	0.643	2.2	54	(36	81)	151	(123	185)
LAM	345779	0.168	0.650	2.1	138	(94	202)	381	(313	463)
SAS	1366902	0.229	0.896	2.3	798	(526	1212)	2171	(1755	2687)
SEA	522462	0.135	0.631	1.8	136	(102	182)	492	(424	571)
CHI	1311659	0.033	0.401	3.0	150	(86	261)	1122	(846	1488)
MAF	143482	0.415	0.990	2.9	197	(116	337)	296	(225	389)
SSA	637887	3.167	5.707	2.2	4958	(3321	7404)	6306	(5141	7737)
SIS	44002	0.252	1.092	1.9	23	(17	31)	75	(63	88)

^a Thousands of people, 2000.

^b Deaths per thousand people.

^c Years of life diseased per thousand people.

^d Regional temperature change for a 2.5°C global warming.

^e Additional deaths, thousands of people (67% confidence interval in brackets).

^f Additional years of life diseased, thousands (67% confidence interval in brackets).

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). Vector-borne diseases fall with economic growth, using a per capita income elasticity of -2.65 with a standard deviation of 0.69.¹ The income elasticity of diarrhea mortality is -1.58 (0.23), for diarrhea morbidity -0.42 (0.12). These elasticities were estimated based on the WHO Global Burden of Diseases data (http://www.who.int/health_topics/global_burden_of_disease/en/).

Carbon dioxide emissions are calculated on the basis of the Kaya identity. Emissions can be modified by political measures, e.g. by a carbon tax. The costs of emission reduction are subject to learning by doing, so that emission abatement in early time periods of the simulations reduces the costs of emission abatement in subsequent periods. The exact specification is given by Tol (2002e). The aspect of greenhouse gas emission reduction is not considered in this paper.

¹ In previous model versions, vector-borne diseases fall linearly to zero at an annual per capita income of \$3100, based on Tol & Dowlatabadi (2001). Increased data availability allowed us to move away from this simple representation.

3. Climate change scenarios

The climate change scenarios used in this study were derived using the climate system model *CLIMBER-2*. The characteristics of this climate model of intermediate complexity are described in detail in Petoukhov *et al.* (2000) and Ganopolski *et al.* (2001). *CLIMBER-2* is particularly useful to assess long-term scenarios that last several centuries up to millenia which have implications on a global scale.

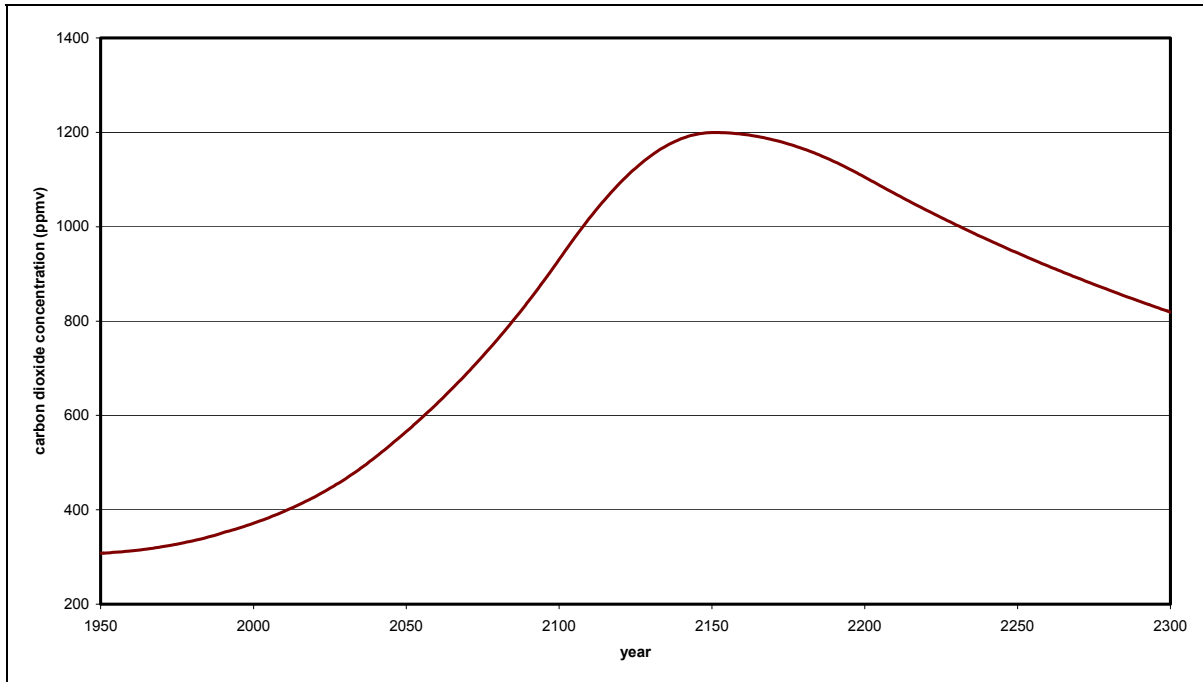


Figure 1: Carbon dioxide forcing scenario (based on Houghton *et al.*, 1995)

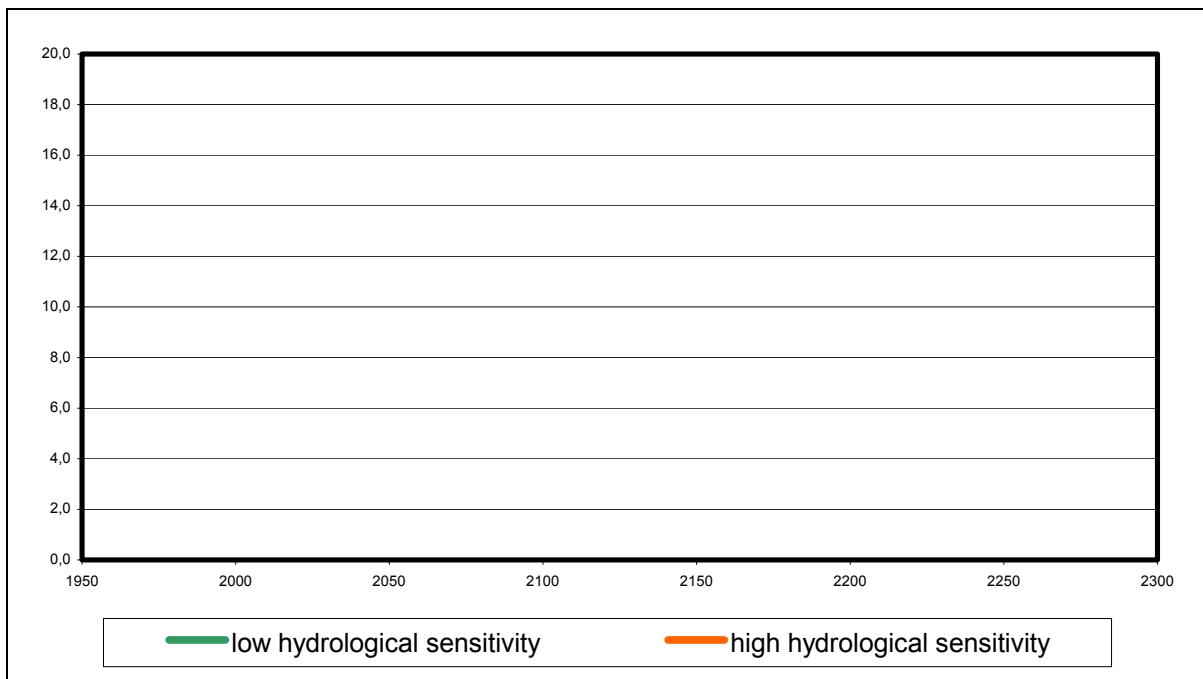


Figure 2: Formation of North Atlantic Deep Water (based on Rahmstorf & Ganopolski, 1999)

In this analysis, *FUND* is driven with climate scenarios that represent the time period between 1950 and 2300 in the long-term climate development simulated in Rahmstorf & Ganopolski (1999) which is based on radiative forcing as described in the IPCC IS92e

scenario (Houghton *et al.*, 1995). In this scenario the carbon dioxide concentrations (Fig. 1) increase rapidly in the 21st and early 22nd centuries until reaching a peak in 2150 at close to 1200 ppmv. After that a long-term decline of the carbon dioxide concentration in the atmosphere sets in. Two scenarios are considered (Fig.2): one in which the thermohaline circulation weakens during the 21st century by approximately 50 per cent but starts to slowly recover in the 22nd century (low hydrological sensitivity), and another in which the thermohaline circulation breaks down completely by the early 23rd century and does not recover (high hydrological sensitivity).

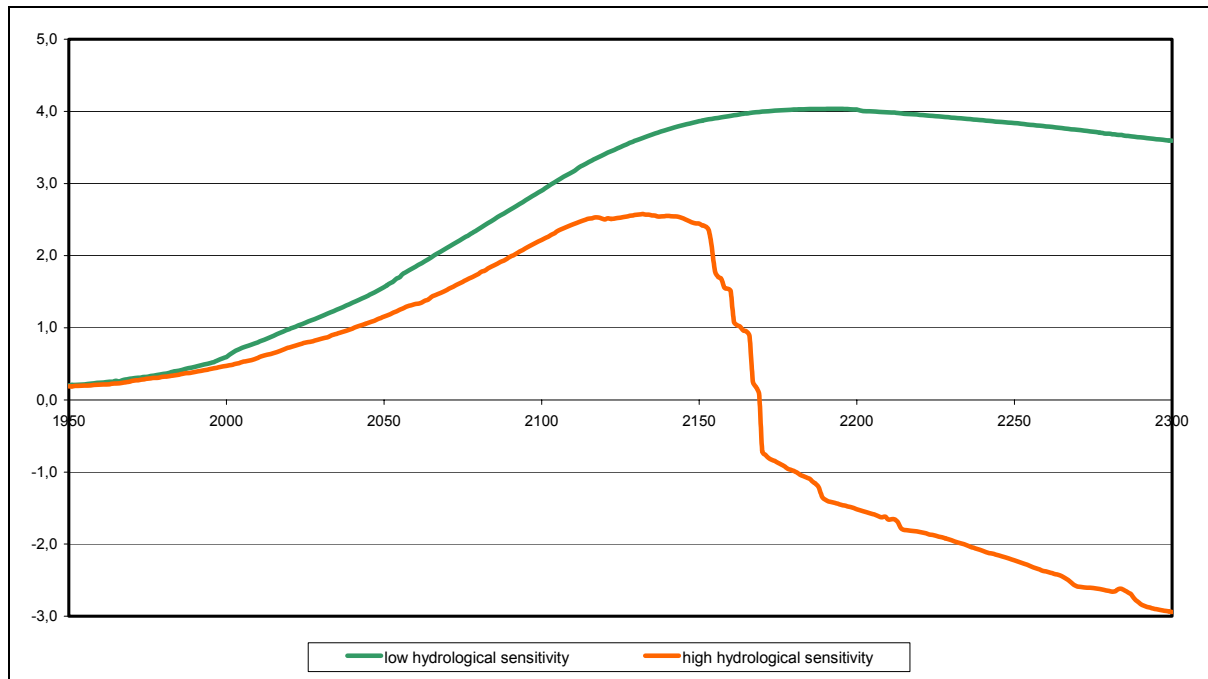


Figure 3: Winter surface air temperature over the North Atlantic Ocean at 56°N (adapted from Rahmstorf & Ganopolski, 1999)

The global annual mean surface air temperature changes are very similar in both scenarios (Rahmstorf & Ganopolski, 1999), but regional differences are significant. If the thermohaline circulation breaks down completely, the North Atlantic region cools strongly after an initial warming period, with a decline of winter temperatures by more than 4°C from its peak in the early 22nd century to the year 2300 (Fig. 3). In contrast, the scenario without a collapse of the thermohaline circulation shows an increase of winter temperatures over the North Atlantic by more than 4°C until a peak in the late 22nd century is reached. After that a slow decline sets in but temperatures always remain much warmer than the initial conditions. The temperature time series were adapted to fit the regions covered by *FUND* and then used to drive the integrated assessment of the development of climate conditions.

4. Results

The three regions most affected by a shutdown of the thermohaline circulation are the USA, Canada, and Western Europe. Figure 4 displays the climate scenarios for the three regions. Figure 4 shows that a thermohaline circulation collapse leads to a cooling relative to the base scenario, but not to an absolute cooling; in fact, the shutdown of the thermohaline circulation merely slows warming.

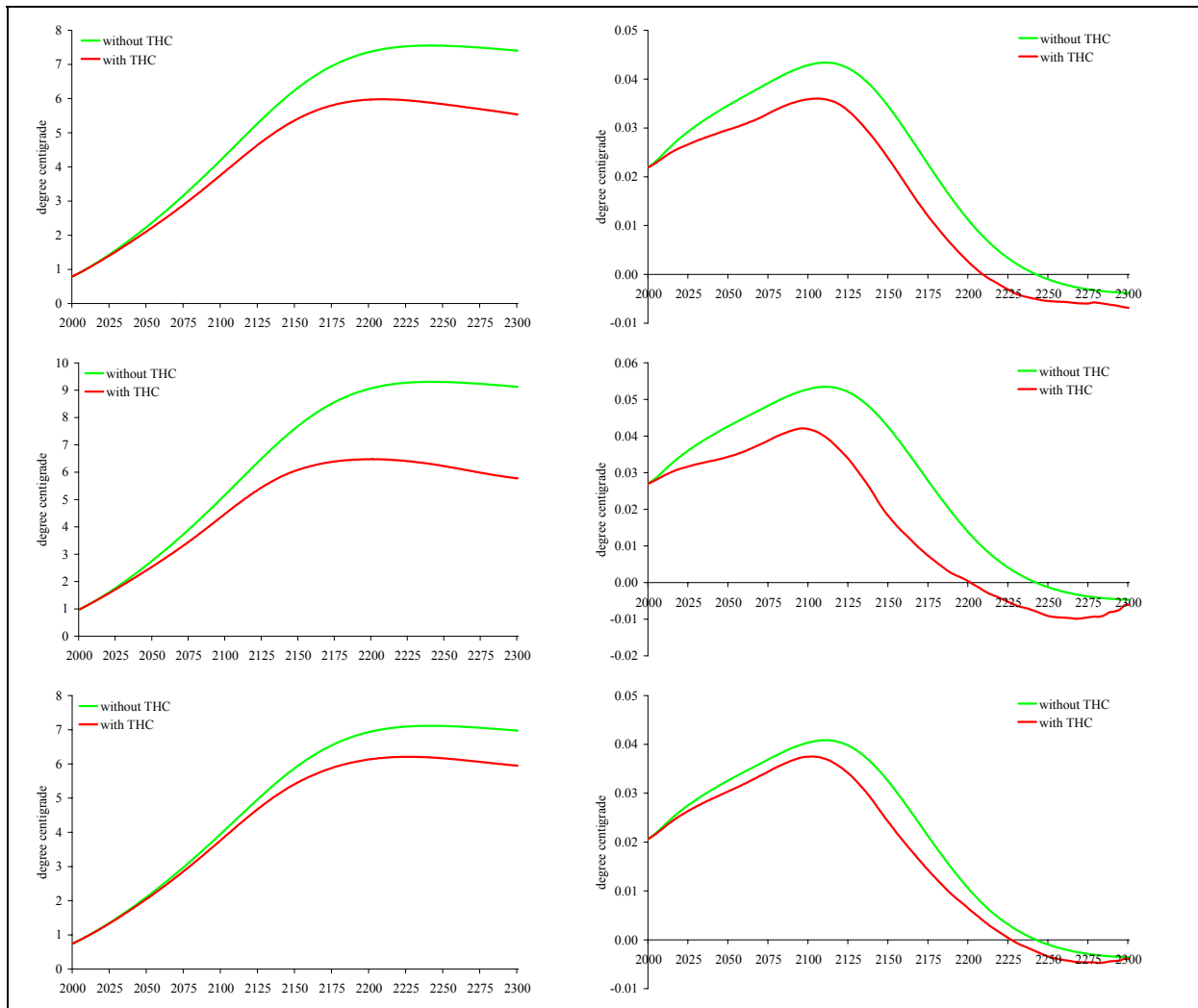


Figure 4: The annual mean temperature of the USA (top panel), Canada (middle panel) and Western Europe (bottom panel) in deviation from the pre-industrial temperature (left panel) and the rate of annual temperature change (right panel).

Figure 5 displays the market and non-market impacts for the three regions for the scenarios with and without a thermohaline circulation collapse. The market impacts are straightforward in their interpretation. Although *FUND* does recognize that climate change may have beneficial impacts, particularly in developed, temperate countries, these benefits occur only in the first half of the 21st century. After that, global warming has reached a point after which additional warming is generally detrimental. As shown in Figure 4, a collapse of the thermohaline circulation would slow warming, and therefore reduce climate change damages. The reduction of market damages is about 0.5% of GDP in Western Europe, and about 0.4% in the USA and Canada. In fact, the overall impacts on Canada are close to zero with a thermohaline circulation collapse.

Non-market impacts are more complicated, although here as well less warming implies less damage. There is a discontinuity in the non-market damages in the USA; this happens at the point at which the warming trend stops and cooling sets in. Species extinction is assumed to be entirely driven by the absolute value of the rate of climate change, which is zero at that point. This point is brought forward in time by a shutdown of the thermohaline circulation. Western Europe follows the same pattern as the USA, but here the two scenarios almost coincide, whereas Canada shows the same patterns but more pronounced as higher latitudes warm faster.

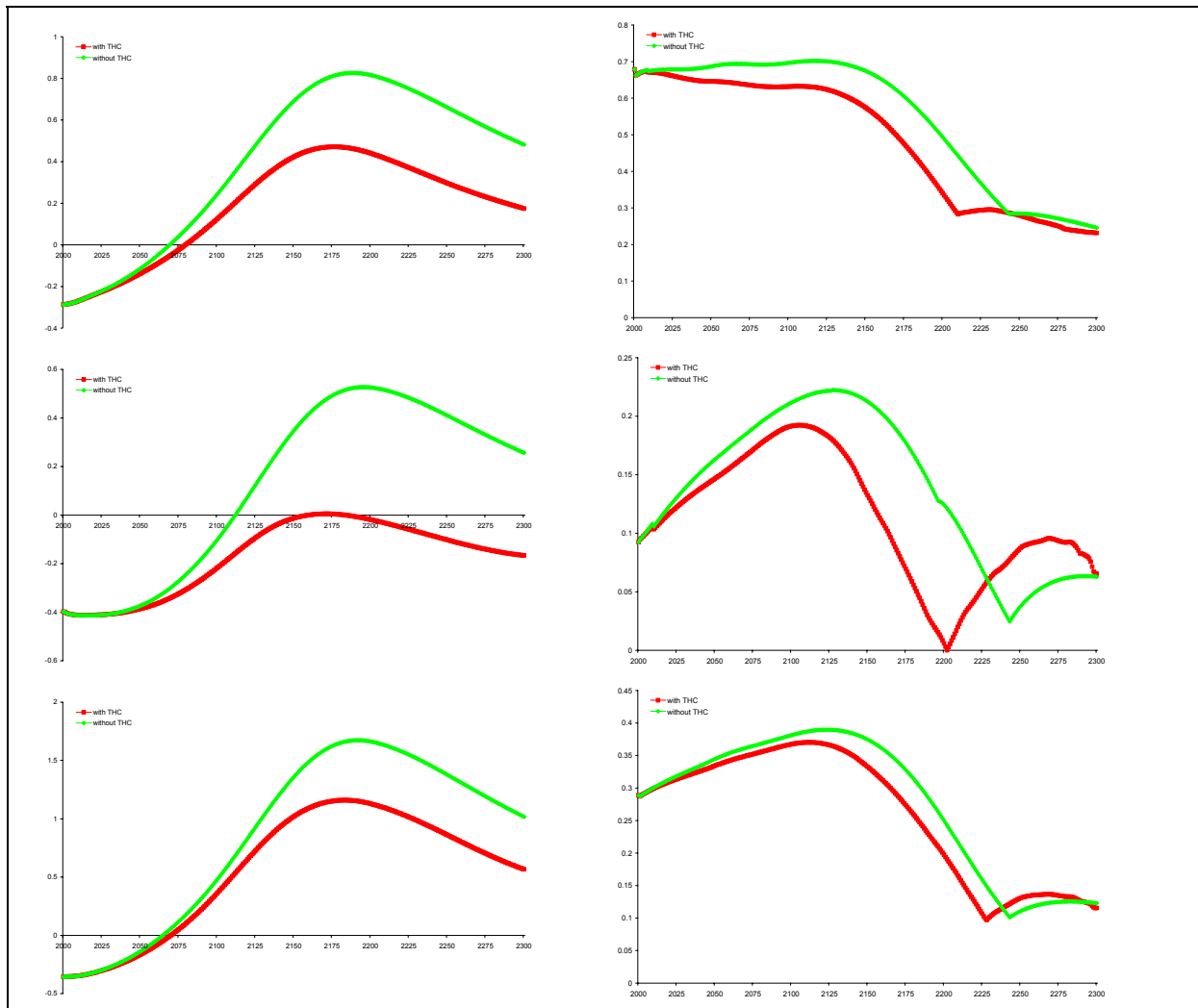


Figure 5: The market (left panel) and non-market (right panel) damages of climate change, expressed as a percentage of GDP for the USA (top panel), Canada (middle panel) and Western Europe (bottom panel) with and without a thermohaline circulation collapse.

Table 3: Marginal damage costs of climate change (\$/t C) with and without a thermohaline circulation collapse (THC), for three alternative discount rates (0, 1 and 3 per cent pure rate of time preference), for simple summation (SS) and equity weighing (EW).

Discount rate	0 %		1 %		3 %	
	SS	EW	SS	EW	SS	EW
No THC	79.0	170.0	25.2	94.1	5.1	45.1
THC	75.6	167.8	24.4	93.6	5.0	45.0

Table 3 shows the marginal damage costs of carbon dioxide emissions. As expected, a collapse of the thermohaline circulation reduces the marginal damage costs, but this reduction is not very pronounced since a thermohaline circulation collapse would only occur near the end of the model duration and discounting – even with a utility discount rate of zero – would weigh that time period less than a time period less far into the future. Another reason is that a collapse of the thermohaline circulation would substantially affect only a certain part of the world.

5. Discussion and conclusion

The potential shutdown of the thermohaline circulation is widely seen as a strong reason for greenhouse gas emission reduction. Indeed, a scenario in which Western Europe would rapidly cool to a Canadian climate would be costly for both people and nature. However, this doom scenario seems to be inspired by a comparison of future climate snapshots with and without a thermohaline circulation collapse. If one would place the cooling due to a shutdown of the thermohaline circulation against the background of continuous global warming, the scenario looks less bleak. It should also be considered that the thermohaline shuts down at a time scale that is in the order of decades which is slow compared to the human time scale.

The climate change impacts model used in this study reflects the basic message of the climate change scenarios: As a thermohaline circulation collapse would slow warming, damages would be reduced. From this narrow perspective, a shutdown of the thermohaline circulation is to be welcomed, not to be feared. However, a thermohaline circulation collapse is part of the overall picture of climate change; it is not a separate decision variable. Climate change is a real problem, as both total and marginal impacts are negative, both with and without a thermohaline circulation collapse.

The impact estimates presented here are not complete, and our conclusions are therefore only tentative. A thermohaline circulation collapse would trigger major changes in the ecosystems of North Atlantic Ocean, which would affect commercially valuable fish stocks, such as cod, and species important to biodiversity and nature protection, such as whales. This is not included in the model. Furthermore, we use a geographical resolution that is coarse. For instance, we estimate the effects for Western Europe as a whole, while the impact of a thermohaline circulation collapse on Iceland, Ireland and Norway would be much more severe than on Greece and Italy. Finally, we compare single realizations of scenarios with and without a thermohaline circulation collapse. One reason to worry about a thermohaline circulation collapse is that it is a regime change, and the uncertainties around the state of the natural system are much greater than without a thermohaline circulation collapse. All these things are subjects for future research.

Acknowledgements

We are grateful to Till Kuhlbrodt for providing the CLIMBER data, and to Andre Krebber for processing them. The German Federal Ministry for Education and Research through the INTEGRATION project, the US National Science Foundation through the Center for Integrated Study of the Human Dimensions of Global Change (SBR-9521914) and the Michael Otto Foundation provided welcome financial support.

References

- Batjes, J.J. & Goldewijk, C.G.M. (1994): *The IMAGE 2 Hundred Year (1890-1990) Database of the Global Environment (HYDE)*, 410100082, Bilthoven: RIVM.
- Broecker, W. (1997): Thermohaline Circulation, the Achilles Heel of our Climate System: Will Man-Made CO₂ Upset the Current Balance?, *Science*, **278**: 1582-1588.
- Cline, W.R. (1992): *The Economics of Global Warming*, Washington, DC, Institute for International Economics, 399 pp.
- Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, N.S., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjörnsdóttir, A.E., Jouzel, J. &

- Bond, G. (1993): Evidence for General Instability of Past Climate from a 250-kyr Ice-Core Record, *Nature*, **364**: 218-220.
- Fankhauser, S. (1994): Protection vs. Retreat - The Economic Costs of Sea Level Rise, *Environment and Planning A*, **27**: 299-319.
- Ganopolski, A., Petoukhov, V., Rahmstorf, S., Brovkin, V., Claussen, M., Eliseev, A. & Kubatzki, C. (2001): CLIMBER-2: a climate system model of intermediate complexity. Part II: model sensitivity, *Climate Dynamics*, **17**: 735-751.
- Hammit, J.K., Lempert, R.J. & Schlesinger, M.E. (1992): A Sequential-Decision Strategy for Abating Climate Change, *Nature*, **357**: 315-318.
- Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. & Maskell, K. (1995): *Climate Change 1995*, Cambridge, Cambridge University Press, 572 pp.
- Kattenberg, A., Giorgi, F., Grassl, H., Mehl, 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: Houghton, J.T., Meiro Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. & 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 edition, Cambridge, Cambridge University Press, pp. 285-357.
- Keller, K., Tan, K., Morel, F.M.M. & Bradford, D.F. (2000): Preserving the Ocean Circulation: Implications for Climate Policy, *Climatic Change*, **47**: 17-43.
- Link, P.M. & Tol, R.S.J. (2003): Economic impacts of changes in population dynamics of fish on the fisheries in the Barents Sea, submitted.
- Maier-Reimer, E. & Hasselmann, K. (1987): Transport and Storage of Carbon Dioxide in the Ocean: An Inorganic Ocean Circulation Carbon Cycle Model, *Climate Dynamics*, **2**: 63-90.
- Manabe, S. & Stouffer, R.J. (1993): Century-scale effects of increased atmospheric CO₂ on the ocean-atmosphere system, *Nature*, **364**: 215-218.
- Mastrandrea, M.D. & Schneider, S.H. (2001): Integrated assessment of abrupt climatic changes, *Climate Policy*, **1**: 433-449.
- Mendelsohn, R., Schlesinger, M. & Williams, L. (2000): Comparing impacts across climate models, *Integrated Assessment*, **1**: 37-48.
- Nordhaus, W.D. (1994): *Managing the Global Commons: The Economics of Climate Change*, Cambridge, MA, The MIT Press, 213 pp.
- Petoukhov, V., Ganopolski, A., Brovkin, V., Claussen, M., Eliseev, A., Kubatzki, C. & Rahmstorf, S. (2000): CLIMBER-2: a climate system model of intermediate complexity. Part I: model description and performance for present climate, *Climate Dynamics*, **16**: 1-17.
- Rahmstorf, S. (1997): Risk of Sea-Change in the Atlantic, *Nature*, **388**: 825-826.
- Rahmstorf, S. & Ganopolski, A. (1999): Long-term global warming scenarios computed with an efficient coupled climate model, *Climatic Change*, **43**: 353-367.

- Prather, M., Derwent, R., Ehhalt, D., Fraser, P., Sanhueza, E., Zhou, X. (1996): Radiative Forcing of Climate Change – 2.2 Other Trace Gases and Atmospheric Chemistry. In: Houghton, J.T., Meiro Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. & 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 edition, Cambridge, Cambridge University Press, pp. 86-103.
- Schmittner, A. & Stocker, T.F. (1999): The Stability of the Thermohaline Circulation in Global Warming Experiments, *Journal of Climate*, **12**: 1117-1133.
- Shine, K.P., Derwent, R.G., Wuebbles, D.J. & Morcrette, J.-J. (1990): Radiative Forcing of Climate. In: Houghton, J.T., Jenkins, G.J. & Ephraums, J.J. (eds.), *Climate Change - The IPCC Scientific Assessment*, 1st edition, Cambridge, Cambridge University Press, 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. (1999a): The Marginal Costs of Greenhouse Gas Emissions, *Energy Journal*, **20** (1): 61-81.
- Tol, R.S.J. (1999b): Time Discounting and Optimal Control of Climate Change – an Application of *FUND*, *Climatic Change*, **41** (3-4): 351-362.
- 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): Spatial and Temporal Efficiency in Climate Change: 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 specifications and optimal control of climate change: an application of *FUND*, *Energy Economics*, **24**: 367-376.
- Tol, R.S.J. (2002b): Estimates of the Damage Costs of Climate Change - Part 1: Benchmark Estimates, *Environmental and Resource Economics*, **21**: 47-73.
- Tol, R.S.J. (2002c): Estimates of the Damage Costs of Climate Change - Part II: Dynamic Estimates, *Environmental and Resource Economics*, **21**: 135-160.
- Tol, R.S.J. (2002d): *Emission Abatement versus Development as Strategies to Reduce Vulnerability to Climate Change: an Application of FUND*, Research Unit Sustainability and Global Change, **FNU-12**, Centre for Marine and Climate Research, Hamburg University, Hamburg, Germany.

Tol, R.S.J. (2002e): *Technology Protocols for Climate Change: an Application of FUND*, Research Unit Sustainability and Global Change, **FNU-14**, Centre for Marine and Climate Research, Hamburg University, Hamburg, Germany.

Tol, R.S.J. & Dowlatabadi, H. (2001): Vector-borne diseases, development and climate change, *Integrated Assessment*, **2**: 173-181.

WRI (2000), *World Resources Database 2000-2001*, Washington, DC, World Resources Institute.

Appendix 1: The regions in FUND

<i>Acronym</i>	<i>Name</i>	<i>Countries</i>
USA	USA	United States of America
CAN	Canada	Canada
WEU	Western Europe	Andorra, Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Malta, Monaco, Netherlands, Norway, Portugal, San Marino, Spain, Sweden, Switzerland, United Kingdom
JPK	Japan and South Korea	Japan, South Korea
ANZ	Australia and New Zealand	Australia, New Zealand
CEE	Central and Eastern Europe	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, FYR Macedonia, Poland, Romania, Slovakia, Slovenia, Yugoslavia
FSU	Former Soviet Union	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
MDE	Middle East	Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, Turkey, United Arab Emirates, West Bank and Gaza, Yemen
CAM	Central America	Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama
SAM	South America	Argentina, Bolivia, Brazil, Chile, French Guiana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela
SAS	South Asia	Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka
SEA	Southeast Asia	Brunei, Cambodia, East Timor, Indonesia, Laos, Malaysia, Myanmar, Papua New Guinea, Philippines, Singapore, Taiwan, Thailand, Vietnam
CHI	China plus	China, Hong Kong, North Korea, Macau, Mongolia
NAF	North Africa	Algeria, Egypt, Libya, Morocco, Tunisia, Western Sahara
SSA	Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Congo-Brazzaville, Congo-Kinshasa, Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mauritania, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe

SIS	Small Island States	Antigua and Barbuda, Aruba, Bahamas, Barbados, Bermuda, Comoros, Cuba, Dominica, Dominican Republic, Fiji, French Polynesia, Grenada, Guadeloupe, Haiti, Jamaica, Kiribati, Maldives, Marshall Islands, Martinique, Mauritius, Micronesia, Nauru, Netherlands Antilles, New Caledonia, Palau, Puerto Rico, Reunion, Samoa, Sao Tome and Principe, Seychelles, Solomon Islands, St Kitts and Nevis, St Lucia, St Vincent and Grenadines, Tonga, Trinidad and Tobago, Tuvalu, Vanuatu, Virgin Islands
-----	---------------------	---

Working Papers
Research Unit Sustainability and Global Change
Centre for Marine and Climate Research, Hamburg University, Hamburg

- 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** (submitted)
- Zhou, Y. and Tol, R.S.J. (2004), *Evaluating the costs of desalination and water transport*, **FNU-41** (submitted)
- Lau, M. (2004), *Küstenzonenmanagement in der Volksrepublik China und Anpassungsstrategien an den Meeresspiegelanstieg*, **FNU-40** (submitted to *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)
- Schwoon, M. and Tol, R.S.J. (2004), *Optimal CO₂-abatement with socio-economic inertia and induced technological change*, **FNU-37** (submitted)
- Hamilton, J.M., Maddison, D.J. and Tol, R.S.J. (2004), *The Effects of Climate Change on International Tourism*, **FNU-36** (submitted)
- 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)
- Tol, R.S.J. (2003), *Adaptation and Mitigation: Trade-offs in Substance and Methods*, **FNU-33** (submitted)
- 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** (submitted)
- 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 in *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 (forthcoming in *Desalination*)

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** (submitted)

Tol, R.S.J., (2003), *The Marginal Costs of Carbon Dioxide Emissions: An Assessment of the Uncertainties*, **FNU-19** (submitted).

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** (submitted).

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** (submitted to *Climate Policy*).

Rehdanz, K (2002), *Hedonic Pricing of Climate Change Impacts to Households in Great Britain*, **FNU-13** (submitted to *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** (submitted to *Environment and Development Economics*).

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

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

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

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).

Kempf, C., W. Lise and R.S.J. Tol (2001), *Games of Climate Change with International Trade*, **FNU-7** (forthcoming in *Environmental and Resource Economics*).

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 to *International Environmental Agreements*).

Kempf, 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).