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CHECKING THE PRICE TAG ON CATASTROPHE: THE SOCIAL COST OF CARBON UNDER NON-LINEAR CLIMATE RESPONSE

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Abstract

Research into the social cost of carbon emissions — the marginal social damage from a ton of emitted carbon — has tended to focus on “best guess” scenarios. Such scenarios generally ignore the potential for low-probability, high-damage events, which are critically important to determining optimal climate policy. This paper uses the FUND integrated assessment model to investigate the influence of three types of non-linear climate responses on the social cost of carbon: the collapse of the thermohaline circulation; the dissociation of oceanic methane hydrates; and climate sensitivities above “best guess” levels. We find that incorporating these impacts can increase the social cost of carbon by a factor of 20. Furthermore, our results suggest that the exclusive focus on thermohaline circulation collapse in the non-linear climate response literature is unwarranted, because other potential non-linear climate responses appear to be significantly more costly.

Keywords: climate change, catastrophe, non-linearity, impacts

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Running Title: Checking the price tag on catastrophe

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1. Introduction

Uncertainty is the defining characteristic of anthropogenic climate change for scientists and policy-makers alike. Although the Intergovernmental Panel on Climate Change (IPCC) and much climate change research focuses on "best guess" scenarios of gradual warming, researchers acknowledge that the uncertainties involved are both massive and numerous (Allen and Ingram, 2002, Intergovernmental Panel on Climate Change, 2001b). Beyond the range of possibilities considered by best guess analyses, within the feedbacks and thresholds poorly understood and thus ignored by most integrated assessment models, lies the potential for a variety of non-linear climate responses to anthropogenic greenhouse gas forcing. The events of the blockbuster film *The Day After Tomorrow* may be fantastical in nature, but it is not difficult to envision dramatic climate change triggered by human actions which will have profound impacts on the biosphere and human societies (Alley, et al., 2003, Higgins, et al., 2002, National Research Council, 2002, Overpeck and Webb, 2000, Schneider, 2003). The estimated probability functions of many relevant parameters and estimates of climate change impacts themselves are strongly right-skewed, indicating that very large damages are possible (Fankhauser, 1995, Tol, 2005, Tol and De Vos, 1998).

Numerous studies have indicated that in the case of non-linear or unexpectedly severe consequences of climate change, optimal abatement increases substantially (Baranzini, et al., 2003, Gjerde, et al., 1998, Keller, et al., 2004, Kolstad, 1994, Mastrandrea, 2001, Tol, 2003, Yohe, 1996, Zickfield and Bruckner, 2003). The potential for non-linear climate responses to anthropogenic greenhouse gas forcing, however, has received little attention in the climate change damage cost literature to date (Alley, et al., 2003, Higgins, et al., 2002, Wright and Erikson, 2003). Non-linear climate responses and their impact on estimates of the cost of climate change is the subject of the research presented here, wherein the integrated-assessment model FUND is used to explore projections of the social cost of carbon in the context of three types of non-linear climate response: thermohaline circulation collapse, marine gas hydrate dissociation, and high climate sensitivity.

An outline of our methodology follows in section 2, comprising a brief overview of FUND, and section 3 explains how the three sets of scenarios were selected, modeled and evaluated. Results are presented in section 4. Section 5 contains a discussion and section 6 concludes.

2. Methodology

FUND (the Climate Framework for Uncertainty, Negotiation and Distribution) is an integrated assessment model linking projections of populations, economic activity and emissions to a simple carbon cycle and climate model, and to a model predicting and monetarizing impacts. Version 2.8, used in this paper, begins in the year 1950 and runs through 2300 in time steps of one year. Climate change impacts are monetarized in 1995 dollars and are modelled over sixteen geographical regions. Modelled impacts include agriculture, forestry, sea level rise, cardiovascular and respiratory disorders influenced by cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems (Link and Tol, 2004). The default FUND scenario lies somewhere in between IIS92a and IS92f (Leggett, et al., 1992). Detailed descriptions of FUND are in (Link and Tol, 2004, Tol, 2001, Tol, 2002a, Tol, 2002b, Tol, 1999a, Tol, 1999b, Tol, 1999c, Tol, 1999d, Tol, 1999e).

The marginal cost of carbon dioxide emissions is computed by taking the difference in the net present value of the impacts due to a small change in emissions over the decade 2000 – 2009. These estimates can be done with all parameters set to their best guess, as well as in Monte Carlo mode where climate parameters are varied.

3. Scenarios

Nine scenarios were modeled in three sets, with three scenarios in each set. The first set of scenarios, each involving a collapse of the thermohaline circulation, comprises an examination of the Younger Dryas period (scenario “T1”), a cold spell 8,000 years ago (“T2”) and THC flickerings (“T3”). The second set of scenarios involves the dissociation of gas hydrates in the ocean, modeled by forcing FUND with a large annual release of methane. We consider three annual release rates: 100MT (“M1”), 2680MT (“M2”) and 8667MT (“M3”). The third set of scenarios involves climate sensitivities higher than the “best guess” values used by the IPCC — we consider sensitivities of 4.5°C (“C1”), 7.7°C (“C2”) and 9.3°C (“C3”). The remainder of this section explains the scientific background for each of the nine scenarios and outlines how they were modeled and evaluated using FUND.

3.1 Thermohaline circulation collapse

The thermohaline circulation (THC) describes the circulation of water in the oceans driven and maintained by thermal and saline (and thus density) differences. Prevailing winds in the tropics move warm surface waters in a predominant direction allowing deep water to upwell. As warm water travels north (travelling the furthest north in the North Atlantic), it cools and becomes denser, eventually sinking. The THC today is thought to carry 1.2 (+/- .2) x 10^{15} W of heat north (Rahmstorf, 1995), nearly half of the total equator-to-pole heat exchange (Wright and Erikson, 2003). The extent to which this moderates Europe’s climate relative to other regions at the same latitude such as Canada is debated, and some theorists argue that a reduction in ocean heat transport will be largely or wholly compensated by increased wind-driven heat and salt transports (National Research Council, 2002). The mixing components of the THC also bring heat, CO_2, and nutrients into the deep ocean (Wright and Erikson, 2003).

The majority of the models used by the IPCC predict a weakening of the THC under increased anthropogenic greenhouse gas forcing during the next century (Intergovernmental Panel on Climate Change, 2001b, National Research Council, 2002). The warmer climate is predicted to intensify the hydrological cycle, increasing the net precipitation over evaporation in the North Atlantic region and thus “freshening” the North Atlantic waters. With this lower saline concentration, the sinking of water in higher latitudes and the formation of deep water in the North Atlantic will likely weaken and possibly stop altogether (Clark, et al., 2003, Manabe and Stouffer, 1993, Manabe and Stouffer, 2000, Manabe, et al., 1991, Marotzke, 2000, Rahmstorf, 1994). Such a collapse could be permanent, even if anthropogenic climate change ended, and lead to cooling in the Northern Hemisphere and warming in the Southern Hemisphere

Changes in the ocean's circulation appear to have been involved in climate change in the past, often dramatic in nature (Blunier, et al., 1998, Broecker, 1997, Clark, et al., 2003, Thorpe, et al., 2004), although the cause and effect dynamics within the climate system are still debated (Broecker, 2003). The direct effect of a reduced THC is simply a redistribution of energy. However, through effects on sea ice and clouds, the strength of trade winds, ventilation of the North Pacific, the strength of the Asian monsoon, or atmospheric carbon dioxide or water vapour, the impact of a THC change could be amplified (Clark, et al., 2003, Ewen, et al., 2004, Hostetler, et al., 1999, Marotzke, 2000). Both models and palaeoclimatic data suggest that the THC may have more than one stable "mode", potentially involving alternative locations of deep water formation of varying stability and permitting rapid shifts from one mode to another as thresholds are reached (Bond, et al., 1993, Broecker, 1994, Broecker, 1997, Rahmstorf, 1995, Rahmstorf and Ganopolski, 1999, Stouffer and Manabe, 2003, Weaver, 1995), although this remains contentious. Greenland ice core records indicate that during the last glacial period, climate conditions over Greenland switched from intense cold to more moderate conditions over a period of years to decades (Broecker, 1997, Dansgaard, et al., 1993, Greenland Ice-core Project (GRIP) members, 1993). Current understanding of these dynamics is insufficient to produce confident predictions of the implications of a change in ocean circulation due to anthropogenic global warming. Models of THC decline produce contrasting results ranging from, for example, a 30% amplification of global cooling due to sea ice growth and increased surface albedo (Ganopolski, et al., 1998) to a zero effect on global mean temperature (Marotzke, 2000) and various results in between (Clark, et al., 2003, Marotzke, 2000, Stocker, 2002).

A number of modelling studies have shown that a change in ocean circulation due to warming could plausibly trigger an abrupt climate change event (Ewen, et al., 2004, Manabe and Stouffer, 1994, Rahmstorf, 1995, Stocker and Schmittner, 1997). Many models of a THC collapse, however, show the effects to be mild and geographically limited to northern latitudes (Intergovernmental Panel on Climate Change, 2001b).

Link and Tol (2004) is the only other paper to study the economic impacts of a THC collapse. Because of the demonstrated limitations in modelling the effects of a shutdown of the THC, the scenarios used here are based upon palaeoclimatic data and imposed upon the model using changes in temperature. Link and Tol (2004) use scenarios from the CLIMBER-2 model (Rahmstorf and Ganopolski, 1999). Note that Keller et al. (2004) and Mastrandrea (2001) use hypothetical impacts.

3.1.1 The Younger Dryas (T1)

Glacial conditions in the northern Atlantic rapidly came to an end approximately 15,500 years ago, replaced by a climate similar to that of today (Broecker, 2000). After 2000 years the North Atlantic region's climate suddenly reverted to near-glacial conditions, which lasted for approximately 1200 years before warming abruptly resumed, marking the beginning of the Holocene. This cold spell, often referred to as the Younger Dryas (YD), was similar to the other dramatic oscillations of the glacial period whose dynamics are not well understood (Bond and Lotti, 1995, Broecker, 2000, Broecker, 1994, Chondrogianni, et al., 2004, Dansgaard, et al., 1993). It is also considered the best supported example of a change in ocean circulation serving as a trigger for large-scale cooling (Clark, et al., 2001). During the cold YD period, palaeo-data indicate that temperatures were very low over western Europe (Manabe and Stouffer, 2000). The YD period ended abruptly, potentially due to a second change in the ocean circulation (Manabe and Stouffer, 2000). A reduction in heat transport to northern latitudes due to changes in the ocean's circulation is thought to be a possible trigger for the onset of ice ages as well as temporary cold spells such as the YD (Broecker, 2000, Marotzke, 2000).

An event similar to the Younger Dryas is crudely modelled in FUND by forcing a 10˚C cooling (Wright and Erikson, 2003) over western Europe (Manabe and Stouffer, 2000) over a 150 year period following a (modelled) THC shutdown in 2150 (as in Link and Tol, 2004). This is arguably a "conservative" description of a catastrophic event, as the forcing is limited to Western

Europe while evidence discussed above indicates that the effects may well be much more widely propagated than is reflected in this scenario.

3.1.2 Cold spell 8,000 years ago (T2)

Greenland ice core records indicate that after temperatures had reached or possibly surpassed modern conditions during the early Holocene, a brief and sudden cold event occurred approximately 8,000 years ago which has been connected to changes in the THC, implying that changes in ocean circulation could have dramatic effects during interglacial as well as glacial times (Broecker, 1997). The event appears to have been approximately half of the amplitude of the YD, with a pattern of cold, dry, windy, low-methane conditions in Greenland coincident with cold North Atlantic temperatures and strong North Atlantic trade winds which matches that of the YD as well as glacial stadial (cold) periods (Alley, et al., 1997). This pattern is consistent with model predictions of the effects of a decline in the North Atlantic oceanic heat transport. Palaeoclimatic records from other regions appear to show concurrent changes in climate (Alley, et al., 1997).

An event similar to this cold spell is modelled in FUND using a method parallel to that of the YD scenario above, with a 5˚C forced cooling in western Europe over 100 years following an (assumed) THC shutdown in 2150. At 2250, the effects of the THC shutdown are reversed over ten years, mirroring the short duration and sudden termination of this event.

3.1.3 Flickerings (T3)

Some models of freshwater forcing in the North Atlantic show oscillations in THC intensity on timescales of several decades to a century, generating repeated warming and cooling on a decadal timescale (Dixon, et al., 2003, Manabe and Stouffer, 2000, Rahmstorf, 1995). Greenland ice core as well as terrestrial data also show signs of such "climate flickerings" during past climate transitions (Broecker, 2000, Lister and Sher, 1995). This appears to reflect some aspect of the climate system that was wavering between two states before stabilizing, hypothetically the ocean circulation rapidly strengthening and weakening leading to rapid changes in wind patterns and thus sources of dust. This theory is supported by attempts to model the stadial-interstadial transitions of the last glaciation (Ganopolski and Rahmstorf, 2001) and past freshwater forcings (Delworth, et al., 1997), which also show “flickerings”.

THC flickerings with weakening induced by anthropogenic climate change is coarsely modelled as described in Table 1, intended to reflect the variability seen in the palaeoclimatic record.

Table 1: Flickerings scenario (T3) modeling approach

Period	**Forced temperature pattern in FUND**
2151 – 2160	Shift to CLIMBER-2 (THC shutdown scenario) values for 2300 over 10 years
2160 – 2170	Hold
2171 – 2180	Shift to values for 2100 over 10 years
2180 – 2190	Hold
2191 – 2210	Shift to values for 2300
2210 – 2230	Hold
2231 – 2240	Shift to values for 2050
2240 – 2260	Hold
2261 – 2280	Shift to values for 2300 over 20 years, hold for remainder of run

3.2 Marine methane hydrate destabilization

Gas hydrates are formed when methane and water are present at low temperature and high pressure in ocean floor sediments and in permafrost (Glasby, 2003, Kvenvolden and Lorenson, 2001). As temperature increases with depth beneath the ocean floor, marine hydrates are only stable in the upper few hundred or few thousand meters of continental margin sediments (depending upon the geothermal gradient), below which gas and water are stable (Glasby, 2003, Hornbach, et al., 2004). Estimates of the amount of methane hydrate in the ocean vary by two orders of magnitude, with best guesses ranging from 6.67×10^5 to 3.2×10^7 MT CH_4; 1.3×10^7 MT CH_4 serves as a consensus value (Kvenvolden, 2002). A free gas zone lies below the gas hydrate stability zone (GHSZ), but the size of this area (and its potential involvement in methane release during gas hydrate destabilization) is poorly understood. According to one estimate (Hornbach, et al., 2004), the global free-gas reservoir could contain between 17% and 67% of the methane contained in hydrate.

Methane hydrates near the GHSZ boundary are sensitive to changes in temperature and pressure (Glasby, 2003, Hornbach, et al., 2004). Observations of hydrates in the Gulf of Mexico and other regions have documented gas releases in response to even small, transient temperature increases (Brewer, 2000). Destabilization of hydrates due to pressure or temperature changes or some other disturbance can produce landslides and trigger further destabilization through positive feedbacks potentially leading to large scale methane release (Bratton, 1999, Glasby, 2003). With gradual warming, destabilization can occur from the sediment-water interface downward (releasing methane into sea water immediately) as well as at the bottom of the stability zone progressing upward (leading to the accumulation of free gas poised for subsequent release beneath the stable hydrate) depending upon the spatial relationship between the GHSZ and the sediment-water interface (Harvey and Huang, 1995).

Evidence is accumulating that methane from hydrates may have played a role in climate change, sometimes abrupt, in the past (MacDonald, 1990, National Research Council, 2002, Nisbet, 1990, Paull, et al., 1991), although this is not undisputed (Brook, et al., 2000, Xu and Lowell, 2001). Data from ice cores indicate that sudden increases in atmospheric CH_4 have accompanied most of the interstadial warming events during the past 110,000 years, although the increases are insufficient to have caused the full observed warming (Broecker, 2000, Glasby, 2003, Kennett, et al., 2000) and atmospheric methane increases may have been an effect rather than a cause of climate change (Thorpe, et al., 1996). Kennett et al. (2000) contend that the stadial-interstadial bottom water temperature shifts of 2-3.5˚C were sufficient to form and destabilize marine gas hydrates over large regions of the north Pacific.

The most widely discussed case is that of the Latest Palaeocene Thermal Maximum (LPTM), a period preceded by long-term (10,000–20,000 years) warming (Dickens, et al., 1997, Dickens, et al., 1995, Zachos, et al., 2001). Coincident with the LPTM, a number of mammalian orders (including primates) appeared in the fossil record, deep-sea (benthic) species underwent a massive extinction, and the $^{13}C/^{12}C$ ratio in global carbon reservoirs dropped precipitously (Bralower, et al., 1997, Kaiho, et al., 1996). It has been hypothesized that a sudden change in ocean circulation destabilized methane hydrates on continental slopes. Some of the released methane would have reacted with dissolved oxygen in the water and decreased dissolved oxygen availability, which may have caused the observed benthic extinctions. A substantial methane release from gas hydrates would provide an explanation for the massive addition of "light" ^{12}C to the carbon cycle. The $^{13}C/^{12}C$ ratio remained constant for the first 10,000 years after the massive carbon input to the global carbon cycle (Dickens, 1999). This suggests balanced inputs and outputs to the global carbon cycle, implying that the carbon cycle may take a considerable amount of time to recover from such a disturbance by removing "extra" carbon from the system. Future anthropogenic global warming could conceivably destabilize gas hydrates via increased bottom water temperatures due to a change in ocean circulation or as a direct response to global warming (Harvey and Huang, 1995). A runaway greenhouse effect propelled by the dissociation of methane hydrates in permafrost and marine sediments is thought to be a possible but low probability consequence of anthropogenic global warming (Harvey and Huang, 1995, Leggett, 1990, Nisbet, 1989).

Recent studies have questioned whether methane releases from hydrates would ever reach the atmosphere to trigger warming, as methane is anaerobically oxidized by microbes in the surface sediment and aerobically oxidized by microbes in the water column (Brewer, 2000, Glasby, 2003, Kastner, 2001, Kvenvolden, 2002). Evidence from analyses of fossilized plant tissue and soil carbonate, however, indicates that the negative excursion (decrease) in the $^{13}C/^{12}C$ ratio observed in the marine carbonate record during the LPTM and the Aptian Stage of the Lower Cretaceous was also seen in atmospheric carbon, suggesting that methane from marine hydrates may have reached the atmosphere where it could have influenced temperatures (Jahren, et al., 2001, Kvenvolden, 2002). In the event of a breach of the hydrate layer that allowed trapped free gas beneath to be released in a "blast of gas", microbial oxidation capacity could be overwhelmed and substantial quantities of methane could reach the atmosphere (Dickens, et al., 1997, Kvenvolden, 2002, Kvenvolden, 1999).

Methane in the atmosphere reacts with hydroxyls (OH^-). A catastrophic methane addition to the atmosphere could overwhelm the hydroxyl supply thus increasing the lifetime of atmospheric methane; however it is also likely that a global warming will increase the amount of water vapour (and thus hydroxyl availability) in the atmosphere (Lashof, 1989).

Three methane scenarios (M1, M2, M3) are modelled using FUND. The triggers for the marine hydrate destabilization envisioned here could be:

1. a rapid decline of the thermohaline circulation (Rahmstorf, 1995, Rahmstorf and Ganopolski, 1999); or
2. high climate sensitivity and rapid warming.

These are hypothesized to lead to a significant (4-8˚C) temperature increase in intermediate and bottom waters in some locations and thus to hydrate destabilization and annual methane emissions to the atmosphere beginning in 2035 and continuing (through a runaway effect) for the duration of the model's projection (through 2300). Because current understanding of the potential for the oxidation of methane in the water column and possible atmospheric hydroxyl shortages is limited and projections vary widely, as discussed above, the potential for marine oxidation and increased atmospheric methane lifetime are both ignored. The variation in flux rate between the scenarios, however, would cover a substantial amount of variation in projections of marine methane quantity, the potential for significant oxidation, and changes in atmospheric methane lifetimes due to hydroxyl availability. In the low methane release scenario (M1), the flux is 100 Mt CH_4/yr to correspond with the low values of Kastner (2001), Dickens (1995, 1997), and Katz (1999), and is also equivalent to the projection of extreme permafrost hydrate destabilization by Nisbet (1989). In the medium methane release scenario (M2), the flux is 2,680 Mt CH_4/yr, the average of the Chamberlain (1983, cited by Harvey and Huang 1995) and the high Harvey and

Huang (1995) projections. In the high methane release scenario (M3), the flux is 8,667 Mt CH_4/yr, the high projection from Kastner (2001).

3.3 High climate sensitivity

The climate sensitivity is as critical as it is uncertain — the cost and consequence of anthropogenic greenhouse gas emissions depends fundamentally upon the climate's sensitivity and response (Andronova and Schlesinger, 2001). Alternative climate sensitivities are readily apparent in palaeoclimatic records, models that try to mimic historical climate events and predict future climate change, and expert elicitation exercises (Kacholia and Peck, 1997). Climate sensitivity estimates range from inconsequential to severe; Andronova and Schlesinger (2001) report a 90% confidence interval of 1-9˚C with a 15% chance that climate sensitivity exceeds 5.8˚C, Stainforth et al. (2005) produced a range of 1.9 – 11.5˚C. Although the majority of experts in this area have best guesses within the IPCC range of 1.4 - 4.5˚C, and generally in the lower end of this range, most still estimate a 5-10% chance of catastrophic warming associated with a doubling of CO_2 (Kacholia and Peck, 1997). Geophysical climate feedbacks such as water vapour, clouds, and sea ice are included in climate models but remain highly uncertain. Biogeochemical feedbacks such as ocean CO_2 absorption and vegetation albedo are often omitted, as are more severe and low-probability feedbacks such as large-scale gas hydrate dissociation. Thus it seems clear that there is a low but real probability that climate sensitivity is very high, and a sizable probability that it is beyond the range considered by the IPCC.

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In order to investigate the effect of higher climate sensitivity on the projected social cost of carbon, the FUND model was run with three fixed climate sensitivities selected to represent the range of estimates beyond the commonly considered IPCC best guess range:

- Scenario C1 = 4.5˚C (the high end of the IPCC's range)
- Scenario C2 = 7.7˚C (within the range predicted by Morgan and Keith's experts (1995) as well as Forest et al. (2002) and Kacholia and Reck (1997))

- Scenario C3 = 9.3˚C (within the range found by Stainforth et al. (2005) and Andronova and Schlesinger (2001))

4. Results

The social cost of carbon resulting from each of the nine scenarios is presented in Table 2. Results are given for four different discounting schemes, three with a constant pure rate of time preference (PRTP) and one based on the United Kingdom's HM Treasury (2003) Green Book, which employs a declining social discount rate beginning at 3.5%. Where a constant PRTP is assumed, the full social discount rate is also a function of per capita consumption growth. This explains why results employing Green Book discounting fall between those with PRTP=0% and PRTP=1%. One other characteristic of note is that for PRTP=0%, the discounted marginal damage is still significant at the end of the model's run in 2299, indicating that the sum of the damages would increase under a longer time horizon.

Table 2: The social cost of carbon (1995$/tC) under different scenarios

Scenario	**PRTP=0%**	**PRTP=1%**	**PRTP=3%**	**Green Book SDR**
Base case	58	11	-2.3	18
THC collapse	54	11	-2.5	17
T1: Younger Dryas	54	13	-0.085	20
T2: Cold snap 8kya	54	10	-2.5	17
T3: Flickerings	55	11	-2.5	18
M1: +100MT p.a. CH_4	58	12	-2.3	18
M2: +2680MT p.a. CH_4	73	16	-1.6	24
M3: +8667MT p.a. CH_4	94	21	-0.74	30
C1: Climate sensitivity 4.5˚C	330	89	17	100
C2: Climate sensitivity 7.7˚C	1,500	360	75	270
C3: Climate sensitivity 9.3˚C	2,400	580	120	360

4.1 Thermohaline circulation collapse

As can be seen in Table 2, results for each of the thermohaline circulation scenarios are nearly identical, and none of them has much impact on the social cost of carbon. The reason behind this, as well as the slightly beneficial impact of a THC shut down in Link and Tol (2004), seems to be the large rise in temperature in western Europe by the time the cooling in these scenarios begins (over 6˚C higher than pre-Industrial times by 2150). Although in scenario T1 (Younger Dryas) western Europe ends up approximately 3˚C colder than pre-Industrial times, the off-setting of the warming is sufficiently beneficial for the agriculture and cooling sectors that these perturbations "save money" relative to the base case scenario of warming.

As adaptation costs are not modelled explicitly in most sectors, the impact on agriculture is the only real test of whether scenario T3 (Flickerings) imposes costs of increased variability. Examining the disaggregated data for the agricultural sector indicates no influence is apparent. It is possible that damages under this scenario would rise if variability-related adaptation costs in other sectors were included, as well as costs due to the changes in hydrologic regimes that would likely occur. As with the base case, with PRTP=0% damages are still significant and positive at 2300 and thus the final marginal damage estimate would likely increase if the time horizon was extended.

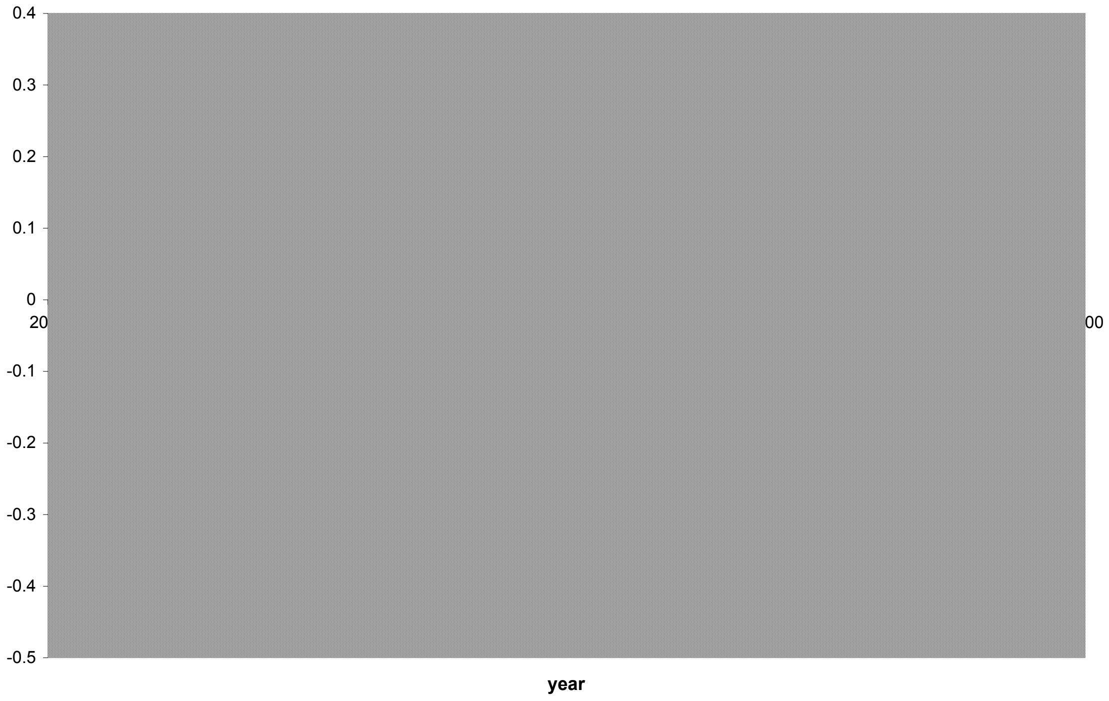
When used with FUND in Monte Carlo mode, each of these scenarios produced one run of over $30,000/tC for marginal damage. Analysis of this run using the disaggregated data indicated that the high cost was due to the dryland sector in China. This outcome was judged implausible, especially as there was no similar response from the wetlands sector. Ignoring this run, the best guess data have a median value of $22/tC, an average value of $33/tC with a standard deviation of $38, a minimum of -$19/tC and a maximum of $210/tC. Runs generating higher damages involve significant costs in the agriculture and cooling sectors and the absence of benefits to agriculture that are observed in early decades in most runs. Damages are also concentrated in the 21st or 21st and 22nd centuries in the high damage runs, and thus are not discounted very heavily.

With PRTP=3%, low damages in all sectors and substantial benefits to the agriculture sector early on, especially in China, generate net benefits.

4.2 Marine methane hydrate destabilization

As can be seen in Figure 1, the three methane scenarios act to amplify the MD curves by increasing amounts with increasing methane quantities (although M1 by a very small amount). The general pattern of damages is the same as that discussed in reference to the thermohaline collapse scenarios above, with damages in China and the agriculture and cooling sectors dominating. As the results in Table 2 suggest, there are no obvious dynamics between these scenarios and the different discounting schemes. Under both PRTP=0% and Green Book discounting, the damages are increased by 1.6 times under M3 and 1.3 times under M2. The relative increase in damages is greater under the other constant discounting schemes, although under PRTP=3% damages are still slightly negative, indicating net benefits.

Figure 1: Impact of methane scenarios on marginal damage calculations

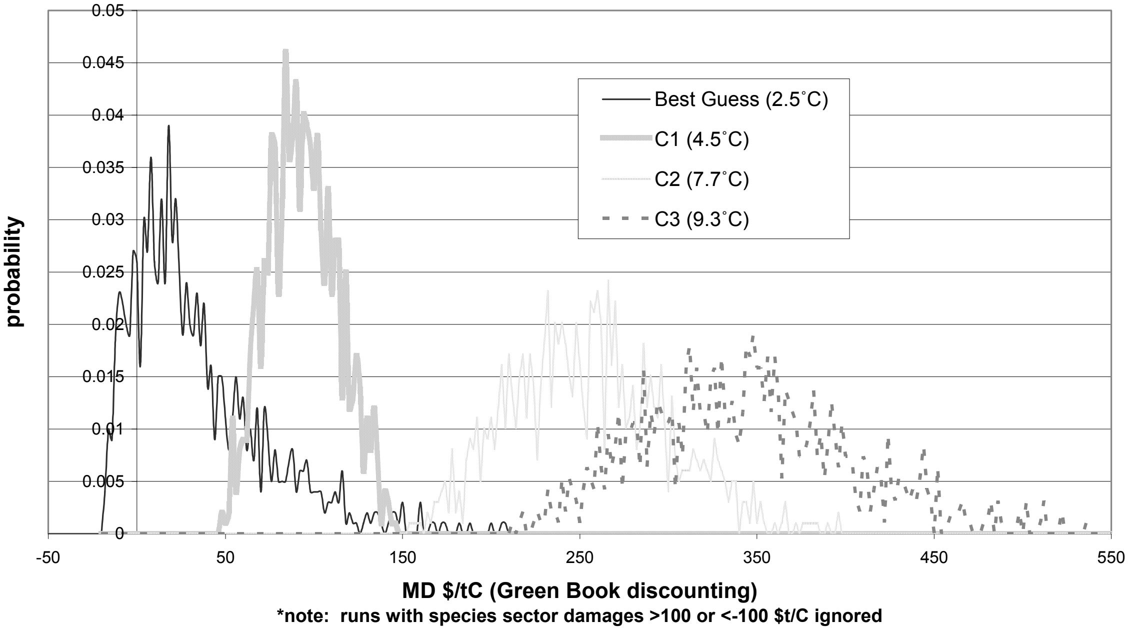


4.3 High climate sensitivity

The results for the climate sensitivity scenarios are the most interesting, with both a strong influence on the marginal damages (in all three scenarios) and a powerful dynamic with discounting methods. Depending upon the discounting scheme chosen, the social cost of carbon under the high climate sensitivity scenario (C3) is a factor of between 20 and over one hundred times greater than the base case (see Table 2). Projected marginal damage with the low climate sensitivity scenario (which is currently the upper bound of the IPCC's best guess range) using PRTP=3% increases from -2.3 in the base case to 17 $/tC and from 58 to 330 $/tC under PRTP=0%. With PRTP=0%, damages continue to rise through 2300, driven by damages to agriculture and by impacts in China. Extending the model's time horizon with these scenarios seems likely to augment the social cost of carbon considerably. Impacts in western Europe comprise a significant contribution to total damages early on (driven by cooling sector (primary) and agriculture sector damages), with the former Soviet Union and North African regions becoming somewhat significant later in the projection due to rising deaths. The rapid rise in agricultural damages is driven both by increasing distance from a climate optimum and the demands of rapid adaptation. Under the other discounting schemes, the damage patterns follow that of the base case, with damages amplified with earlier and higher peaks as is logical in the projected context of faster and greater warming.

The probability density function generated from 1000 Monte Carlo runs is shown in Figure 2. The very high and very low damage runs with scenarios C2 and C3 are driven by massive damages and benefits to the species sector. As the sector is simply a measure of how much individuals are willing to pay for a loss of biodiversity, very high damages (up to thousands of dollars per ton of carbon in some runs) seem implausible. In order to reduce the influence of this seemingly unlikely result, all runs where species damages were greater than $100/tC or less than -$100/tC were excluded from analysis (8 runs with Scenario C2 and 54 runs with Scenario C3). This is a crude adjustment, but does provide a sense of the shape of the uncertainty in parameter interaction. The remaining high and low runs are, as above, dominated by agriculture and cooling (particularly in China), with some contribution from the death, water and species sectors.

Figure 2: Frequency distributions (1000 runs) for climate sensitivity scenarios



5. Discussion

Although it remains difficult, if not impossible, to quantify the probability of anthropogenic climate change triggering non-linear climate responses, there is general agreement that the probability of such responses increases with the rate and quantity of greenhouse gas emissions (Alley, et al., 2003, Broecker, 1997, Intergovernmental Panel on Climate Change, 2001a, National Research Council, 2002, Schneider and Azar, 2001). Potential damages under the scenarios discussed here range as high as $360/tC under Green Book discounting and as high as $2,400/tC with a 0% pure rate of time preference. Even if the probability is small, these projections provide useful context for the "best guess" estimates of marginal damage, which are generally considerably smaller than $50/tC (Tol, 2005). Moreover, it is possible that the range of damages found here underestimates the actual range, as only climate parameters (not impact) were varied in the Monte Carlo uncertainty analysis.

Furthermore, much of the climate change impacts research, including this study, omits many impacts and likely undervalues others (Tol, 2002a, Tol, 2002b). The models also ignore interactions between sectors (e.g., between agriculture and water) and changes in weather variability and extremes, except to the limited degree these are included in the underlying literature. Three important potential non-linear climate responses—West-Antarctic ice sheet destabilization, ecosystem service degradation, and intense hydrologic variation—could not be explored here because the predictions are not sufficiently quantitative or because such scenarios would take the impact models outside of their range of validation. It seems likely that damages due to such climate responses would be very large. Thus estimates of potential impacts—including the estimates of costs with non-linear climate responses presented here—may well be underestimates of anthropogenic climate change damages. In addition, the uncertainties involved in (possibly irreversibly) forcing the climate into a new, totally unknown regime is, in and of itself, a compelling reason to abate anthropogenic climate change (Tol, 2002b). The uncertainties involved in our ability to model the future climate and climate change damages in addition to the potential for non-linear climate responses with large damages make the use of "best guess" climate scenarios to dictate optimal mitigation investment pathways inappropriate in a policy context.

Economic modelling studies clearly indicate that although aggressive climate change mitigation investments are inefficient today with "best guess" climate change projections (Maddison, 2001, Mendelsohn, 2001), the possibility of non-linear climate responses which involve large damages supports much larger public investment in mitigation (Kolstad, 1994, Tol, 2003). The work presented here shows, for the first time, that non-linear climate responses currently discussed in the scientific literature would likely have significant impacts on projections of marginal damage as calculated in integrated assessment models such as FUND. This is evidence that the earlier work showing that hypothetical "catastrophic" outcomes can justify aggressive near-term abatement within a cost-benefit framework is valid.

Yet even if it is apparent that non-linear climate responses ought to be taken into account, the critical question of what value of marginal damage to use in policy making remains. Specifying a consensus value (or range of values) is important because otherwise a default value of zero is employed, or a range of different values inconsistently applied. Although some have urged the IPCC and other practitioners to assign probabilities to various possible climate futures (Giles, 2002), doing so is both highly subjective and possibly inappropriate given that practitioners have fundamental (and scientifically valid) disagreements about the future of the climate system, many value judgments are implicit in the valuation of costs and benefits, and the cumulative uncertainties are massive (Lempert and Schlesinger, 2001, Schneider and Azar, 2001). The appropriate response, instead, is the creation of robust policies that will be suitable given a range of potential impact scenarios. Specifically, this means finding the most efficient way of keeping open the possibility of stabilizing greenhouse gases at a low atmospheric concentration (not much higher than that of today) in the event that high damage scenarios are not ruled out as the field of study advances. Because of the inertia in capital stocks, R&D investment, and political systems, preserving this option realistically means using a relatively high value for the social cost of carbon in current policy analysis.[i]

Of course, not all of the scenarios discussed above had a significant influence on marginal damage projections. The projections of a slight lowering of damages with the three scenarios associated with a THC shut-down are interesting in their own right for several reasons. First, it seems likely that the hydrologic variability and ecosystem impacts induced by the THC changes projected in these scenarios would produce damages not seen here. It is unlikely that these are large (in human eyes), as they would occur largely over the ocean. FUND may, however, overstate the possibilities to adapt. Second, in terms of changes in utility as measured by models such as FUND, impacts associated with a THC collapse seem unlikely to be significant—and thus perhaps the exclusive focus on this particular non-linear climate response within the catastrophic climate change impact literature is unwarranted. Third, a THC shut-down is a negative feedback in a warming world, and thus projections of a beneficial impact should not be surprising.

6. Conclusions

Uncertainty is fundamental to the study and policy of climate change. Enormous uncertainties in the climate system are compounded by the complexity and uncertainty in social and economic systems. Nevertheless, most economic research on climate change impacts has focussed on "best guess" scenarios in which the climate warms gradually and fairly benevolently. Using such scenarios, most estimates of the social cost of carbon are under $50/tC. The implication is that although emission cuts are warranted, most reductions should be delayed while technologies develop.

The problem with employing "best guess" modelling is that it disregards the importance and the nature of the uncertainties involved. The estimated probability distribution functions of many relevant parameters and estimates of climate change impacts themselves are strongly right-skewed, indicating the potential for very large damages. Part of this skew is due to the nature of the climate system, which contains multiple feedbacks and thresholds that allow the possibility of non-linear responses to anthropogenic greenhouse gas forcings. Our attempt to include selected extreme climate scenarios found estimates of marginal damages as high as $360/tC under Green Book declining discounting scheme and as high as $2,400/tC with a 0% pure rate of time preference. Many "catastrophic" scenarios of non-linear climate responses cannot yet be modelled, either because our understanding of the non-linear systems is too limited or because the impact models are unable to run such scenarios. The heavy emphasis on potential thermohaline circulation collapse within the catastrophic impacts literature seems unfortunate given the low expected damages discussed here, and more importantly, because of the corresponding lack of attention paid to other non-linear climate responses such as hydrologic variability, West-Antarctic ice sheet collapse, methane hydrate destabilization, ecosystem service degradation, and high climate sensitivity.

Climate change impacts will be long-term and potentially irreversible on the timescale of human societies. Yet as models extend both the climate and the economy into the future, uncertainties grow rapidly. Furthermore, interactions between damage sectors (such as agricultural damages leading to emigration), potential social amplification of impacts (such as a series of droughts leading to political instability), and the degradation of ecosystem services are generally not included in integrated assessment models.

Thus the marginal damage estimates found in the impacts literature may well be underestimates. Even more importantly, they do not reflect the real possibility of catastrophic and highly expensive outcomes. Governments should take the possibility of highly negative and likely irreversible outcomes into consideration in cost benefit analysis. The question is how best to do so, when the uncertainties are so great that it is impossible to determine precise thresholds of non-linear economic or climate response. The longer emissions cuts are postponed and the longer the economy develops without strong signals to reduce emissions, the more difficult and costly it will likely become to stabilize atmospheric greenhouse gas concentrations at lower levels. The primary goal of policy must be to find the optimal, efficient path that realistically preserves the option of meeting a low atmospheric greenhouse gas concentration ceiling, while allowing the possibility that this pathway may be relaxed as uncertainties are lessened. The second goal, and of similar importance, should be to reduce the uncertainties involved in both best guess and non-linear climate and impact predictions.

[1] Although not discussed in reference to the scenarios presented here, with equity weighting the projected damages of climate change increase significantly, including in explorations of severe climate change damages (Tol, 2003). Choices about discount schemes are critical to the final

marginal damage projections, and these are partly ethical decisions about how to treat future generations that can only be made by policy-makers.

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References

Allen, M.R. and Ingram, W.J.: 2002, 'Constraints on future changes in climate and the hydrologic cycle', Nature 419, 232.

Alley, R.B., Marotzke, J., Nordhaus, W.D., Overpeck, J., Peteet, D.M., Pielke, R.A., Pierrehumbert, R.T., Rhines, P.B., Stocker, T.F., Talley, L.D. and Wallace, J.M.: 2003, 'Abrupt climate change', Science 299, 2005-2010.

Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C. and Clark, P.U.: 1997, 'Holocene climate instability: A prominent, widespread event 8200 yr ago', Geology 25, 483-486.

Andronova, N. and Schlesinger, M.E.: 2001, 'Objective estimates of the probability density function for climate sensitivity', Journal of Geophysical Research 106, 22605-22611.

Baranzini, A., Chesney, M. and Morisset, J.: 2003, 'The impact of possible climate catastrophes on global warming policy', Energy Policy 31, 691-701.

Blunier, T., Chappellaz, J., Schwander, J., Dallenbach, A., Stauffer, B., Stocker, T.F., Raynaud, D., Jouzel, J., Clausen, H.B., Hammer, C.U. and Johnsen, S.J.: 1998, 'Asynchrony of Antarctic and Greenland climate change during the last glacial period', Nature 394, 739-743.

Bond, G., Broecker, W.S., Johnsen, S.J., McManus, J.F., Labeyrie, L., Jouzel, J. and Bonani, G.: 1993, 'Correlations between climate records from North Atlantic sediments and Greenland ice', Nature 365, 143-147.

Bond, G. and Lotti, R.: 1995, 'Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation', Science 267, 1005-1010.

Bralower, T.J.B., Thomas, D.J., Zachos, J.C., Hirschmann, M.M., Rohl, U., Sigurdsson, H., Thomas, E. and Whitney, D.L.: 1997, 'High-resolution records of the late Paleocene thermal maximum and circum-Caribbean volcanism: Is there a causal link?' Geology 25, 961-1056.

Bratton, J.: 1999, 'Clathrate eustasy: Methane hydrate melting as a mechanism for geologically rapid sea-level fall', Geology 27, 915-918.

Brewer, P.: 2000, 'Gas hydrates and global climate change', Annals of the New York Academy of Sciences 912, 195-199.

Broecker, W.S.: 2000, 'Abrupt climate change: Causal constraints provided by the paleoclimate record', Earth-Science Reviews 51, 137-154.

Broecker, W.S.: 2003, 'Does the trigger for abrupt climate change reside in the ocean or in the atmosphere?' Science 300, 1519-1522.

Broecker, W.S.: 1994, 'Massive iceberg discharges as triggers for global climate change', Nature 372, 421-424.

Broecker, W.S.: 1997, 'Thermohaline circulation, the Achilles heel of our climate system: Will man-made CO2 upset the current balance?' Science 278, 1582-1588.

Brook, E., Harder, S., Severinghaus, J., Steig, E. and Sucher, C.: 2000, 'On the origin and timing of rapid changes in atmospheric methane during the last glacial period', Global Biogeochemical Cycles 14, 559-572.

Chondrogianni, C., Ariztegui, D., Rolph, T., Juggins, S., Shemesh, A., Rietti-Shati, M., Niessen, F., Guilizzoni, P., Lami, A., McKenzie, J.A. and Oldfield, F.: 2004, 'Millennial to interannual climate variability in the Mediterranean during the Last Glacial Maximum', Quaternary International 122, 31-41.

Clark, P.U., Marshall, S.J., Clarke, G.K.C., Hostetler, S.W., Licciardi, J.M. and Teller, J.T.: 2001, 'Freshwater Forcing of Abrupt Climate Change During the Last Glaciation', Science 293, 283-287.

Clark, P.U., Pisias, N., Stocker, T.F. and Weaver, A.: 2003, 'The role of the thermohaline circulation in abrupt climate change', Nature 415, 863-869.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Stevensen, J.P., Sveinbjörnsdóttir, Á.E., Jouzel, J. and Bond, G.:

1993, 'Evidence for general instability of past climate from a 250-kyr ice-core record', Nature 364, 218-220.

Delworth, T., Manabe, S. and Stouffer, R.J.: 1997, 'Multidecadal climate variability in the Greenland Sea and surrounding regions: A coupled model simulation', Geophysical Research Letters 24, 257-260.

Dickens, G.: 1999, 'The blast in the past', Nature 401, 752-755.

Dickens, G., Castillo, M. and Walker, J.: 1997, 'A blast of gas in the latest Paleocene: Simulating first-order effects of massive dissociation of oceanic methane hydrate', Geology 25, 259-262.

Dickens, G., O'Neil, J., Rea, D. and Owen, R.: 1995, 'Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene', Paleoceanography 10, 965-971.

Dixon, K., Delworth, T., Knutson, T., Spelman, M. and Stouffer, R.J.: 2003, 'A comparison of climate change simulations produced by two GFDL coupled climate models', Global and Planetary Change 37, 81-102.

Ewen, T., Weaver, A. and Schmittner, A.: 2004, 'Modelling carbon cycle feedbacks during abrupt climate change', Quaternary Science Reviews 23, 431-448.

Fankhauser, S.: 1995, Valuing climate change: The economics of the greenhouse, Earthscan Publications Limited.

Ganopolski, A. and Rahmstorf, S.: 2001, 'Rapid changes of glacial climate simulated in a coupled climate model', Nature 409, 153-158.

Ganopolski, A., Rahmstorf, S., Petoukhov, V. and Claussen, M.: 1998, 'Simulation of modern and glacial climates with a coupled global model of intermediate complexity', Nature 391, 351-356.

Giles, J.: 2002, 'Scientific uncertainty: When doubt is a sure thing', Nature 418, 476-478.

Gjerde, J., Grepperud, S. and Kverndokk, S.: 1998, 'Optimal climate policy under the possibility of a catasatrophe', Environmental Economics 21, 289-317.

Glasby, G.P.: 2003, 'Potential impact on climate of the exploitation of methane hydrate deposits offshore', Marine and Petroleum Geology 20, 163-175.

Greenland Ice-core Project (GRIP) members: 1993, 'Climate instability during the last interglacial period recorded in the GRIP ice core', Nature 364, 203-207.

Harvey, D. and Huang, Z.: 1995, 'Evaluation of the potential impact of methane clathrate destabilization on future global warming', Journal of Geophysical Research 100, 2905-2926.

Higgins, P., Mastrandrea, M. and Schneider, S.H.: 2002, 'Dynamics of climate and ecosystem coupling: Abrupt changes and multiple equilibria', Philosophical Transactions of the Royal Society 357, 647-655.

Hornbach, M., Saffer, D. and Holbrook, S.: 2004, 'Critically pressured free-gas reservoirs below gas-hydrate provinces', Nature 427, 142-144.

Hostetler, S.W., Clark, P.U., Bartlein, P.J., Mix, A.C. and Pisias, N.J.: 1999, 'Atmospheric transmission of North Atlantic Heinrich events', Journal of Geophysical Research 104, 3947-3952.

Intergovernmental Panel on Climate Change: 2001a, *Climate Change 2001: Synthesis Report*, United Nations Environmental Program, World Meteorological Organization, Geneva.

Intergovernmental Panel on Climate Change: 2001b, *Working Group I: The Scientific Basis*, United Nations Environmental Program, World Meteorological Organization, Geneva.

Jahren, A.H., Arens, N., Sarmiento, G., Guerrero, J. and Amundson, R.: 2001, 'Terrestrial record of methane hydrate dissociation in the Early Cretaceous', Geology 29, 159-162.

Kacholia, K. and Peck, R.A.: 1997, 'Comparison of global climate change simulations for 2xCO2-induced warming: An intercomparison of 108 temperature change projections', Climatic Change 35, 53-69.

Kaiho, K., Arinobu, T., Ishiwatari, R., Morgans, H., Okada, H., Takeda, N., Tazaki, K., Zhou, G., Kajiwara, Y., Matsumoto, R., Hirai, A., Niitsuma, N. and Wada, H.: 1996, 'Latest Paleocene benthic formaminiferal extinction and environmental changes at Tawanui, New Zealand', Paleoceanography 11, 447-465.

Kastner, M.: 2001, 'Gas hydrates in convergent margins: Formation, occurrence, geochemistry, and global significance', in Paull, C. and Dillon, W. (ed.), Natural Gas Hydrates: Occurrence, Distribution, and Detection, American Geophysical Union, Washington, D.C., 67-86.

Keller, K., Bolker, B. and Bradford, D.: 2004, 'Uncertain climate thresholds and optimal economic growth', Journal of Environmental Economics and Management 48, 723-741.

Kennett, J.P., Cannariato, K.G., Hendy, I.L. and Behl, R.J.: 2000, 'Carbon isotopic evidence for methane hydrate instability during quaternary interstadials', Science 288, 128-133.

Kolstad, C.D.: 1994, 'George Bush versus Al Gore: Irreversibilities in greenhouse gas accumulation and emission control investment', Energy Policy 22, 771-778.

Kvenvolden, K.: 2002, 'Methane hydrate in the global organic carbon cycle', Terra Nova 14, 302-306.

Kvenvolden, K.: 1999, 'Potential effects of gas hydrate on human welfare', Proceedings of the National Academy of Sciences 96, 3420-3426.

Kvenvolden, K. and Lorenson, T.: 2001, 'The global occurrence of natural gas hydrate', in Paull, C. and Dillon, W. (ed.), Natural Gas Hydrates: Occurrence, Distribution, and Detection, American Geophysical Union, Washington, D.C., 3-18.

Lashof, D.: 1989, 'The dynamic greenhouse: Feedback processes that may influence future concentrations of atmospheric trace gases and climatic change', Climatic Change 14, 213-242.

Leggett, J.: 1990, Global Warming: The Greenpeace Report, Oxford University Press, Oxford.

Leggett, J., Pepper, W.J. and Swart, R.J.: 1992, *Emissions scenarios for the IPCC: An update*, Intergovernmental Panel on Climate Change, Geneva.

Lempert, R. and Schlesinger, M.E.: 2001, 'Climate change strategy needs to be robust', Nature 412, 375.

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.

Lister, A. and Sher, A.V.: 1995, 'Ice cores and mammoth extinction', Nature 378, 24-25.

MacDonald, G.: 1990, 'Role of methane clathrates in past and future climates', Climatic Change 16, 247-282.

Maddison, D.: 2001, The amenity value of the global climate, Earthscan Publications Limited.

Manabe, S. and Stouffer, R.J.: 1993, 'Century-scale effects of increased atmospheric CO2 on the ocean-atmosphere system', Nature 364, 215-218.

Manabe, S. and Stouffer, R.J.: 1994, 'Multiple-century response of a coupled ocean-atmosphere model to an incrase of atmospheric carbon dioxide', Journal of Climate 7, 5-24.

Manabe, S. and Stouffer, R.J.: 2000, 'Study of abrupt climate change by a coupled ocean-atmosphere model', Quaternary Science Reviews 19, 285-299.

Manabe, S., Stouffer, R.J., Spelman, M.J. and Bryan, K.: 1991, 'Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO2. Part I: Annual mean response', Journal of Climate 4, 785-818.

Marotzke, J.: 2000, 'Abrupt climate change and thermohaline circulation: Mechanisms and predictability', PNAS 97, 1347-1350.

Mastrandrea, M.: 2001, 'Integrated assessment of abrupt climate changes', Climate Policy 1, 433-449.

Mendelsohn, R.O. (ed.): 2001, Global warming and the American economy: A regional assessment of climate change impacts, Electric Power Research Institute, Cheltenham.

National Research Council: 2002, *Abrupt climate change: Inevitable surprises*, Committee on Abrupt Climate Change: Ocean Studies Board, Polar Research Board, Board on Atmospheric Sciences and Climate, Division on Earth and Life Sciences, National Research Council, Washington, D.C.

Nisbet, E.G.: 1990, 'The end of the ice age', Canadian Journal of Earth Sciences 27, 148-157.

Nisbet, E.G.: 1989, 'Some northern sources of atmospheric methane: Production, history, and future implications', Canadian Journal of Earth Sciences 26, 1603-1611.

Overpeck, J. and Webb, R.: 2000, 'Nonglacial rapid climate events: Past and future', PNAS 97, 1335-1338.

Paull, C., Ussler, W., III and Dillon, W.: 1991, 'Is the extent of glaciation limited by marine gas-hydrates?' Geophysical Research Letters 18, 432-434.

Rahmstorf, S.: 1995, 'Bifurcations of the Atlantic thermohaline circulation in response to changes in the hydrological cycle', Nature 1995, 145-149.

Rahmstorf, S.: 1994, 'Rapid climate transitions in a coupled ocean-atmosphere model', Nature 372, 82-85.

Rahmstorf, S. and Ganopolski, A.: 1999, 'Long-term global warming scenarios computed with an efficient coupled climate model', Climatic Change 43, 353-367.

Schneider, S.H.: 2003, 'Abrupt non-linear climate change, irreversibility and surprise', in *OECD Workshop on the Benefits of Climate Policy: Improving Information for Policy Makers, Working Party on Global and Structural Policies*, Paris.

Schneider, S.H. and Azar, C.: 2001, *Are uncertainties in climate and energy systems a justification for stronger near-term mitigation policies?* Pew Center on Global Climate Change, Arlington.

Stocker, T.F.: 2002, 'Climate change: North-South connections', Science 297, 1814-1815.

Stocker, T.F. and Schmittner, A.: 1997, 'Influence of CO2 emission rates on the stability of the thermohaline circulation', Nature 388, 862-865.

Stouffer, R.J. and Manabe, S.: 2003, 'Equilibrium response of thermohaline circulation to large changes in atmospheric CO2 concentration', Climate Dynamics 20, 759-773.

Thorpe, R.B., Law, K.S., Bekki, S., Pyle, J.A. and Nisbet, E.G.: 1996, 'Is methane-driven deglaciation consistent with the ice core record?' Journal of Geophysical Research 101, 28627-28635.

Thorpe, R.B., Wood, R.A. and Mitchell, J.F.B.: 2004, 'Sensitivity of the modelled thermohaline circulation to the parameterization of mixing across the Greenland-Scotland ridge', Ocean Modelling 7, 259-268.

Tol, R.S.J.: 2001, 'Equitable cost-benefit analysis of climate change', Ecological Economics 36, 71-85.

Tol, R.S.J.: 2002a, 'Estimates of the damage costs of climate change, Part II. Dynamic estimates', Environmental and Resource Economics 21, 135-160.

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.: 2003, 'Is the uncertainty about climate change too large for expected cost-benefit analysis?' Climatic Change 56, 265-289.

Tol, R.S.J.: 1999a, 'Kyoto, efficiency, and cost-effectiveness: Applications of FUND', Energy Journal 130-156.

Tol, R.S.J.: 1999b, 'The marginal costs of greenhouse gas emissions', The Energy Journal 20, 61- 80.

Tol, R.S.J.: 2005, 'The marginal damage costs of carbon dioxide emissions: An assessment of the uncertainties', Energy Policy 33, 2064-2074.

Tol, R.S.J.: 1999c, 'Safe policies in an uncertain climate: an application of FUND', Global Environmental Change 9, 221-232.

Tol, R.S.J.: 1999d, 'Spatial and temporal efficiency in climate change: Applications of FUND', Environmental and Resource Economics 14, 33-49.

Tol, R.S.J.: 1999e, 'Time discounting and optimal control of climate change - an application of FUND', Climatic Change 41, 351-362.

Tol, R.S.J. and De Vos, A.F.: 1998, 'A Bayesian statistical analysis of the enhanced greenhouse effect', Climatic Change 38, 87-112.

Weaver, A.J.: 1995, 'Driving the ocean conveyor', Nature 378, 135-136.

Wright, E. and Erikson, J.: 2003, 'Incorporating catastrophes into integrated assessment: Science, impacts and adaptation', Climatic Change 57, 265-286.

Xu, W. and Lowell, R.: 2001, 'Effect of sea floor temperature and pressure variations on methane flux from a gas hydrate layer: Comparisons between current and late Paleocene climate conditions', Journal of Geophysical Research 106, 26413-26423.

Yohe, G.: 1996, 'Exercises in hedging against extreme consequences of global change and the expected value of information', Global Environmental Change 6, 87-101.

Zachos, J., Pagani, M., Sloan, L., Thomas, E. and Billups, K.: 2001, 'Trends, rhythms, and aberrations in global climate 65ma to present', Science 292, 686-693.

Zickfield, K. and Bruckner, T.: 2003, 'Reducing the risk of abrupt climate change: Emissions corridors preserving the Atlantic thermohaline circulation', Integrated Assessment 4, 106-115.

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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).
