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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 tonne 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 low-probability, high-impact climate responses on the social cost of carbon: the collapse of the Atlantic Ocean Meridional Overturning Circulation; large scale dissociation of oceanic methane hydrates; and climate sensitivities above "best guess" levels. We find that incorporating these events can increase the social cost of carbon by a factor of over 3.

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

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1. Introduction

Uncertainty is arguably 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, or a limited range of economic and demographic futures such as those from the IPCC's Special Report on Emission Scenarios (SRES), researchers acknowledge that the uncertainties involved are both massive and numerous (Oppenheimer et al., 2010, Weitzman, 2009, Allen and Ingram, 2002, Intergovernmental Panel on Climate Change, 2007a). Beyond the range of possibilities considered by best guess or middle of the road 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 and high-damage climate responses to anthropogenic greenhouse gas forcing. The events of the blockbuster film *The Day After Tomorrow* may be fantastic 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 welfare impacts themselves are strongly right-skewed, indicating that very large damages are possible (Weitzman, 2009, Fankhauser, 1995, Tol, 2005, Tol and De Vos, 1998). Weitzman (2009) makes a compelling argument that the fat right tail[1] of the climate impact distribution, if properly taken into account, should dominate economic and policy analysis.

Numerous studies have indicated that in the case of non-linear and very severe climate change impacts, 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 and low-probability 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, Tol, 2009, Wright and Erikson, 2003). Low-probability climate responses and their effect on

[1] Weitzman defines the "fat right tail" as a probability distribution function where the "tail probability approaches 0 more slowly than exponentially." (2009 at 2). Weitzman notes that "the planetary welfare effect of climate changes that might accompany mean temperature increases from 10˚C up to 20˚C with probabilities anything remotely resembling 5% down to 1% implies a nonnegligible probability of worldwide catastrophe. . . . Standard approaches to modelling the economics of climate change (even those that purport to treat risk by Monte Carlo simulations) very likely fail to account adequately for the implications of large impacts with small probabilities. . . . For situations where there do not exist prior limits on damages (like climate change from greenhouse warming), CBA is likely to be dominated by considerations and concepts related more to catastrophe insurance than to the consumption smoothly consequences of long-term discounting—even at empirically plausible interest rates." *Id.* at 1-2.

estimates of the cost of climate change is the subject of the research presented here, which uses the integrated-assessment model FUND to explore projections of the social cost of carbon, or marginal social damage from a tonne of emitted carbon, in the context of three types of low-probability, high-impact climate response: Atlantic Ocean Meridional Overturning Circulation (MOC) collapse, large scale 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 and discussed in Section 5. 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 monetizing welfare impacts caused by climate change. Climate change welfare impacts are monetized in dollars and are modeled over sixteen geographical regions.[2] sea-levelThe source code, data, and a technical description of the model (version 3.6) can be found at http://www.fund-model.org.

Essentially, FUND consists of a set of exogenous scenarios and endogenous perturbations. The version used in this paper runs from 1950 to 2300 in time steps of one year. The primary reason for starting in 1950 is to initialize the climate change impact module. In FUND, the welfare impacts of climate change are assumed to depend in part on the impacts during the previous year, reflecting the process of adjustment to climate change. Because the initial values cannot be approximated very well, both physical impacts and monetized welfare 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 Atlantic MOC as well as other catastrophic events would be disregarded if the time horizon of the simulations was shorter.

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

[2] These are the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States.

The scenarios are defined by varied rates of population growth, economic growth, autonomous energy efficiency improvements, and decarbonization of energy use (autonomous carbon efficiency improvements), as well as by emissions of carbon dioxide from land use change, methane emissions, and nitrous oxide emissions. The scenarios of economic and population growth are perturbed by the effects of climatic change. Population decreases are a result of changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (WRI, 2000). It is extrapolated based on the statistical relationship between urbanization and per-capita income, which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are unrealistically assumed to assimilate immediately and completely with the respective host population, as the focus here is not on "socially-contingent" impacts.

The tangible welfare impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. As a result, climate change reduces long-term economic growth, although consumption is particularly affected in the short-term. 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 as our focus is on the range of economic damages under business-as-usual emission scenarios.

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

The radiative forcing of carbon dioxide, methane, and nitrous oxide aerosols is determined based on Shine *et al*. (1990). The global mean temperature, T, is governed by a geometric build-up to its equilibrium (determined by the radiative forcing, RF), with the e-folding time depending on the climate sensitivity. In the base case, the global mean temperature rises in equilibrium by 3.0°C for a doubling of carbon dioxide equivalents. Regional temperature is derived by 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 an e-folding time of 500 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 welfare impact module, based on Tol (2002a,b) includes the following categories: agriculture, forestry, sea-level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages are triggered by either the rate of temperature change (above 0.04°C/yr) or the level of temperature change (above 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation.

In the model individuals can die prematurely due to temperature stress or vector-borne diseasessea-level. The value of a statistical life is set to be 200 times the annual per capita income, which lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration, which is driven by sea-level rise, is set to be 3 times the per capita income (Tol, 1995, 1996); the gain from immigration is 40 per cent of the per capita income in the host region (Cline, 1992). Losses of dryland and wetlands due to sea-level rise are modelled explicitly. The monetary value of a loss of one square kilometre of dryland was on average $4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at $2 million per square kilometre on average in the OECD in 1990 (cf. Fankhauser, 1994). The wetland value is assumed to have logistic relationship 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 welfare 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. Modelled effects of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative.

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

The marginal social damage from an additional tonne of emitted carbon—the social cost of carbon in $/tC—is computed by taking the difference in the net present value of the welfare impacts due to a small change in emissions over the decade 2010 – 2019, normalized by the change in emissions. These estimates can be done with all parameters set to their best guess, as well as in Monte Carlo mode.

In the Monte Carlo analyses, essentially all parameters are varied. The probability density functions are mostly based on expert guesses, but where possible "objective" estimates were used. Parameters are assumed to vary independently of one another. Details of the Monte Carlo analysis can be found on FUND's website at http://www.fund-model.org.

Below, we define a number of extreme climate scenarios, and estimate the marginal social damage from a tonne of emitted carbon for these scenarios. This should be interpreted as an assessment of the sensitivity of damage estimates to departures from "best-guess" scenarios. Climate change welfare impact models are not validated. These models are calibrated to data and to other models, but as climate change is mostly in the future, validation is not possible. Assessing extreme climate scenarios, using FUND or any model, is inherently therefore largely an exercise in extrapolation. This is potentially problematic when the departure from business-as-usual is so great that the underlying assumptions about growth and relative prices become inapplicable, and the usual short cuts involved in cost-benefit analysis fail to apply (Dietz and Hepburn, 2011). One advantage of employing an integrated assessment model like FUND is that it enables full comparison of impacts and welfare analysis along different pathways. Nevertheless the reporting of a "marginal" social cost of carbon, as we do in this paper, must be treated with caution. Results should be viewed in this light: rankings and orders of magnitudes are sound but precise estimates are not.

3. Scenarios

Seven scenarios were modeled in three sets. The first scenario extrapolates possible effects of a collapse of the Atlantic MOC. 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, a potent greenhouse gas. We consider three annual release rates: 200MT ("M1"), 1784MT ("M2") and 7800MT ("M3"). The third set of scenarios involves climate sensitivities higher than the "best guess" values traditionally used in social cost of carbon modeling—we consider sensitivities of 4.5°C ("C1"), 7.7°C ("C2") and 9.3°C ("C3"). Obviously, Atlantic MOC collapse and gas hydrate dissociation are specific non-linear responses, whereas high climate sensitivity is a more general low-probability climate response to greenhouse gas forcings. Given the structure of integrated assessment models and dearth of empirical projections of specific potential non-linear and low-probability climate responses, there are limited ways in which low-probability climate responses can be explored using these models. Both specific non-linear climate responses and overall climate sensitivity are sources of uncertainty in predicting climate change welfare impacts, and therefore both types of scenario provide useful context for considering "best guess" social cost of carbon estimates. The remainder of this section explains the scientific background for each of the scenarios and outlines how they were modeled and evaluated using FUND.

3.1 Atlantic Ocean Meridional Overturning Circulation collapse

The Atlantic Ocean Meridional Overturning Circulation (MOC) 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 (deep water formation). The MOC 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 would be largely or wholly compensated by increased wind-driven heat and salt transports (National Research Council, 2002).

Increases in atmospheric CO_2 appear to have been associated with reductions in overturning circulation in the Northern Hemisphere in the past (Ahn and Brook, 2008). The majority of the models reported by the IPCC predict a weakening of the MOC under increased anthropogenic greenhouse gas forcing during the 21st century (Intergovernmental Panel on Climate Change, 2007b, 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 will likely weaken (Clark, et al., 2003, Manabe and Stouffer, 2000, Marotzke, 2000). The melting and disintegration of icesheets such as the Greenland Ice Sheet or the Antarctic Ice Sheet due to warming temperatures would lead to an influx of freshwater into the oceans that could weaken or stop the MOC altogether (IPCC, 2007b). Such a collapse could be permanent on human timescales, 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 have been associated with dramatic climate change in the past (Roberts et al., 2010, 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 debated (Broecker, 2003). The direct effect of a reduced MOC 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 effect of a MOC 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 MOC 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 (Broecker, 1997, Rahmstorf and Ganopolski, 1999, Stouffer and Manabe, 2003, Weaver, 1995), although this remains contentious. Greenland ice core records, for example, 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).

A cold spell often referred to as the Younger Dryas (YD) is considered the best-supported example of a change in ocean circulation serving as a trigger for large-scale cooling (Clark, et al., 2001). Approximately 15,500 years ago, glacial conditions in the northern Atlantic rapidly came to an end, replaced by a climate similar to that of today (Broecker, 2000). After 2,000 years the North Atlantic region's climate suddenly reverted to near-glacial conditions, which lasted for approximately 1,200 years before warming abruptly resumed, marking the beginning of the Holocene. The YD was similar to the other dramatic oscillations of the glacial period whose dynamics are not well understood (Broecker, 2000, Broecker, 1994, Chondrogianni, et al., 2004). 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).

Greenland ice core records also 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 MOC, 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 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).

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 MOC 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 no 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 MOC collapse, however, show the effects to be mild and geographically limited to northern latitudes (Intergovernmental Panel on Climate Change, 2001b).

Analysis of the impact of a MOC collapse on SCC estimates has been limited. Keller et al. (2004) and Mastrandrea and Schneider (2001) use assumed welfare impacts, but Link and Tol (2004) model the total welfare impacts of a MOC collapse. Both this paper and Link and Tol (2004) use a scenario of MOC collapse from the CLIMBER-2 model (Rahmstorf and Ganopolski, 1999). In this scenario, circulation breaks down completely by the early 23rd century and does not recover. The North Atlantic region warms initially and then undergoes strong cooling as the MOC weakens and stops. Winter temperatures in the region peak in the early 22nd century and drop more than 4ºC by 2300. Link and Tol (2011) also model the total welfare impacts of a MOC collapse, using the scenario of Vellinga and Wood (2002) and focussing on the differential impacts between countries. The current paper, in contrast, estimates the impacts of an MOC collapse on the marginal damage cost of carbon dioxide emissions.

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). Because 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 size of the marine gas hydrate stability zone (GHSZ) vary. Recent estimates of the amount of methane hydrate in the ocean are in the range of 5.0 to 31.2 km^3 and 100 to 74,400 Gt carbon (Fyke and Weaver, 2006). A free gas zone lies below the 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). The Storegga Slide in the Norwegian continental margin is thought to have been triggered by an earthquake, but the sediments must have been previously destabilized, potentially due to rising ocean temperatures. The landslide is thought to have released as much as 5 Gton C CH_4 (Archer, 2007). Surveys of the ocean floor have discovered similar structures that indicate other large releases at the seafloor (Reagan and Moridis, 2007).

Evidence suggests that methane from hydrates may have played a role in climate change, sometimes abrupt, in the past (MacDonald, 1990, National Research Council, 2002, Nisbet, 2002, Pagani, 2006, Paull, et al., 1991, Reagan and Moridis, 2007), 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 Paleocene-Eocene Thermal Maximum (PETM, also known as the Latest Palaeocene Thermal Maximum). About 55 million years ago, the Earth underwent a period of global warming that lasted approximately 170,000 years (Pagani et al., 2006). At the beginning of this period, temperature reconstructions indicate that global temperatures increased by at least 5ºC in less than 10,000 years. Coincident with the rapid warming, 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 the warming resulted from a sudden change in ocean circulation which destabilized methane hydrates on continental slopes, releasing large amounts of methane into the atmosphere. 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 (involving inflows of warmer water to areas containing hydrates) or directly, by warming the ocean (Harvey and Huang, 1995; Reagan and Moridis, 2007, Reid et al., 2009). Although global temperature changes will take a long time to affect deep ocean marine hydrates because of the time needed for diffusion of heat into the sediment column, hydrates in shallow ocean sediments are much more sensitive to the warming projected for this century. 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, Reagan and Moridis, 2007).

Some studies have questioned whether significant methane releases from hydrates would ever reach the atmosphere to trigger warming, as methane can be 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, Lamarque, 2007). 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 reached the atmosphere (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). Even assuming normal release conditions, an oxidation lifetime of methane of 50 years (estimated for the high-latitude North Atlantic) is enough time to allow a significant fraction of the methane dissolving from bubbles to reach the atmosphere before it is oxidized (Archer 2007). Further, a large destabilization of hydrates in sediment could release hydrates to float to the surface, where large quantities methane could be released to the atmosphere (Reid et al., 2009).

Methane in the atmosphere reacts with hydroxyls (OH^-), and therefore OH- availability alters the lifetime of atmospheric methane. Atmospheric OH- levels are increased by NO_x and water vapor availability and decreased by hydrocarbon increases. The balance of these factors is likely to keep OH- availability and CH_4 lifetime approximately unchanged from present values (Intergovernmental Panel on Climate Change, 2007b). However, depending upon emission rates, OH- concentration could change by -18% to 5% during the 21st Century (Intergovernmental Panel on Climate Change, 2007b). A catastrophic methane addition to the atmosphere could overwhelm the hydroxyl supply, thus significantly increasing the lifetime of atmospheric methane (Lashof, 1989).

There is some evidence that the process of methane destabilization due to warming has already begun. The Arctic region has warmed more rapidly than predicted in response to increased greenhouse gas concentrations, and the warming appears to be thawing both land-based hydrates in permafrost and marine hydrates. The East Siberian Arctic Seas (ESAS) are shallow seas covering flooded Siberian tundra (including the Laptev, East Siberian, and Russian part of the Chuckchi seas). The annual average temperature of the ESAS bottom seawater is 12º to 17ºC warmer than the annual average surface temperature over adjacent terrestrial permafrost, and therefore likely more vulnerable to thawing. Extensive summer seawater sampling in this region between 2003 and 2008 indicate that most of the ESAS near-bottom waters are supersaturated with methane, with over half of the ESAS surface waters also supersaturated (Shakhova et al., 2010). Winter sampling indicated even higher saturation levels. Because the average sea depth in the ESAS is 45 m, there is much less opportunity for the CH_4 to be oxidized in the water column before it can reach the sea surface and be vented to the atmosphere. Overall flux to the atmosphere is estimated at 7.98 Mt C-CH_4, not including “catastrophic event” spikes due to sudden releases of larger quantities of methane from the seabed. This estimate is of the same magnitude as previous estimates of worldwide oceanic CH_4 fluxes to the atmosphere, and indicates that sub-sea permafrost is no longer acting as a lid keep the shallow methane reservoir in place—opening the possibility of a more massive CH_4 release period in the future.

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 meridional overturning circulation, which could change temperature and pressure in ocean sediment where hydrates are located (Fyke and Weaver, 2006, Rahmstorf, 1995, Rahmstorf and Ganopolski, 1999);
2. high climate sensitivity and rapid warming affecting ocean temperatures; or
3. loss of sea ice, decreased albedo, and increased absorption of radiation by the ocean surface in relatively shallow, high-latitude areas (Fyke and Weaver, 2006).

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 2050 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, as discussed above, the potential for marine oxidation and increased atmospheric methane lifetime are not modelled. Of course, marine oxidation and extended atmospheric methane lifetime have significant potential to counteract each other. Further, the variation in flux rate between the scenarios 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. If, however, both microbial oxidation and hydroxyl availability were overwhelmed and atmospheric methane quantity and lifetime both increased, the projections here would likely be significant underestimates. In the low methane release scenario (M1), the flux is 200 Mt CH_4/yr, the average of the low values of Kastner (2001), Dickens (1995, 1997), and Katz (1999). In the medium methane release scenario (M2), the flux is 1,784 Mt CH_4/yr the average of Lamarque (2008) and the high flux projection from Harvey and Huang (1995). In the high methane release scenario (M3), the flux is 7,800 Mt CH_4/yr, based on the high hydrate destabilization projection from Kastner (2001) (assuming 10% loss from oxidation). The quantity of methane that is released in these scenarios is also within the range of the hydrate carbon quantities in the Arctic Ocean, Gulf of Mexico, peat, and permafrost that Archer (2007) projects as potentially disturbed within centuries of warming.

We are not aware of any previous estimate of the total or marginal damage cost of methane hydrate destabilization.

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 to greenhouse gas forcings (Andronova and Schlesinger, 2001, Keller, et al., 2004). Palaeoclimatic records, models that try to mimic historical climate events and predict future climate change, and expert elicitation exercises all elicit ranges of climate sensitivity values (Royer et al., 2007, 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; Sanderson et al. (2008) show a 90% confidence interval of 2.45 to 7.75˚C across four different models; Stainforth et al. (2005) produced a range of 1.9 – 11.5˚C. The IPCC's recent review of climate sensitivity estimates suggests that climate sensitivity is likely between 2 and 4.5°C, with a best guess of approximately 3°C (IPCC, 2007a). However, because uncertainties are large, probability distribution functions of climate sensitivity estimates tend to have long right tails, and neither these studies nor most experts rule out high values (Köhler et al., 2010, Intergovernmental Panel on Climate Change, 2007a, Roe and Baker, 2007, 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 the terrestrial carbon cycle 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 best guess range of 2 to 4.5°C. It is also likely that climate sensitivity will remain uncertain even with advances in understanding of climate forcings and feedbacks (Roe and Baker, 2007).

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 range commonly considered in social cost of carbon modelling:

- Scenario C1 = 4.5˚C (the high end of the best guess IPCC range);
- Scenario C2 = 7.7˚C (within the range predicted by Morgan and Keith's experts (1995) as well those reported by Forest et al. (2002), Kacholia and Peck (1997), Sanderson et al. (2008), and Roe and Baker (2007)); and
- Scenario C3 = 9.3˚C (based on the high end of the ranges found by Stainforth et al. (2005) and Andronova and Schlesinger (2001) and within the range reported by Roe and Baker (2007)).

While studies that estimate the total or marginal impact of climate change routinely include a sensitivity analysis on the climate sensitivity, we are not aware of any study that considers as high a value as we do in this paper.

4. Results

The expected (mean) social cost of carbon resulting from each of the seven scenarios is presented in Table 1. All results are in 2010 USD for a marginal emission in the year 2010. Results are given for three different values for the pure rate of time preference (PRTP). The elasticity of marginal utility is assumed to be constant and equal to one, as is standard in many climate change economic analyses (Stern, 2007, Nordhaus, 2007; but see Dasgupta, 2007, Gollier, 2006). The effective consumption discount rate used to compute the net present value of impacts is, of course, higher than the PRTP, because it also depends on the realized growth rates of per capita consumption in the Monte Carlo runs and the correlation of impacts with the stochastic discount factor that FUND computes.[3] One other characteristic of note is that for PRTP=0%, the discounted marginal social damage from a tonne of emitted carbon is still significant at the end of the model's run in 2299, indicating that the sum of the damages would increase with a longer time horizon.

Table 1 presents probabilistic results: all parameters are varied in a Monte Carlo analysis. We also computed deterministic results; in these cases all parameters that are uncertain in the probabilistic analysis are set at their single best guess values (not presented). The deterministic results are in general much lower than the probabilistic social cost of carbon estimates that attempt to take into account many of the uncertainties surrounding climate change. In the case of the base scenario, for example, the probabilistic results are between 1.3 and 1.7 times larger than their best guess counterparts.

[3] The discounting follows the standard consumption based capital asset pricing model, see Cochrane (2005) for an introduction.

4.1 Atlantic Ocean Meridional Overturning Circulation collapse

As can be seen in Table 1 and Figure 4, the MOC scenario generates a slightly lower social cost of carbon than in the baseline scenario, but the difference is very small. This is due to the large rise in temperature in Western Europe (over 6˚C above pre-Industrial times by 2150) that has occurred by the time the cooling in this scenario begins. The cooling offsets the warming, which is a benefit (Link and Tol, 2004).

The difference between the probabilistic and deterministic results is largest for the MOC scenario. Probabilistic results are between 2.6 and 3.7 times larger than their best guess counterpart estimates. Monte Carlo runs generating higher damages involve significant costs in agriculture and cooling. Particularly, while the majority of runs see benefits to agriculture in early decades, such benefits are absent in the high damage runs. Because damages that occur in the 21st century are not discounted very heavily, runs with significant 21st century impacts tend to generate the highest SCC values.

4.2 Marine methane hydrate destabilization

As can be seen in Figure 1, the three methane scenarios act to amplify the marginal damage curves by increasing amounts with increasing methane quantities (although in M1 by a very small amount). Given the extremely low likelihood of widespread methane hydrate destabilization occurring as early as 2050, the social cost of carbon estimates themselves cannot be seen as robust. The rigorous result is that destabilization of methane hydrates could significantly amplify the social cost of carbon.

The general pattern of damages is the same as that discussed in reference to the meridional overturning circulation collapse scenarios above, with damages in the agriculture and cooling sectors dominating. As the results in Table 1 suggest, there are no obvious dynamics between these scenarios and the different discounting schemes. The damages are increased by a factor of 1.3 under M2 for all discounting schemes, and by a factor of 1.7-1.9 for M3. Mean atmospheric methane concentrations for all three scenarios are shown in Figure 6.

4.3 High climate sensitivity

The results for the climate sensitivity scenarios are the most interesting, with both a strong influence on the marginal social damages from a tonne of emitted carbon (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 2.4 or 3.4 times greater than the base case (see Table 1). Projected marginal social damage from a tonne of emitted carbon with the low climate sensitivity scenario using PRTP=3% increases from 8 in the base case to 12 $/tC and from 553 to 831 $/tC under PRTP=0%. With PRTP=0%, discounted damages continue to rise through 2300, driven by damages to agriculture and by welfare impacts in China. Extending the model's time horizon with these scenarios seems likely to augment the social cost of carbon considerably. Welfare impacts in western Europe comprise a significant contribution to total damages early on (driven by impacts to the cooling and agriculture sectors), with the former Soviet Union and North Africa becoming somewhat significant later in the projection due to rising mortality. 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 10,000 Monte Carlo runs using the three climate sensitivity scenarios is shown in Figure 2. The very high and low runs are, as above, dominated by agriculture and cooling sector damages (particularly in China), with some contribution from human health, water and species loss. The impact of the climate sensitivity scenarios on the expected (mean) social cost of carbon estimates using a 1% PRTP is shown in Figure 3.

5. Discussion

Although it may never be possible to quantify the probability of anthropogenic climate change triggering non-linear and catastrophic 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 $19/tC for a PRTP of 3%, as high as $290/tC with a PRTP of 1% and as high as $1,879/tC with a 0% PRTP. Even if the probability of such events coming to pass is small, these projections provide useful context for the "best guess" estimates of marginal social damage from a tonne of emitted carbon. An analysis of social cost of carbon estimates by Tol (2009) generated an average social cost of carbon of $26/tC (3% PRTP); $123/tC (1% PRTP); and $335/tC (0% PRTP); modal estimates, however, were in the range of $19/tC.[4]

Moreover, it is possible that the range of damages found here underestimates the actual range, as

much of the climate change welfare impacts research, including this study, omits many welfare 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. It should be noted that this paper is merely a first effort at modeling potential non-linear and low-probability climate responses to greenhouse gas emissions. We have not considered possible interactions between the scenarios we modeled. We have not

[4] Converted to $2010 using the consumer price index.

incorporated the potential for social amplification of physical impacts, such as conflict due to climate-related migration, drought, or food shortages. Furthermore, three important potential non-linear climate responses—West-Antarctic ice sheet destabilization, ecosystem service degradation, and intense hydrologic variation—are not explored here because the relevant impact predictions are not sufficiently quantitative or because the impact models are not yet able to adequately handle these scenarios. It seems likely that damages due to such climate responses would be very large. Thus estimates of potential impacts—including the estimates of costs presented here—may well be underestimates of anthropogenic climate change damages.

The uncertainties involved in (possibly irreversibly) forcing the climate into a new, totally unknown regime may be seen, in and of themselves, as a compelling reason to abate anthropogenic climate change (Tol, 2002b). Given the limitations in our ability to model the future climate and climate change damages, in addition to the potential for non-linear and low-probability catastrophic climate responses with large damages, it is inappropriate to rely on "best guess" climate scenarios to dictate optimal mitigation investment pathways in a policy context. As with other policy areas involving low-probability but high damage potential impacts—terrorism, nuclear proliferation, oil spills, and flood prevention come to mind—worst case scenarios must be considered when crafting policy.

Economic modelling studies clearly indicate that although aggressive climate change mitigation investments are inefficient today when analyzing "best guess" climate change projections using conventional discount rates[5] (Maddison, 2001, Mendelsohn, 2001), the possibility of non-linear climate responses which involve large damages supports much larger public investment in mitigation (Keller, et al., 2004, Kolstad, 1994, Tol, 2003). The work presented here shows, for the first time, that non-linear and low-probability climate responses currently discussed in the scientific literature would likely have significant effects on projections of marginal social damage from a tonne of emitted carbon as calculated in integrated assessment models such as FUND. These results reinforce the validity of earlier work showing that "catastrophic" outcomes can justify aggressive near-term abatement within a cost-benefit framework.

Yet even if it is apparent that non-linear and low-probability climate responses ought to be taken into account, the critical question of what value of marginal social damage from a tonne of emitted carbon 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 to

[5] Choices about discount rates are critical to the marginal damage computations, and these are partly ethical decisions about how to treat future generations that can only be made by policy-makers. Further, 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).

assign probabilities to various possible climate futures (Giles, 2002), doing so is both highly subjective and likely 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 development of policies that will be robust to a range of potential physical and welfare 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 may imply using a relatively high value for the social cost of carbon in current policy analysis.

Of course, not all of the scenarios discussed above had a significant influence on marginal social damage projections. The projections of a slight lowering of damages with the MOC shut-down scenario are interesting in their own right for several reasons. First, it seems likely that the hydrologic variability and ecosystem impacts induced by the MOC changes projected in this scenario would produce damages not seen here. It is unlikely that these are large (in terms of human welfare), as they would primarily occur over the ocean. Fisheries could be affected, although this is small part of the economy and increasingly managed. FUND may also overstate adaptive capacity. In addition, if a MOC shut-down led to a decreased uptake of CO_2 in the ocean, climate change and its impacts would be worse. Second, in terms of changes in utility as measured by models such as FUND, welfare impacts associated with a MOC collapse seem unlikely to be significant—and thus perhaps the strong focus on this particular non-linear climate response within the catastrophic climate change welfare impact literature is unwarranted. Third, an Atlantic MOC shut-down is a negative regional feedback in a warming world, and thus projections of a beneficial welfare impact in Western Europe should not be surprising.

6. Conclusions

Uncertainty is fundamental to the study and policy of climate change. Enormous uncertainties in predicting the climate system's response to rising atmospheric greenhouse gas concentrations are compounded by the difficulty of predicting how a changing climate will affect highly complex social and economic systems. Nevertheless, most economic research on climate change welfare impacts has focused on "best guess" scenarios in which the climate warms gradually and relatively benevolently. Using such scenarios, most estimates of the social cost of carbon are under $72/tC. The implication is that although emission cuts are warranted, most reductions should be delayed while technologies are further developed.

The limitation 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 welfare 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 and low-probability responses to anthropogenic greenhouse gas forcings. Our attempt to include selected extreme climate scenarios found estimates of marginal social damages from a tonne of emitted carbon as high as $1,879/tC with a 0% pure rate of time preference. Many "catastrophic" scenarios of non-linear and low-probabilty 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 physical impacts of climate change on the Earth 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, uncertainty levels 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 social damage estimates found in the welfare impacts literature may well be underestimates. Even more importantly, they do not reflect the real possibility of catastrophic and highly expensive outcomes—outcomes which are low-probability but not zero probability. This research suggests that it is inappropriate for governments to ignore the possibility of highly negative and likely irreversible outcomes 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 world's economies (and research agendas) develop without strong signals to reduce emissions, the more difficult and costly it will likely become to stabilize atmospheric greenhouse gas concentrations at lower levels. Where catastrophic outcomes remain a real possibility, the primary goal of policy should 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 or tightened as uncertainties are lessened. The second goal should be to reduce the uncertainties involved in both best guess and non-linear climate and welfare impact predictions.

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Tables

Table 1: The mean social cost of carbon (2010$/tC) under different scenarios. "MC" columns present Monte Carlo results; "BG" columns present Best Guess.

Scenario	PRTP=0%		PRTP=1%		PRTP=3%	
	MC	BG	MC	BG	MC	BG
Base case	553	359	108	85	8	5
MOC collapse	536	341	105	81	8	4
M1: +200MT p.a. CH_4	578	367	112	87	8	5
M2: +1784MT p.a. CH_4	711	423	135	99	11	6
M3: +7800MT p.a. CH_4	1021	583	187	131	15	10
C1: Climate sensitivity 4.5˚C	831	722	155	145	12	9
C2: Climate sensitivity 7.7˚C	1608	1426	258	236	18	14
C3: Climate sensitivity 9.3˚C	1879	1670	290	265	19	15

Figures

Figure 1: Impact of methane scenarios on marginal social damage calculations using a 1% pure rate of time preference

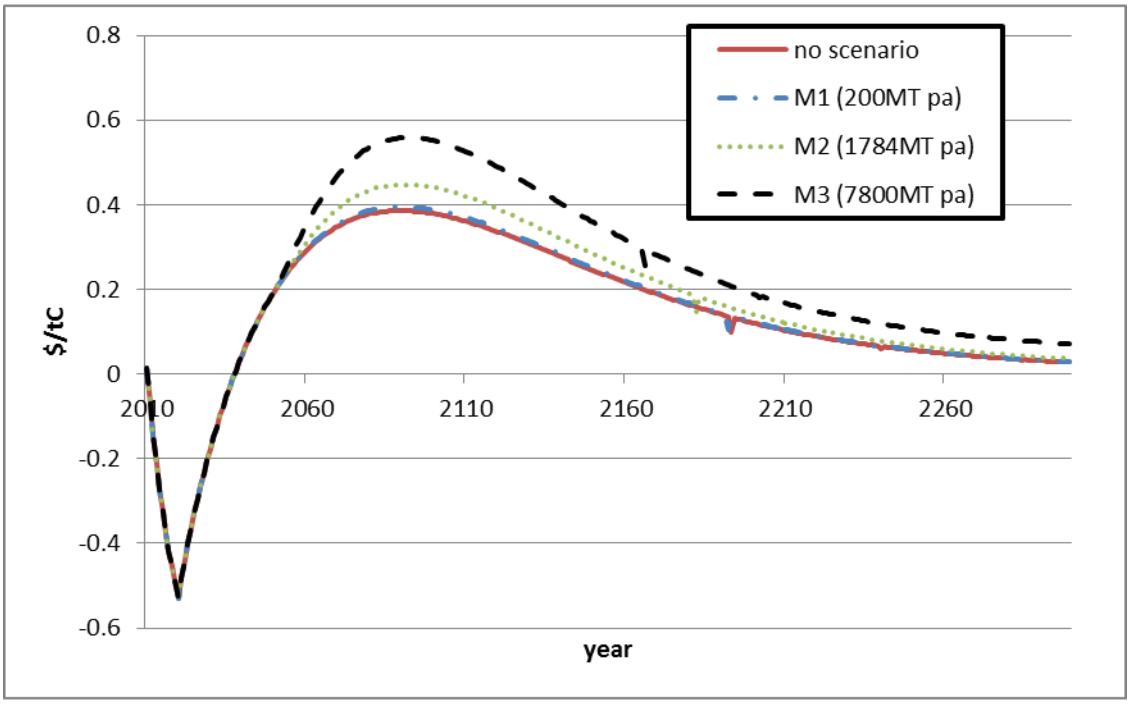


Figure 2: Frequency distributions (10,000 runs) for climate sensitivity scenarios using a pure rate of time preference of 1%

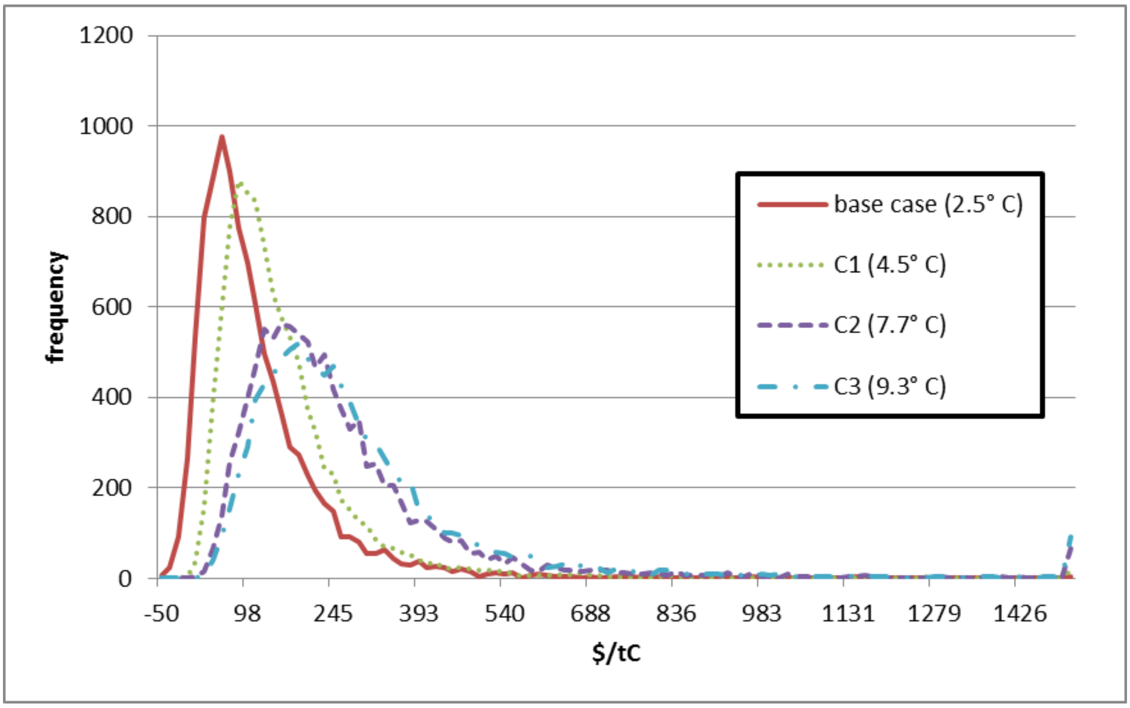


Figure 3: Impact of climate sensitivity scenarios on marginal social damage calculations using a 1% pure rate of time preference

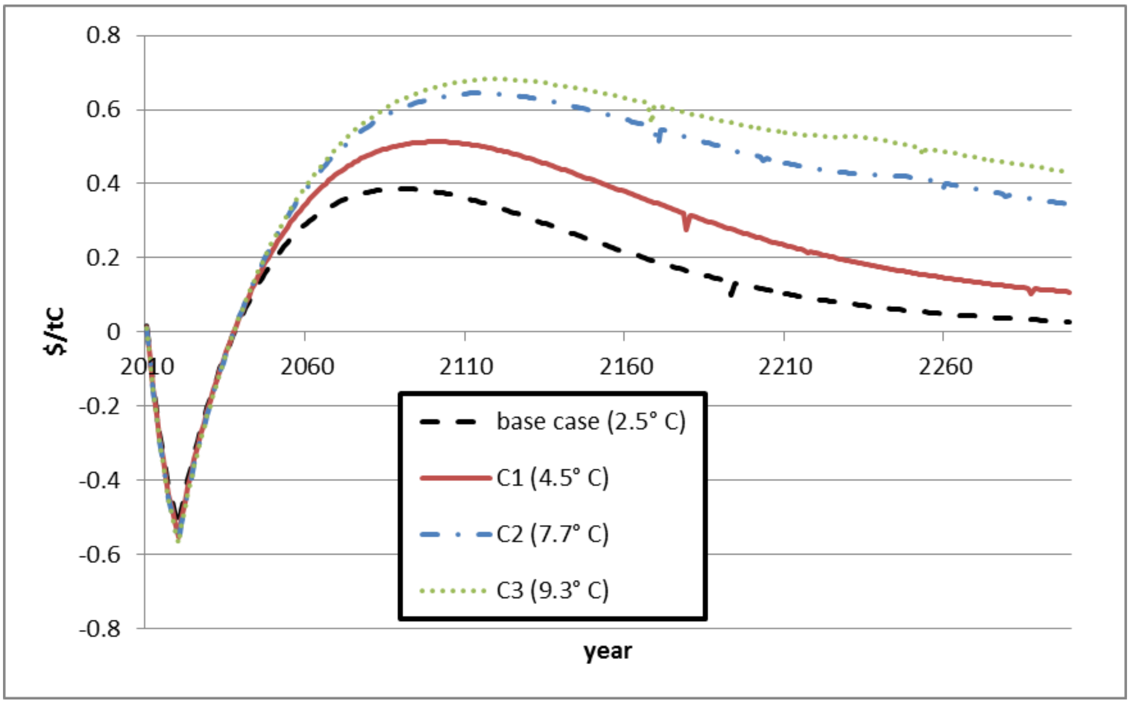


Figure 4: Impact of MOC scenario on marginal social damage calculations using a 1% pure rate of time preference

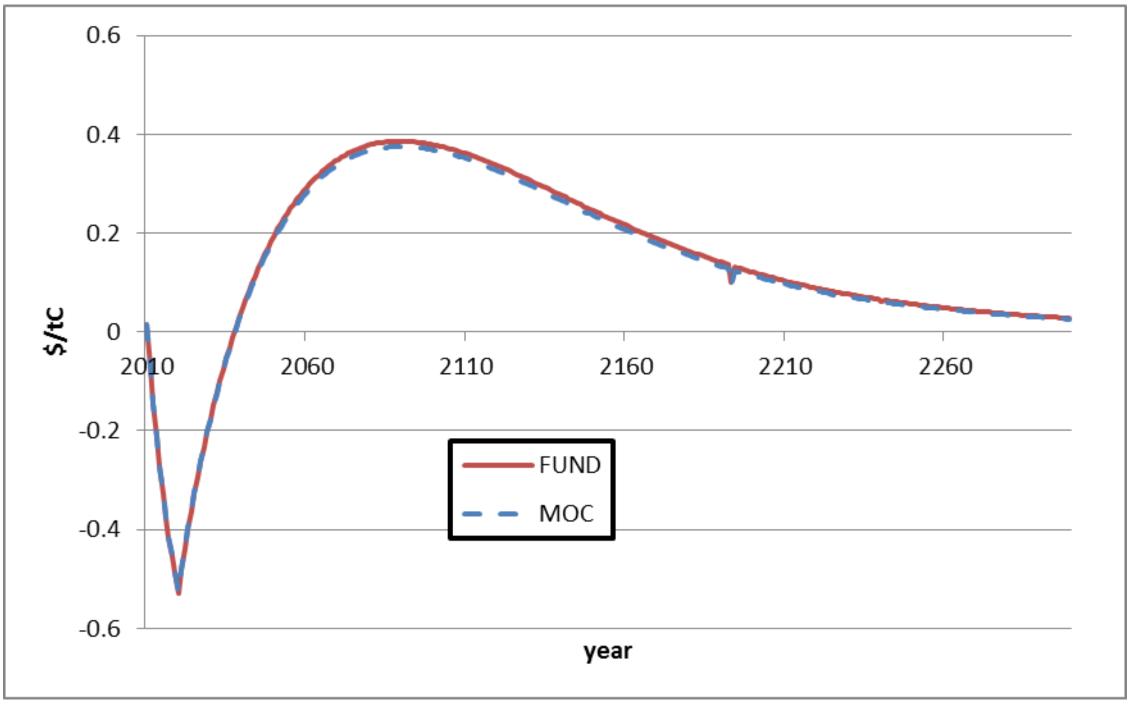


Figure 5: Mean temperature projections for all scenarios

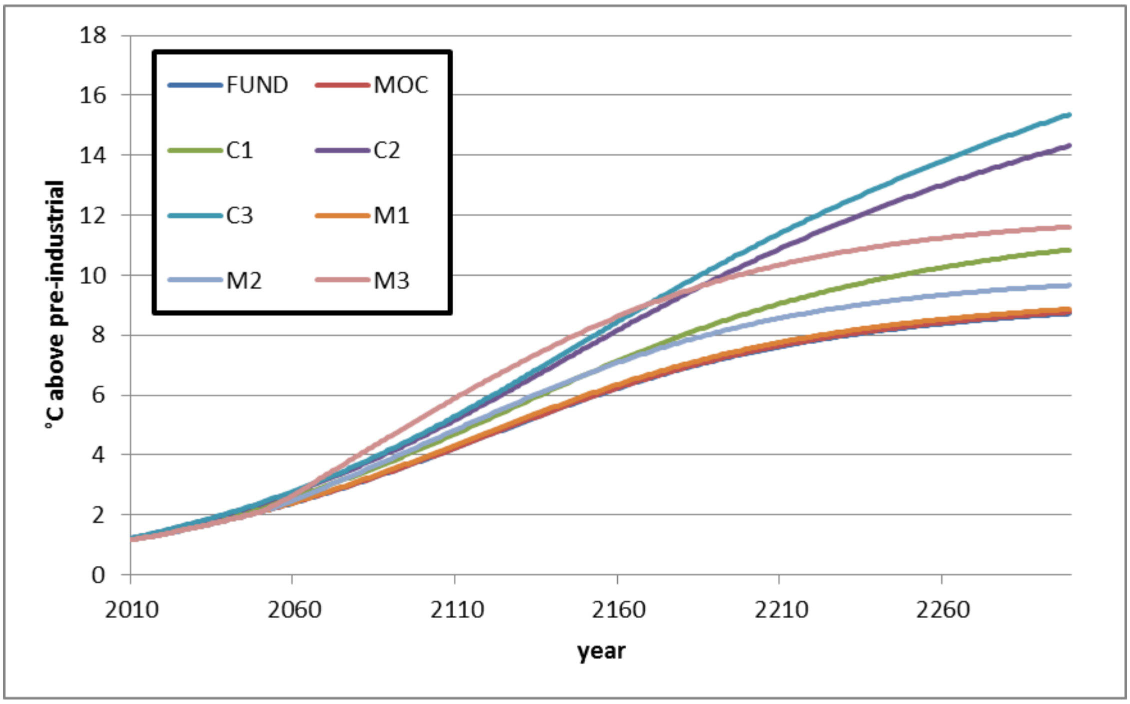
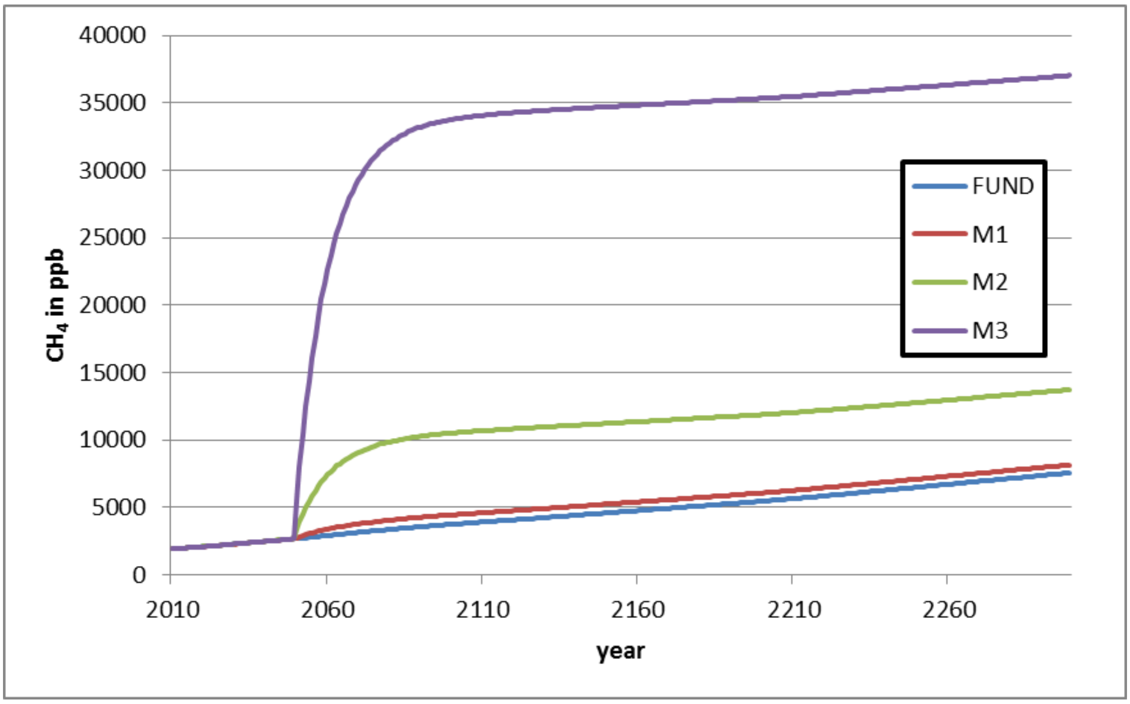


Figure 6: Mean atmospheric CH_4 concentration for all methane scenarios



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