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Calculating the Benefits of Climate Policy: Examining the Assumptions of Integrated Assessment Models

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Abstract

Policy-relevant results of Integrated Assessment Models (IAMs) are sensitive to a number of uncertain assumptions that govern model simulation of the climate, society, and the policy response to climate change. Uncertainties remain in understanding of the rate and magnitude of climate change, the nature and severity of climate impacts, and the ability to cope with those impacts. Methods for quantifying and comparing climate damages across different regions and different time periods are fiercely debated. This paper examines assumptions that are central to model estimates of the benefits of climate policy in three well-known IAMs, and discusses their consistency with current natural and social scientific research. Different IAMs take different approaches to dealing with these uncertainties, and understanding their assumptions is critical to interpreting their results, since those results can change dramatically when assumptions are varied.

Introduction

Integrated Assessment Models (IAMs) employ simplified representations of society, the climate system, and key interactions between them: climate change, its impacts on social and natural systems, and the costs of policy measures to reduce those impacts. Their primary purpose is to inform policy decisions regarding climate mitigation (greenhouse gas emissions reduction). IAMs that attempt to translate climate impacts into monetary damages are used for social cost of carbon (SCC) calculations (monetary estimates of the cost to society of emitting one ton of carbon today) and cost-benefit analyses (CBAs) to determine "optimal" policy. The benefits of climate policy, in this context, represent avoided climate impacts that would otherwise cause damages to society in the future.

In March 2009, the Pew Center on Global Climate Change held a workshop involving 75 of the world's leading experts on modeling the benefits of climate policy. A prominent focus of the workshop was the sensitivity of IAMs and their policy-relevant results to assumptions about key uncertain parameters. Different models make different assumptions about how to represent remaining uncertainties in scientific understanding of the climate system and its response to increasing greenhouse gases. They also make different assumptions about how to value climate impacts across time and space. It is critical to understand these underlying assumptions when interpreting model results, because results can vary dramatically when these assumptions are changed. For example, Tol (2007a) surveyed 211 estimates of the SCC that ranged from small negative values (meaning additional tons of carbon emitted are beneficial) up to positive values of several hundred dollars per ton or more.

The purpose of this paper is to examine the key assumptions governing quantification of the benefits of climate policy in three commonly used IAMs, and to compare the consistency of model assumptions with current natural and social scientific research. The main sections that follow examine model assumptions about the sensitivity of the climate response to emissions and the representation of climate impacts. Additional sections more briefly discuss the treatment of adaptation and discounting in the context of the valuation of benefits. Table 1 presents a summary of the model components and key assumptions covered in these sections. The concluding section discusses the implications of this analysis and recommendations for future work.

Table 1.

Model Component	**Key uncertainties/assumptions**
Climate Response	Climate sensitivity, transient climate response, carbon sinks
Impacts	Damage function shape and magnitude, treatment of non-market and catastrophic impacts
Adaptation	Adaptation potential and effectiveness
Discounting	Discount rate, equity weighting, time horizon

The Models

The three models examined here are the Dynamic Integrated Model of the Climate and Economy (DICE) (Nordhaus and Boyer, 2000; Nordhaus, 2008), the Policy Analysis for the Greenhouse Effect Model (PAGE) (Hope, 2006; Hope, 2008), and the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) (Tol, 2002a; Tol, 2005). These models have been applied in two main approaches for providing policy-relevant information: policy evaluation and policy optimization. Policy evaluation experiments calculate the consequences of specific climate policy strategies (e.g., represented by different emissions scenarios) in terms of a suite of environmental, economic, and social performance measures. Policy optimization experiments calculate the "best" trajectory for future emission reductions based on a specific performance measure, such as minimizing the sum of discounted mitigation costs and monetized damages from climate impacts.[1] Fundamental aspects of the policy optimization framework and its applicability to climate policy have been heavily critiqued, such as intergenerational discounting, economic valuation of non-market climate change damages, and the fact that "optimal" solutions based on a host of uncertain parameters can change significantly when key parameter values are varied, as is discussed in this paper. The debate over the applicability of this modeling

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[1] In this case, increasing investment in mitigation reduces future climate change and related damages, and the model calculates an "optimal" balance between the two.

framework is outside the scope of this paper, but is discussed in detail elsewhere (e.g., Ackerman et al., 2009a).

As mentioned above, model results are highly sensitive to uncertainties in model representations of climate and social systems and their interactions, and different IAMs take different approaches to incorporating uncertainty. *Deterministic analyses* employ “best-guess” (or expected) values for all model parameters. The effect of alternative parameter choices on model outputs and the importance of uncertainty in specific parameters can be determined through sensitivity analyses: examining differences in model outputs across runs which vary a specific parameter, in order to quantify the sensitivity of model results to changes in that parameter (e.g., Nordhaus, 2008). *Probabilistic analyses* specify probability distributions for some or all uncertain model parameters, resulting in probability distributions for model outputs (e.g., Hope, 2006; Warren et al., 2008). DICE and FUND have been most commonly run as deterministic models (generally presenting sensitivity analyses to explore uncertainty), while PAGE has only been run as a probabilistic model. Both DICE (e.g., Mastrandrea and Schneider, 2004; Nordhaus, 2008) and FUND (e.g., Anthoff et al., 2009), however, have also been used in probabilistic applications, and the newest version of FUND is probabilistic in some aspects. Variation of model parameters across reasonable values can significantly change model results, and treatment of uncertainty is itself a critical assumption in IAMs. As will be discussed in the concluding section, accounting for uncertainty generally increases policy stringency in an optimization framework.

IAM developers, of course, update their models over time in an attempt to reflect the latest research. In general, this model evolution suggests that results from newer versions of each model should take precedence over results from previous versions, and that comparisons or meta-analyses of results for the purpose of informing policy decisions should rely on results from the most recent versions of models, rather than including results from previous model versions. This approach was recently adopted by DOE in estimating the benefits of avoided CO_2 emissions of a proposed efficiency rule for commercial beverage vending machines (Department of Energy, 2009). Thus, this paper focuses on the most recent versions of these models: DICE-2007 (Nordhaus, 2008), PAGE2002 (Hope, 2006a; Hope, 2008), and FUND3.5 (Anthoff et al., 2009; Tol, 2009). The same model versions are often run with different sets of assumptions in different modeling studies. In general, this paper focuses on the default model assumptions, introducing alternatives when the results are illustrative of model behavior.

Climate Response

A key determinant of the benefits of climate policy is the modeled response of the climate system to greenhouse gas emissions. Projected climate changes (e.g., temperature increase) drive modeled climate impacts, and the difference in projected climate change between a "business as usual" scenario and a given policy scenario determines the benefits (avoided damages) associated with that scenario. The climate response can be thought of in three components: (1) the long-term temperature increase associated with an increase in greenhouse gas concentrations in the atmosphere, (2) the rate at which temperature increase approaches this level, and (3) feedbacks between climate change and the carbon cycle, which can affect the removal of carbon dioxide by natural processes and thus affect the fraction of emissions from human activities that remain in the atmosphere, and the rate of increase of greenhouse gas concentrations.

Equilibrium Temperature Response

The long-term temperature response is generally expressed as the climate sensitivity, defined as the long-term temperature increase associated with a sustained doubling of carbon dioxide concentrations in the atmosphere. The higher the climate sensitivity, the greater the temperature increase induced by a given level of greenhouse gas emissions, and the greater the damages. Therefore, a higher climate sensitivity will increase calculated benefits of climate policy, all else being equal.

Climate sensitivity is subject to considerable uncertainty. The most recent (2007) report of the Intergovernmental Panel on Climate Change (IPCC) presented a "likely" range[2] for the climate sensitivity of 2-4.5°C, with a best estimate of 3°C (Solomon et al., 2007). In DICE, one value for climate sensitivity is specified under standard assumptions (3°C in DICE-2007, increased from 2.91°C in previous versions). In FUND, a gamma distribution is specified with a most likely value of 2.5°C and a standard deviation of 1°C, yielding a mean of 2.85°C (previous versions of FUND used a single value for climate sensitivity of 2.5°C). In PAGE, a triangular probability distribution is specified with a minimum value of 1.5°C, a most likely value of 2.5°C, and a maximum value of 5°C, yielding a mean of 3°C. Thus, model values fall within the IPCC range, with both DICE and PAGE (mean) consistent with the IPCC "best estimate," and FUND (mean) slightly lower. However, while the climate sensitivity value in DICE is consistent with current scientific understanding, the model does not capture existing uncertainty. This uncertainty is better captured by the PAGE and FUND distributions.

Transient Temperature Response

The rate at which temperature changes over time, the transient climate response, can be just as important as the climate sensitivity. The faster temperature increases in response to increasing greenhouse gas concentrations, the sooner impacts will materialize (an important consideration in IAMs involving some form of discounting, as do the three discussed in this paper). In addition, more rapid changes

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[2] In IPCC terminology, "likely" corresponds to between a two-thirds and nine-tenths chance that the true value is within the range provided.

are generally more difficult and/or more costly to cope with. Transient temperature response is influenced by equilibrium climate sensitivity, but also by other factors, and different models take different approaches. FUND and PAGE employ a “half-life” term that governs the rate of temperature increase towards its equilibrium level. In PAGE and FUND, the most likely value is 50 years and minimum value is 25 years, while the maximum value in PAGE is 75 years and in FUND is 100 years (implying a greater potential for slower temperature response in FUND). DICE employs a simple representation of heat uptake by the ocean that affects the rate of atmospheric temperature increase.

The most straightforward way to compare model behavior is by running the same scenario in each model and comparing model responses. Such “model intercomparison projects” are commonly run for climate models (e.g., Meehl et al., 2007a) and more complex energy-economy models (e.g., De La Chesnaye and Weyant, 2006). van Vuuren et al. (2009) and Warren et al. (2009) present comparisons of the climate response of DICE, FUND, and PAGE (as well as other IAMs), with each other and with the behavior of complex climate models. In general, compared to the other two models, temperature increase is slower and smaller in FUND for a given emissions scenario, leading to lower and more-discounted climate impacts and lower calculated benefits of climate policy (all else being equal). This slower response time also implies that the difference in temperature increase between different emissions pathways will also be smaller, decreasing the calculated benefits of climate policy.

One experiment run by van Vuuren et al. (2009) compares the temperature response across models to an instantaneous increase in greenhouse gas concentrations equivalent to a doubling of carbon dioxide in the atmosphere. Under such an experiment, temperatures approach equilibrium temperature increase equivalent to their climate sensitivity (which is defined in terms of a doubling of carbon dioxide). This process takes hundreds of years, with much of the increase occurring in the first 50-100 years. Of the three models considered here, DICE displays the most rapid initial rate of increase. Temperatures in PAGE (assuming mean values for uncertain parameters) initially increase more slowly than in DICE, but level off more slowly, such that temperature increase is greater in PAGE after roughly ~75 years. Temperatures in FUND increase more slowly, and approach a lower level, given that the climate sensitivity in FUND is lower than in DICE and PAGE (mean). A second experiment compared the IAMs' transient response to that of complex climate models. In general, the initial (50 to 100-year) response of DICE and PAGE fell in the middle of the range of climate model response, while FUND exhibited a slower response than the suite of climate models examined.

Carbon Cycle Feedbacks

Finally, the driving force behind the temperature response is human-induced increases in greenhouse gas concentrations. Currently, around half of carbon dioxide emissions from human activities are rapidly removed from the atmosphere by the world's oceans and terrestrial ecosystems. Modeling studies have projected a weakening of these natural carbon sinks over time in response to climate change, but the strength of this feedback is uncertain (e.g., Friedlingstein et al., 2006). This feedback is quite policy-relevant, as weakening sinks will make it more difficult to meet a given policy target designed, e.g., to reach a certain temperature or concentration target, and will increase calculated benefits of climate policy.

In DICE, major reservoirs of carbon (ocean, atmosphere, and biosphere) are represented, with fixed rates of carbon flow between them. DICE does not include feedbacks that affect the carbon cycle. In FUND, major reservoirs are represented separately, each receiving a fraction of emissions and with an exponential removal rate. Until the most recent version of FUND, the model did not include carbon cycle feedbacks. A terrestrial biosphere feedback has been added in version 3.5 (Tol, 2009), that increases net emissions as a function of temperature. PAGE explicitly represents only atmospheric carbon, with a constant fraction of emissions removed immediately, and an exponential removal rate similar to that used in FUND. PAGE also, however, includes a “natural emissions” term that increases as a function of temperature, meant to represent all carbon cycle feedbacks.

van Vuuren et al. (2009) also examined the carbon cycle behavior of these models (although they use an earlier version of FUND that does not include carbon cycle feedbacks). Under a potential “baseline” scenario (the IPCC Special Report on Emissions Scenarios A2 scenario), all three models exhibit behavior consistent with each other and with the range of climate models. Their behavior differs, however, when considering a scenario with lower emissions. A stylized experiment examined the fraction of carbon dioxide remaining in the atmosphere over time from an instantaneous doubling of concentrations over their preindustrial level. In such an experiment, concentrations decline over time as carbon is taken out of the atmosphere by natural removal processes. For the first 50 years, all models fall within the range of the behavior of climate models. Beyond that, however, differences emerge. FUND remains within this range, while DICE exhibits faster long-term removal of carbon dioxide (beyond ~150 years). PAGE, on the other hand, displays significantly different behavior, with the fraction of carbon dioxide remaining in the atmosphere reversing its decline after 50 years, and increasing significantly. This reversal is due to the “natural emissions” term mentioned above, which implies a strong temperature-dependent carbon cycle feedback. van Vuuren et al. (2009) conclude that the PAGE carbon cycle feedback is consistent with climate models under the (higher) A2 scenario, but is stronger than that in climate models under lower emissions. This suggests that under lower emissions scenarios, atmospheric concentrations in PAGE will remain higher than in other models, perhaps even continuing to increase when concentrations would decline in other models (thus suggesting greater temperature increase and associated impacts).

Moving Forward

Systematic comparisons of IAMs and comparisons of their behavior with complex climate models provide important information which can be used to ensure the consistency of IAM climate components with advances in climate modeling, and help benchmark IAMs' behavior against the range of uncertainty in scientific understanding of the climate response. Such analyses suggest updates that would improve IAM representations of the climate system, revealing a simulated transient temperature response in FUND that is slower than in climate models, and a modeled carbon cycle feedback in PAGE that is stronger than most climate models. Also relevant is the lack of any carbon cycle feedback in DICE, which precludes consideration of this important uncertainty.

Climate Impacts

The modeled climate response in IAMs is generally translated into impacts on society through one or more *climate damage functions* for each model region. These damage functions provide monetary estimates of climate impacts as a function of average temperature increase, often expressed in terms of percentage loss of GDP. Functions are either specified for individual market and non-market sectors or for aggregate damages across sectors. In general, damages are assumed to rise nonlinearly with increasing temperature—each additional degree of temperature rise leads to a greater increase in damages. Different models assume different curvature and steepness of the rising damage function. The larger the damages for a given level of temperature increase and the faster damages increase as temperature increases, the greater the calculated benefits of climate policy.

Of the three models, FUND's representation of impacts is the most disaggregated. FUND includes sector and region-specific impact functions for agriculture, forestry, water resources, energy consumption, sea level rise, ecosystems, health (split into functions for diarrhea, vector-borne diseases, and cardiovascular and respiratory illnesses affected by heat and cold), and damages from tropical and extratropical storms. These functions are described in FUND's technical description (Anthoff and Tol, 2008), and are dependent on both the magnitude and in some cases (e.g., agriculture, ecosystems) the rate of temperature increase. The vulnerability of different impact sectors to climate change is assumed to be affected by socioeconomic development. Water resources (with population growth), heat-related health (with urbanization), and ecosystems and health (with per capita income growth) become more vulnerable. Energy consumption (with technological advancement), agriculture (with economic growth), and vector- and water-borne diseases (with improved health care) become less vulnerable. Thus, impacts in these sectors are dependent on the assumed baseline scenario for socioeconomic development. The parameters that specify these sensitivities are estimated either by calibration to published literature, or expert judgment (Tol, 2002b; Anthoff and Tol, 2008).

DICE uses a single global aggregate damage function dependent on the magnitude of temperature increase. Damages in DICE are based on impact estimates for a list of sectors similar to those in FUND: agriculture, other market sectors (e.g., energy, water, forestry), coastal vulnerability, health, non-market impacts (e.g., outdoor recreation), human settlements, and ecosystems. DICE also includes damages from potential abrupt climate changes such as shutdown of ocean currents, large-scale melting of ice sheets, or release of methane from permafrost. These damage estimates are derived from a climate impact analysis most completely described by Nordhaus and Boyer (2000), Chapter 4, in which damages from the listed categories are estimated for two benchmark levels of temperature increase (2.5°C and 6°C) in terms of percentage loss of GDP. These estimates are then aggregated, and used to specify a global damage function that intersects these two points (and zero damages at zero temperature increase). Thus, the contribution of impacts in different sectors to overall damages is not explicitly represented in the model.

PAGE2002 simulates region-specific aggregate economic and non-economic damages, as well as damages from abrupt climate changes (discontinuities). PAGE is more disaggregated that DICE, specifying three damage functions (economic, non-economic, and discontinuities) for each model region that are dependent on the magnitude of temperature increase as in DICE. Also as in DICE, the contribution of impacts in different sectors to overall damages is not explicitly represented. Total economic and non-economic damages in terms of percentage loss of GDP are calibrated to be consistent with impact estimates summarized in the IPCC Third Assessment Report, including estimates by Tol (1999) and Nordhaus and Boyer (2000) that inform the damage estimates in DICE and FUND. Impacts in PAGE2002 are described in Hope (2006a). Among optimizing IAMs, PAGE and now FUND explicitly incorporate uncertainty in impact estimates through probability distributions for the parameters of their climate damage functions. Nordhaus (2008) also includes a Monte Carlo analysis in which one damage function parameter (the coefficient on the function) is varied along with other model parameters. Implementation of a probabilistic damage function has also been explored in DICE (Mastrandrea and Schneider, 2004), as have the implications of uncertainty in sectoral climate damages (Tol, 2005; Anthoff et al., 2009) in FUND.

Damage estimates in these models are often based on studies from one country or region, since similar studies do not exist for other regions of the world.

Market and non-market damages in DICE are based on studies of impacts on the United States that are then scaled up or down for application to other regions. Many of the estimates to which market damages in PAGE are calibrated are also based on an extrapolation of studies of the United States. Only FUND uses regional and sector-specific estimates. However, in some sectors these estimates also originate in one country, or may be dominated by estimates from one region. For example, in the energy sector, the sector which accounts for most of the economic damages in FUND, estimates for the UK are scaled across the world.

The treatment of other aspects of climate impacts also varies among models. For example, only FUND's damage functions take into account the rate of temperature change as well as its magnitude, but only for the agricultural and ecosystem sectors. Only FUND's damage functions directly include sensitivity to alternative socioeconomic development pathways, for the sectors outlined above. Models also have various ways of simulating damage due to abrupt climate changes, but all are necessarily simplistic. DICE includes these damages in its aggregate function, while PAGE represents them as a separate (uncertain) source of damages that increase in likelihood after temperature crosses an uncertain threshold. FUND does not include impacts from abrupt climate changes in its default damage estimates, although it has been employed to examine estimates of damages from specific abrupt climate changes, such as shutdown of the North Atlantic thermohaline circulation (Link and Tol, 2006).

Global Damage Functions

Figure 1 displays global damage estimates from DICE, FUND, and PAGE. Panel a compares damages in terms of percentage loss of global GDP (with losses as positive values) as a function of global temperature increase above preindustrial levels, for DICE and PAGE (assuming mean values for PAGE as reported in Hof et al. (2008)). In Panel b, the probabilistic structure of PAGE generates a range of relationships between temperature and damages, which are displayed separately for economic, non-economic, and discontinuity damages. Panel c, from FUND2.9,[3] represents losses as negative values (the opposite of the other two Panels), as a function of temperature increase above 1990 levels (~0.6°C higher than the preindustrial level). Note that damage estimates expressed in terms of percent loss of GDP are dependent on the chosen GDP growth scenario, which varies among models. Panel c displays damage functions based on several growth scenarios consistent with four IPCC Special Report on Emissions Scenarios (SRES) storylines. For comparison, GDP growth rates in PAGE are those of the SRES A2 scenario, and GDP growth is determined endogenously in the DICE-2007 model.

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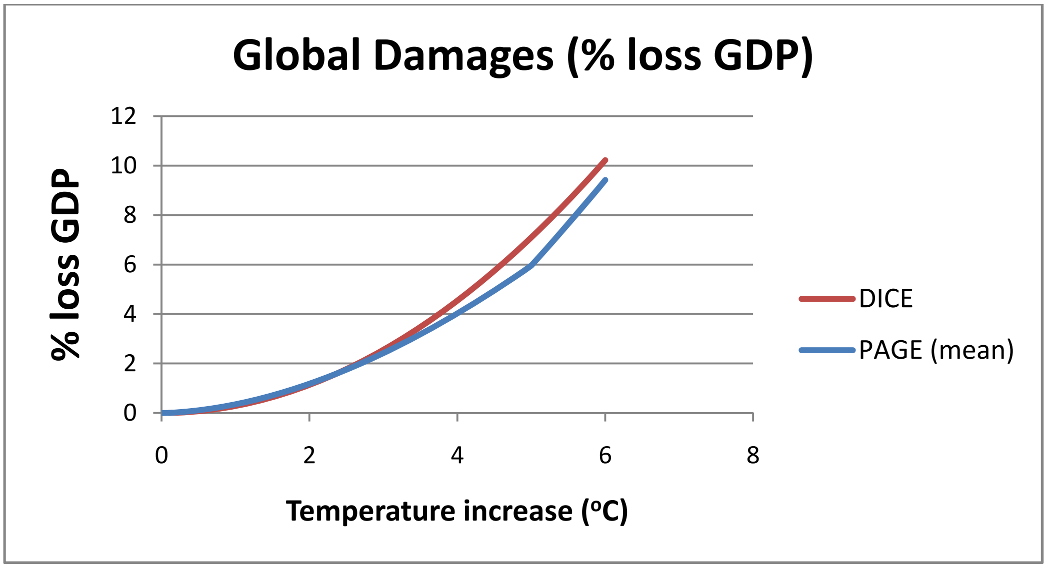
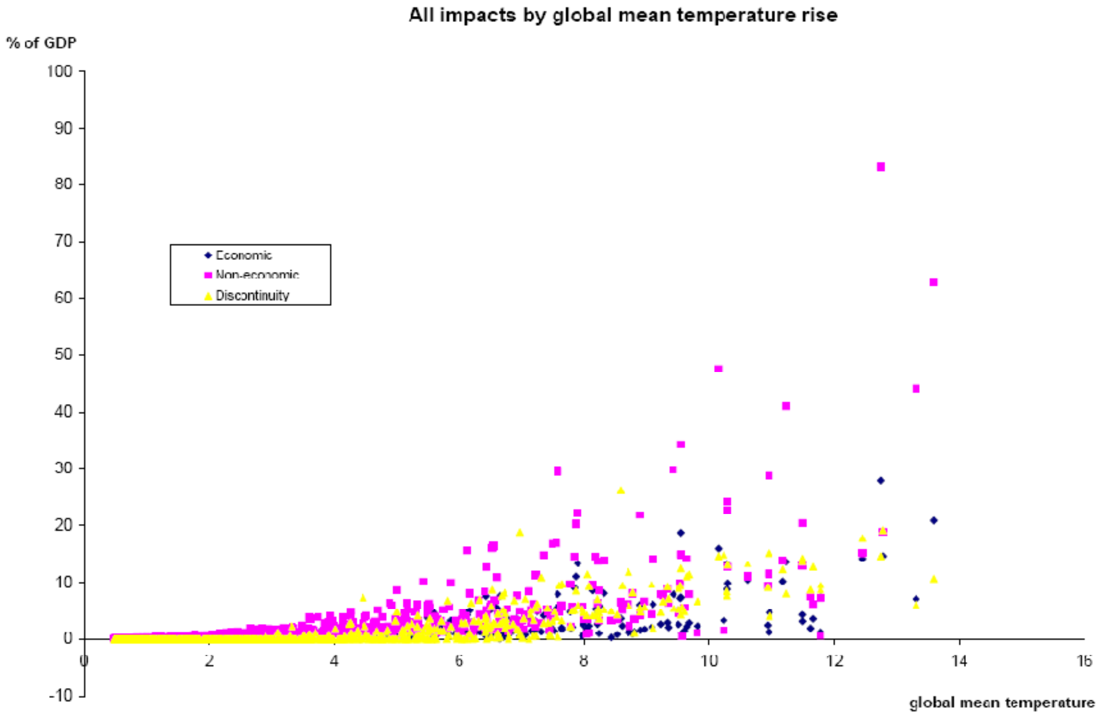
[3] FUND2.9 does not include updated ecosystem impacts and storm damages and uncertainty in impacts functions included in FUND3.4. See below for further discussion.

a) DICE and PAGE (mean)



b) PAGE (range)



c) FUND

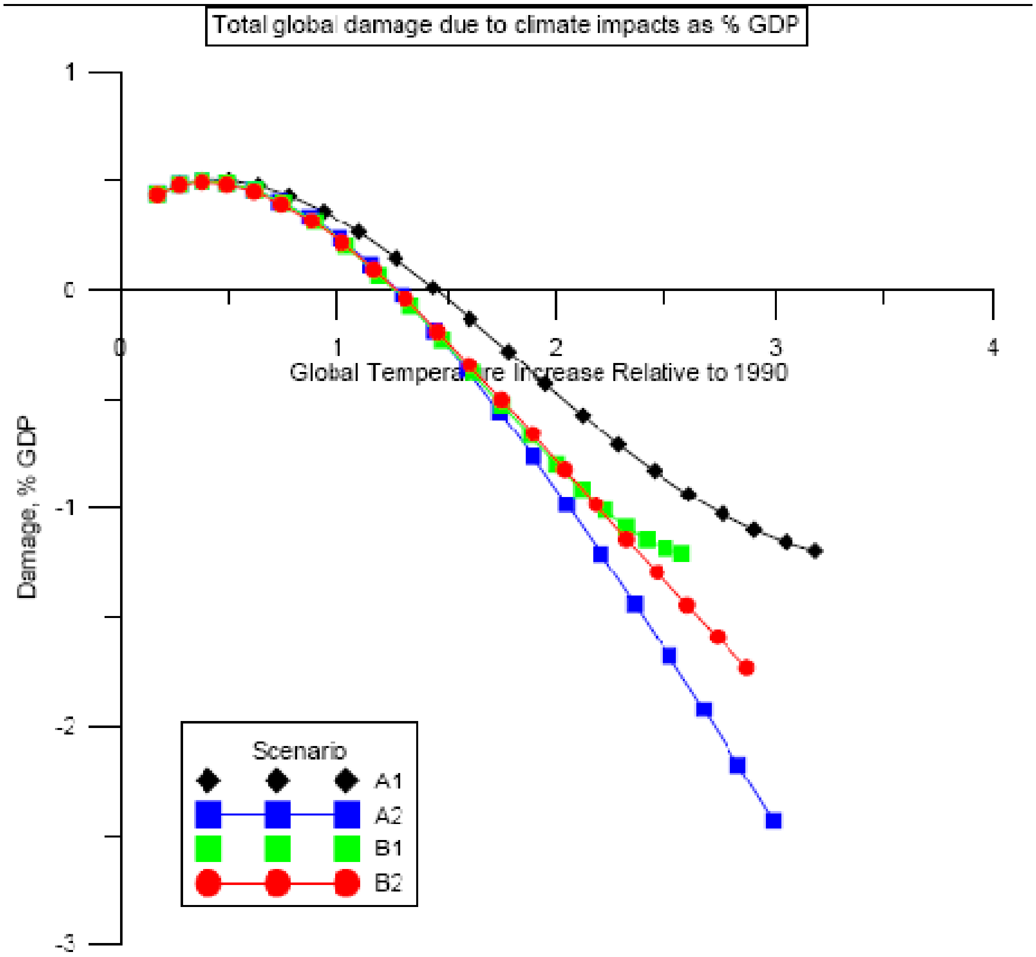


Figure 1. *Global damage estimates in terms of percentage loss of global gross domestic product (percent GDP) as a function of global average temperature increase (°C), for DICE (a), PAGE (a,b), and FUND (c). Panels b and c are adapted from Warren et al. (2007).*

Although the differences in formulation across models do not allow a perfectly parallel comparison, it is clear that the relationship between temperature increase and climate damages varies significantly among IAMs. In FUND, aggregate damages are a net positive (i.e. economically beneficial) for the first 1-1.5°C of temperature increase above 1990 levels. Initial positive impacts primarily arise from the health sector, where reduced cold-related deaths and illnesses outweigh negative health impacts through ~3°C of warming, and the energy sector, where impacts are initially positive for the first 1°C of warming due to reduced heating needs, but then sharply decrease and become the largest contribution to negative impacts at higher levels of warming, due to increased air conditioning needs. The displayed damage functions from FUND2.9 do not include updated ecosystem impacts, storm damages, and uncertainty in impact parameters that are included in FUND3.4, but these changes do not fundamentally change the shape of the damage functions. Damages in FUND from storms are described in Narita et al. (2009a; 2009b), and amount to 0.0074 percent GDP loss from tropical storm damage in 2100 for the scenario run (under a warming of 3.2°C), and 0.0007 percent GDP loss from extratropical storm damage.

In DICE and PAGE, impacts are always negative, increasing nonlinearly as temperature increases, and estimates are higher than for FUND. The DICE-2007 damage function has been increased (higher damages at a given level of temperature increase) compared to previous versions of the model. The primary differences are a recalibration of the costs of catastrophic damages, refining estimates for regions with large temperature increase, and revision upward of overall damages at low levels of temperature increase, that previously were assumed to provide a small but positive net benefit (Nordhaus, 2008). PAGE's mean results (panel a) indicate that damages are similar to those in DICE, falling slightly lower at higher levels of temperature increase. But PAGE's probabilistic results (panel b) indicate the possibility of much higher damages, particularly for non-market impacts (those estimates spreading above the main clustering).

Current Damage Estimates

Estimates of climate impacts in economic terms necessarily lag behind the scientific impacts research on which they are based. The core impact estimates of these IAMs are based on literature from 2000 and earlier. IAM developers, of course, update their models over time in an attempt to reflect the latest science. Recent updates to DICE and FUND are described above. The probabilistic structure of PAGE generates a range of relationships between temperature and damages, and this distribution can be adjusted as new information emerges. But modelers are also reliant on a relatively limited number of economic assessments of future damages from climate change (e.g., Nordhaus and Boyer, 2000; Nordhaus, 2006; Tol, 2002b,c; Mendelsohn et al., 2000; Stern, 2007; Ackerman et al., 2008a; 2008b). Moreover, such assessments are recognized to provide only an incomplete picture of the full impacts of climate change (see, e.g., Hall and Behl, 2006; Yohe and Tirpak, 2008), and while there certainly may be unassessed positive impacts from climate change, such summaries suggest that they are likely to be outweighed by unassessed negative impacts (e.g., Yohe and Tirpak, 2008; Tol, 2008).

Scientific understanding of climate impacts continues to advance, and has led to, in general, the association of greater risks with lower levels of temperature increase (see, e.g., Smith et al., 2009). For example, there is now higher confidence in projections of increases in extreme events (e.g., droughts, heat waves, wildfires, and floods) as well as their adverse impacts (Core Writing Team et al., 2007). More recent studies have also estimated potential economic damages from increased extreme weather events (e.g., Rosenzweig et al., 2002; Climate Risk Management Limited, 2005; Nicholls et al., 2008), which if included are very likely to increase aggregate estimates of climate damages. As discussed above, storm damages have been added to FUND, but estimated damages do not constitute a large fraction of GDP (Narita et al., 2009a; 2009b).[4] See below for an alternative estimate.

There is also now increased attention paid to abrupt climate change and instabilities that could induce large-scale changes in the climate system (e.g., Hall and Behl, 2006; Lenton et al., 2008). A primary example is the risk of significant sea level rise from melting of the Greenland and West Antarctic ice sheets, which may be more rapid than previously thought and may occur with smaller increases in temperature, potentially increasing the magnitude of sea level rise and associated damages for a given amount of temperature increase and for a given point in time (Core Writing

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[4] Damages of increased hurricane intensity in the United States, for example, are estimated to be 0.012 percent of national GDP in FUND for a 3.2°C increase. Ackerman et al. (2008a; 2008b), discussed below, estimate damages that are ~20 times higher (0.24 percent of GDP for a temperature increase of 3.6°C).

Team et al., 2007; Mote, 2007; Pfeffer et al., 2008, Rahmstorf et al. 2007). Estimates that attempt to incorporate this behavior project sea level rise greater than one meter by the end of the century under stronger warming scenarios. For example, Rahmstorf et al. (2007) project sea level rise of 8 to 16 in (~0.2 to 0.4 m) by mid century, and 20 to 55 in (0.5 to 1.4 m) by the end of the century across the range of (lower and higher) IPCC SRES emissions scenarios.

Climate impacts from changes in water resources are also an increasing source of concern in certain regions, and such impacts are not generally a large component in impact estimates incorporated into IAMs (e.g., water resource impacts in DICE are viewed as negligible). For example, semi-arid climates around the world (including areas such as California and other parts of the North American West) are projected to become dryer (Meehl et al., 2007b), and to see large changes in patterns of water demand and supply, as warmer conditions cause more precipitation to fall as rain instead of snow, reducing snowpack buildup and the availability of water from this important source during dry summer months, as well as increasing urban and particularly agricultural water demand (e.g., Hayhoe et al., 2004; Core Writing Team et al., 2007).

New categories of impacts are also emerging for which market and non-market damages are as yet unclear, but may be significant. One example is ocean acidification, which may create significant adverse impacts on coral reefs, fisheries, and other aspects of marine ecosystems (e.g., Orr et al., 2005; Brander et al., 2009), as well as related industries (e.g., fishing, tourism). A related, more general example is the concept of ecosystem services, providing economic valuation of functions provided by natural ecosystems such as forests preserving watersheds by preventing soil erosion, marshes filtering toxins and buffering against storm surges, and species pollinating crops and providing sources for new medicines (e.g., Daily et al., 2000). Increasingly, ecosystem services are becoming recognized as valuable natural assets that may be expensive or impossible to replace if degraded or lost, but the incorporation of ecosystem services into economic accounting is still in its infancy (Daily and Matson, 2008; Mäler et al., 2008).

Models and the impact estimates on which they are based generally also treat impacts in different sectors separately, and do not take into account interactions between sectors. In reality, impacts can concurrently affect multiple sectors in the same region, potentially leading to further damages than if each impact occurred in isolation. For example, more frequent or intense heat waves can simultaneously cause increased public health effects (heat-related mortality and hospitalizations, lost productivity due to illness, aggravation of respiratory illness from degraded air quality, etc.) and disruption of electricity generation and/or transmission, which can lead to further heat exposure if air conditioning fails.

A specific example can provide further insight into the potential magnitude of climate damages in the United States. Ackerman et al. (2008a; 2008b) present damage estimates for the United States, based on sectoral assessments and the U.S. component of the version of the PAGE model used in the Stern Review.[5] They present estimates of market damages from four major climate impacts, and general estimates of additional (market and non-market) damages from other changes, including abrupt climate changes. Table 2 displays their estimates for market damages in the United States from increased hurricane intensity, sea level rise, impacts on water resources and supply, and increase energy demand for cooling, for 2050 and 2100, under a scenario with 2.4°C global average warming above preindustrial levels in 2050, and 4.8°C global average warming in 2100. Estimated damages in these four sectors sum to 1.47 percent of GDP in 2050, and 1.84 percent of GDP in 2100. Total US damages in 2100, including these sectoral estimates, non-market impacts, and impacts from potential abrupt climate changes, are estimated to amount to a 3.6 percent loss of GDP in 2100 (for a 4.8°C temperature increase).[6]

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[5] As discussed in the section on discounting, the version of PAGE used for the Stern Review used a lower discount rate and used purchasing power parity exchange rates.

[6] This estimate combines the sectoral estimates in Table 2 with 83rd-percentile results from the PAGE model for non-market impacts and impacts from abrupt climate changes, rather than mean results. Using mean results from PAGE, the total would be 2.34 percent rather than 3.6 percent. See Ackerman et al., (2008b) for further details.

Table 2.

	2050 (2.4°C increase)	2100 (4.8°C increase)
Hurricane Damages	0.12%	0.41%
Sea Level Rise	0.23%	0.35%
Water Resources	0.14%	0.14%
Energy Costs	0.98%	0.93%
Subtotal (for these impacts)	**1.47%**	**1.84%**

These estimates are considerably higher than the damages estimated for the United States under standard PAGE assumptions, where all market damages are estimated to represent a 0.6 percent loss of GDP in 2100 under the same scenario (Ackerman et al., 2009b). They are also much higher than damages estimated for North America in FUND, where warming is assumed to be beneficial for the first 2.5-3°C of warming (driven largely by benefits in the health sector) (Warren et al., 2007). DICE includes only a global damage function, and thus a direct comparison cannot be made.

In summary, existing analyses of the economic damages of climate change focus primarily on market impacts. Researchers note the sensitivity of the coping capacity of different systems and sectors to the pathway of future socioeconomic development, and thus the site-specificity of the severity of climate impacts (Yohe and Tirpak, 2008). Some studies (and IAMs) attempt to include categories of non-market impacts and impacts from abrupt climate changes, and such impacts contribute significantly to damages in DICE and PAGE. Even so, such damages are both highly uncertain and difficult to quantify, and no IAM fully accounts for all of these factors. Based on examples such as those discussed above, therefore, IAMs are likely to underestimate the magnitude of damages from climate change and calculated benefits of climate policy. Thus, when employed for CBA, they are likely to underestimate optimal emissions reductions.

Moving Forward

Expanding and updating economic assessments of climate damages can certainly provide an improved basis for updating IAM damage functions. Climate impacts research is increasingly providing more detailed information about the regional and sectoral impacts of climate change in many regions of the world, which can be used for this purpose. For example, “Global Climate Change Impacts in the United States” (Karl et al., 2009), released by the U.S. Global Change Research Program, provides a summary of climate impacts on different sectors and regions of the United States.

But not all problematic elements can be addressed in this way. No matter how detailed estimates become, uncertainty will always remain regarding future climate impacts and their damages. Moreover, important impacts of climate change in areas such as human health (loss of life and well-being), natural ecosystems (species extinction and loss of biodiversity), and social conflict (forced migration and impacted security) cannot easily, and arguably should not be quantified in monetary terms. An alternative approach is the explicit consideration of multiple metrics by which to measure climate risks (e.g., Yohe and Tirpak, 2008; Smith et al., 2009). Such an approach moves away from a traditional optimization framework toward a broader examination of the benefits of climate policy beyond those that are quantifiable in monetary terms.

A simple case of considering non-monetary metrics to which IAMs, including DICE (Nordhaus, 2008), have been applied, is calculating pathways that avoid (or avoid with a certain likelihood) a specific threshold of temperature increase, for instance one that is chosen to avoid unacceptable climate impacts associated with temperature increase above that level. In this approach, the choice of policy target is specified outside of the IAM framework, rather than emerging as a product of the model calculations. In this context, the role of IAMs shifts from cost-benefit analysis to cost-effectiveness analysis, examining pathways to avoid thresholds for unacceptable risk to society identified through examination of climate impacts across a range of metrics.

Adaptation

Even with aggressive global efforts to reduce emissions, the climate will continue to change significantly for many decades because of the magnitude of past emissions and the inertia of social and physical systems. Alongside mitigation, then, policies focused on *adaptation* are also a necessary response to climate change. There is growing recognition that the two strategies must be complementary and concurrent. Mitigation can keep warming on a lower trajectory, and delays in mitigation will lock in further warming, making adaptation that much harder. Adaptation, in contrast, is a response to warming, not a means of slowing it. It is a response designed to reduce the damages from climate impacts associated with the climate change that does occur in the future. The potential for adaptation to reduce damages to human society is generally much higher than the potential for reducing the biophysical impacts of climate change. In some cases, the distinction between impacts and adaptation is not completely clear, such relocation or migration due to sea level rise, which can be characterized either as an impact or an adaptation.

Two types of adaptation are generally considered: autonomous and planned. Autonomous adaptation is not guided by policy; it is a reactive response prompted by the initial impacts of climate change. For example, people who now live in warmer areas have acclimatized to those conditions, becoming less vulnerable to temperatures that would cause significant heat-related illnesses for people living in more temperate areas. Even so, there are limits to such adaptation, particularly if warmer temperatures spur increased use of air conditioning (a planned adaptation), and therefore less acclimatization.

Planned adaptation can also be reactive. For example, after the 2003 European heat wave, European countries instituted more coordinated plans to deal with periods of extreme heat. Buying additional water rights to offset declining water supply or purchasing crop insurance where available are also reactive responses. Another kind of planned adaptation—anticipatory or proactive—has greater policy potential. Anticipatory adaptation might include improving or expanding irrigation for agriculture, engineering crop varieties that are better able to cope with changing climate conditions, building sea walls to protect coastal infrastructure, and constructing reservoirs or implementing water recycling strategies to improve water management. Such actions may be similar in substance to reactive adaptation, but they anticipate future changes rather than responding to past shifts. Some anticipatory actions may be implemented without specific policy intervention, such as protection of long-lived coastal infrastructure vulnerable to sea level rise, before inundation occurs. Other potentially anticipatory actions may only be implemented reactively unless policy incentives are established. An iconic example of a failure to implement potential “adaptation” (regardless of its linkage to climate change) is Hurricane Katrina, where resources could have been used to strengthen levees and undertake other protections that would likely have made the damages from Katrina far less severe, but these actions were not taken, in spite of warnings that a strong hurricane would likely overwhelm the existing defenses (e.g., Stone et al. 1997).

IAMs, in general, focus on the tradeoff between mitigation costs and climate change damages, and do not explicitly consider adaptation. Adaptation is either omitted, or considered as part of the calibration of the damage function (e.g., for agricultural impacts), where any assumed adaptation lowers the damages associated with a given level of temperature increase, and any assumed adaptation costs are added to estimated damages. DICE considers adaptation implicitly, in that some of the original papers on which its damage estimates are based make assumptions about adaptation that lower estimated damages. For example, its agricultural impact estimates assume that farmers can make changes to land use in response to changing climate conditions, and its health impact estimates assume improvements in healthcare (Nordhaus and Boyer, 2000; Warren et al., 2007). In addition, impacts on forestry, water systems, construction, fisheries, and outdoor recreation are assumed to be negligible, implying, very optimistically, costless and unlimited adaptation in these sectors (Nordhaus and Boyer, 2000; Warren et al., 2007). Costs of resettlement due to inundation of coastal areas from sea level rise are incorporated into damage estimates, but their magnitude is not clearly reported. In general, DICE assumes very effective adaptation, and largely ignores adaptation costs.

In FUND, as in DICE, adaptation is included implicitly in the damage estimates on which its damage functions are based, reducing damages where considered feasible. Unlike DICE, adaptation and its costs are also included as an explicit component of damage functions for agriculture and impacts from sea level rise, but not for other sectors. Adaptation is included in the context of land use transitions for agricultural land, and protection for coastal land. In addition, the reduced vulnerability of impacts in some sectors dependent on socioeconomic development described above—for energy consumption (with technological advancement), agriculture (with economic growth), and vector- and water-borne diseases (with improved health care)—reflect embedded assumptions about adaptation. In general, adaptation is assumed to be very effective in FUND, and adaptation costs are considered only partially. In the case of agriculture, damages are negative (benefits) for at least the first 3°C of warming in all regions except Australasia, due in part to the incorporation of adaptation.

PAGE, on the other hand, explicitly includes adaptation as a decision variable in the model that can be set by the user (but is not included in optimization calculations, instead being treated as another assumption once specified). In PAGE, adaptation is assumed to be low-cost, and very effective. In OECD countries, all market damages from warming less than 2°C, and 90 percent of market damages from warming greater than 2°C, can be avoided via adaptation. 50 percent of market damages can be avoided in developing countries. Adaptation can also avoid 25 percent of non-market damages in all countries. Adaptation does not affect damages from abrupt climate change. These assumptions have been described as unrealistic or optimistic by some researchers (de Bruin et al., 2009; Ackerman et al., 2009b).

A detailed discussion of the costs of adaptation is outside the scope of this paper, but estimates vary widely (see, e.g., Parry et al., 1998a, b; Fankhauser, 1998; Mendelsohn, 2000; Parry et al., 2009a, b; de Bruin et al., 2009). Estimates of the effectiveness and limits to adaptation, however, are a critical component of calculations of the benefits of climate mitigation policy, given that IAMs assume, either implicitly or explicitly, that adaptation leads to a reduction of damages associated with a given level of temperature increase as specified by the damage function, lowering calculated benefits of mitigation policy.

While considerable potential exists for planned adaptation to reduce damages from future warming, there is increasing recognition of the complexities, barriers, and limits inherent in actual implementation of adaptation strategies (e.g., Adger et al., 2009). In short, there is a crucial difference between potential adaptation, and implemented adaptation (see, e.g., Adger and Barnett, 2009). Events such as Katrina and the 2003 heat wave in Europe highlight the vulnerability of specific populations and regions, even within highly developed nations, to climate events.

The uncertainty inherent in projections of future climate change, in addition to the potential for unprecedented changes outside the range of historical experience, complicate efforts to improve adaptation planning and implementation. For example, building codes and flood risk maps used for insurance purposes are based on estimated historical flood frequencies, and are only very slowly moving to incorporate future risks from projected sea level rise and changes in storm frequency and intensity. The potential for maladaptation, actions that reduce rather than enhance society's ability to cope with future changes, should not be underestimated. For example, the high degree of natural variability of weather may mask clear identification of emerging climatic trends. Imagine a sequence of weather anomalies: say, a series of very wet years, which are precisely the opposite of the "true" long-term climatic trend toward dryer conditions. Such a sequence could easily be mistaken for a new climatic regime and actually lead to maladaptive practices, such as investing in additional flood protection that becomes unnecessary, instead of investing in additional water storage.

Moving Forward

Despite these challenges, the benefits of mitigation will take time to materialize, and therefore adaptation is essential in responding to near-term climate changes already in the pipeline. The need for both strategies raises the possibility of whether adaptation and mitigation should be considered as trade-offs. This treatment is adopted in Tol (2007b), in an application of FUND that focuses on coastal protection and sea level rise damages. The paper concludes that adaptation through investment in protection is an important option to reduce damages from sea level rise, and that adaptation and mitigation must be considered together, as higher levels of mitigation mean less adaptation is necessary, but could also limit resources available for adaptation.

Adaptation and mitigation decisions will certainly affect each other, and can have both positive and negative synergies. For example, certain adaptation strategies can entail increased energy use (e.g., desalination plants built to respond to projected decreases in water supply) compared to other strategies (e.g., demand management through increased efficiency of water use), and thus have significant implications for meeting mitigation targets. In summary, given the importance of adaptation as a response strategy to climate impacts, its treatment in IAMs is necessary. Current treatment of adaptation may overestimate the capacity of adaptation to offset damages (over-optimistic assumptions) and underestimate adaptation costs (either again through optimistic assumptions, or through incomplete incorporation). The inclusion of adaptation as a decision variable as in PAGE is an approach that allows explicit consideration of a range of levels of adaptation, rather than an approach that embeds specific assumptions within the damage function as in DICE and FUND. Regardless of its treatment, given the significant uncertainties that exist regarding both the limits to and efficacy of adaptation, as well as its costs, the assumptions that govern the relationship to estimated damages and other model components should be transparent.

Discounting

A final critical influence on the calculated benefits of climate policy is how damages are valued and compared as they evolve over time and affect different regions of the world. This valuation is governed by the discount rate, and assumptions made about its components profoundly affect IAM results, determining to what extent benefits (or costs) that occur further in the future are given less weight than those that occur sooner. In models with different discount rates, identical scenarios of future climate change and climate damages can be valued very differently, and thus will result in different calculations of the benefits of climate policy.

As originally presented by Ramsey (1928), the discount rate r can be expressed as:

$$r = \rho + \eta g$$

where ρ is the pure rate of time preference (the rate of preference for present versus future consumption), η is the negative of the elasticity of the marginal utility[7] of consumption (the rate at which additional consumption provides smaller increases in welfare as consumption increases), and g is the growth rate of per capita consumption. In IAMs, the growth rate of per capita consumption is determined by the assumed or calculated pathway for socioeconomic growth. The other two terms, however, are specified, and there is no one "correct" set of values—their proper specification in IAMs continues to be a source of considerable debate on economic and ethical grounds. There is also a key difference between the models in the influence of changes to these terms. In FUND and PAGE, economic growth is defined exogenously and is not affected by changing these terms. DICE, however, uses a growth framework in which changing either term changes the optimal savings rate, and therefore the projection of economic growth as well.

A larger pure rate of time preference gives greater weight to the present, under the assumption that people put more weight on the present than the future (are impatient), and therefore the future should be discounted. Under default assumptions, the DICE model assumes a rate of 1.5 percent (Nordhaus, 2008). In earlier versions, FUND assumed a rate of 1 percent (Tol, 1997), but most recent applications of FUND have reported results for rates of 0 percent, 1 percent, and 3

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[7] Utility used here in the economic sense, the satisfaction generated by consumption of goods and services.

percent (e.g., Anthoff et al., 2009). DICE has also been run with a range of higher and lower values (e.g., Nordhaus, 2007). In PAGE, the pure rate of time preference is represented by a triangular probability distribution with a minimum value of 1 percent, a most likely value of 2 percent, and a maximum value of 3 percent, although more recent applications (such as in Stern) have employed lower rates. Once again, there is no one "right" answer. A recent iteration of this debate over the pure rate of time preference focused on the Stern Review (Stern, 2007), which employed a modified version of the PAGE model that assumed a low pure rate of time preference of 0.1 percent, which gives greater weight to future damages. Critics of the review favored a higher rate (e.g., Nordhaus, 2008; Tol and Yohe, 2006), while the authors defended their assumption (Dietz et al., 2007). A detailed discussion of the debate is outside the scope of this paper. See Ackerman et al. (2009a) and Anthoff et al. (2009) for further discussion. In general, a higher pure rate of time preference will lower calculations of the benefits of climate policy, because future climate damages will be discounted more heavily.

While much debate has focused on pure rate of time preference, the elasticity of the marginal utility of consumption is also a critical parameter that has received less attention. This term can serve multiple important roles in IAM calculations. Most generally, it represents the rate at which each additional dollar of consumption provides less utility as consumption increases (and therefore represents the assumption that future dollars should be discounted because future generations that are richer than the present one will derive less utility from the same number of dollars). All three models examined here employ this parameter in this context. But it can also be thought of as playing a role in how consumption (or loss of consumption from climate damages) is weighted across regions with different levels of income. These so-called equity weights are employed to reflect the fact that a dollar of damage in a poorer region will have more of an impact than in a richer region, and therefore they should not be treated as equivalent. Finally, this parameter can also be interpreted as a measure of risk aversion (e.g., the degree to which society should hedge against uncertain but highly negative outcomes). See Anthoff et al. (2009a; 2009b) and Newbold and Daigneault (2009) for further discussion.

In DICE, this parameter is set to 2, and is not related to equity weighting, since impacts are only considered at a global level. Therefore, it reflects the smaller utility of a dollar's worth of consumption in a richer future. In PAGE, this parameter is specified as a triangular distribution with minimum value 0.5, median value 1, and maximum value 1.5, with regional equity weights defined independently of this parameter. In FUND, it is set to 1, and it is directly related to equity weighting. A value of 1, in this context, means that a $1 loss to someone with an income of $10,000 is equivalent to a $10 loss to someone with an income of $100,000. FUND has been used in applications where this parameter has been varied (Anthoff et al., 2009), and where equity weights have been varied while the elasticity of the marginal utility of consumption has not (Tol, 2002a). Once again, there is no "right" answer, but a key point to note is that where the negative of the elasticity of the marginal utility of consumption is employed as both a component of the discount rate and the calculation of equity weights, increasing the equity weighting (giving more weight to impacts in poorer regions) also increases the discount rate. In general, poorer regions are more vulnerable to climate impacts, and therefore increasing weighting of impacts in these regions will increase calculated benefits of climate policy. But increasing the discount rate decreases the weighting of future impacts in general, decreasing calculated benefits of climate policy. Which of these influences is stronger is unclear, and is model-dependent.[8] In PAGE (see Figure 2 below), the influence on the discount rate appears to be stronger, but in FUND, the relationship is more complex. Using the default value for the pure rate of time preference, increasing the negative of the elasticity of the marginal utility of consumption from its default value of 1 initially decreases calculated benefits of climate policy, but this decrease reverses as the value is increased further. This behavior is also different for different values of the pure rate of time preference, where the influence of increasing the negative of the elasticity of the marginal utility of consumption always decreases calculated benefits

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[8] The role of the negative of the elasticity of the marginal utility of consumption as a measure of risk aversion is another reason that its effect on benefits estimates may be ambiguous—at least in the context of a probabilistic assessment estimating willingness to pay in an expected utility framework. See Weitzman (2009) and Newbold and Daigneault (2009) for further discussion.

of climate policy across the same range. See Anthoff et al. (2009) for a detailed discussion.

A final related assumption in IAMs is the time horizon over which the model is run. A model that is run until 2100, for example, will not consider damages that occur beyond 2100. In general, increasing the time horizon increases calculated benefits of climate policy, as damages occurring further in the future are accounted for. This assumption becomes less important, however, the larger the discount rate assumed. PAGE has the shortest time horizon, running out to 2200 (which may affect calculations of the benefits of climate policy when a low discount rate is used). DICE runs out to 2600, and FUND out to 3000, likely far enough that any variation will have little effect on policy calculations.

Summary and Synthesis

Table 3 summarizes how various IAM assumptions influence the calculated benefits of climate policy as discussed in the preceding sections. Assumptions made about all of these parameters influence model results, but the sensitivity of results to variations in different parameters differs significantly. The relative importance of different assumptions has been studied to a certain extent in all three models, but most extensively in PAGE. Figure 2, from Hope (2008), shows the relative strength of major influences on the calculation of SCC in PAGE. Climate sensitivity has the largest influence on SCC, followed by the pure rate of time preference. Consistent with Table

3, larger climate sensitivity has a positive effect on SCC, and larger pure rate of time preference has a negative effect. Next is a parameter related to the magnitude of non-market impacts (positive), followed by the negative of the marginal utility of income, which in the PAGE model has a negative effect on SCC, as noted above. The final three parameters in Figure 2 are the half-life of global warming (the speed of transient temperature change), a parameter related to the magnitude of market impacts, and a parameter related to the strength of carbon sinks.

Table 3.

Assumption	Benefits of Mitigation Policy
Climate Sensitivity ⬆	⇧
Transient Response ⬆	⇧
Carbon Sink Strength ⬇	⇧
Climate Damages ⬆	⇧
Adaptation Effectiveness ⬆	⇩
Pure Rate of Time Preference ⬆	⇩
Marginal Utility of Consumption/ Equity Weighting ⬆	⇧ ⇩
Time Horizon ⬆	⇧

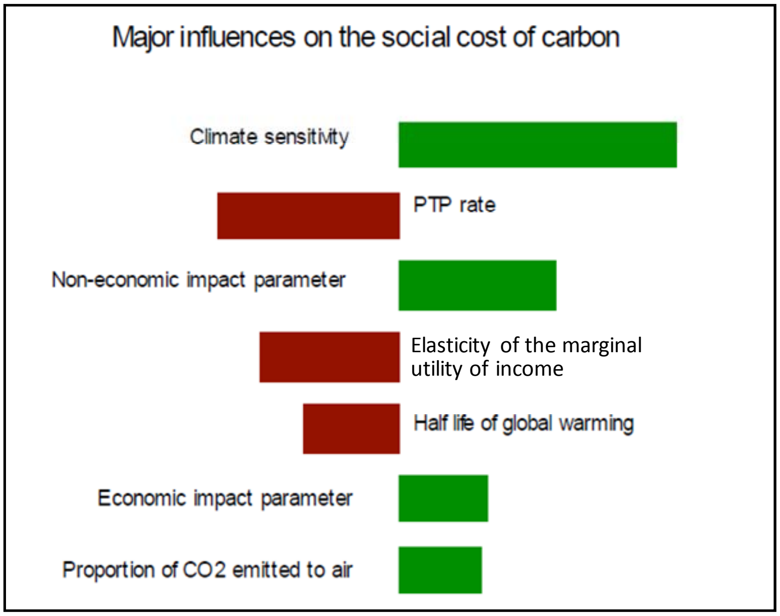

Figure 2. *Relative influence of uncertain parameters on SCC estimates.*

Note that the relative strength of each of these influences is not only related to the sensitivity of results to a given parameter, but also the range over which that parameter is varied in the model (the probability distributions for these parameters assumed in PAGE). In other words, a parameter to which results are less sensitive, but which is varied over a larger range, can have the same influence on results in such an analysis as a second parameter to which results are more sensitive, but which is varied over a smaller range. Climate sensitivity, for example, is varied over a larger range than the pure rate of time preference. Thus, the specific ordering in Figure 2 is model-dependent, but the parameters included are illustrative of those to which results are most sensitive.

A sensitivity analysis of SCC calculations including some of the corresponding parameters in the DICE model was conducted by Nordhaus (2008) using the DICE baseline scenario. Climate sensitivity, the coefficient on the DICE global damage function, and a carbon sink parameter were included, but the analysis did not include discount rate components or a parameter related to the transient climate response. In DICE, SCC calculations were more sensitive to variation in the damage function coefficient than to variation in climate sensitivity, even though climate sensitivity was varied over a larger range. Results were relatively insensitive to changes in the carbon cycle parameter.

The sensitivity of model results to variation in each of these parameters is not independent. The higher the discount rate, the lower the sensitivity of model results to variation in damage function and climate response parameters, since future damages are discounted to a greater extent. Thus, at low discount rates results will likely be most sensitive to parameters such as the climate sensitivity, and those governing the magnitude and shape of the damage function. At higher discount rates, this sensitivity will decrease significantly, highlighting the importance of assumptions about discount rate components. In addition, results will be more sensitive to equity weighting in models where damages are concentrated more heavily in poorer regions.

Assumptions Combined: Model Results

This paper has refrained from presenting specific numerical model results, such as calculated SCC, during the examination of model assumptions. Armed with this examination, however, it is the hope of the author that such results can more easily be viewed in the context of their sensitivity to underlying assumptions and how they might change if those assumptions were altered. These results also, of course, represent the combined effect of all model assumptions. With that in mind, it is useful to examine specific model results for each of the models discussed here, which also highlight other important aspects of IAM behavior.

First, Hope (2008) presented SCC results calculated by PAGE consistent with the sensitivity analysis presented in the previous section and the standard assumptions presented in this paper. Mean SCC in 2000 is calculated to be \$12 per ton of carbon (\$3.3 per ton of CO_2), with a 5-95th percentile range of \$2-35 per ton of carbon (\$0.5-9.5 per ton of CO_2). Hope (2009) presented SCC results calculated by PAGE under a different set of discounting assumptions (pure rate of time preference set to 0.1 percent, the negative of the elasticity of the marginal utility of consumption set to 1, a much lower discount rate). As expected, mean SCC is calculated to be much higher—\$63 per ton of carbon (\$17.2 per ton of CO_2)—with a 5-95th percentile range of \$13-189 per ton of carbon (\$3.5-51.5 per ton of CO_2). These values are lower than the mean SCC of ~\$300 per ton of carbon (~\$82 per ton of CO_2) reported in the Stern

Review using PAGE with similar low discount rates (Stern, 2007), mainly because the version of PAGE in Hope (2009) used market exchange rates, whereas the Stern Review used purchasing power parity rates to aggregate damages across different regions. In general, using purchasing power parity rates gives greater weight to the impacts in poorer countries, where the majority of climate change impacts will occur (Stern, 2007), producing an effect similar to equity weighting.

Nordhaus (2007) reports results for the DICE model run under three combinations of pure rate of time preference and the negative of the elasticity of the marginal utility of consumption: default DICE assumptions (1.5 percent and 2, respectively), "Stern discounting" (0.1 percent, and 1), and a "recalibrated" combination (0.1 percent and 3) where the pure rate of time preference is kept low, but the negative of the elasticity of the marginal utility of consumption is modified to be higher, increasing the real discount rate (see Nordhaus, 2007 for further explanation). For default discounting, SCC in 2015 is $35 per ton of carbon ($9.5 per ton of CO_2), for Stern discounting, SCC is $360 per ton of carbon ($98.2 per ton of CO_2) and is similar in magnitude to the results from PAGE, and for the recalibrated combination, SCC is $36 per ton of carbon ($9.8 per ton of CO_2). These results demonstrate that calculations of SCC are very sensitive to the real discount rate, which is determined by both the pure rate of time preference and the negative of the elasticity of the marginal utility of consumption. Using a low pure rate of time preference does not necessarily imply a low real discount rate, because a high real discount rate can also be produced by a high negative of the elasticity of the marginal utility of consumption, as Nordhaus used in the third example here. Note that DICE does not include equity weighting, and thus increasing the negative of the elasticity of the marginal utility of consumption does not increase weighting of impacts in poorer regions; as discussed above, equity weighting would increase calculated SCC, working in the opposite direction to the increase in discount rate.

As mentioned in the introduction, the treatment of uncertainty itself is an important model assumption. Note that in the SCC distributions presented for PAGE above, the right-hand tail is much larger, implying a greater potential for SCC higher than the mean than lower than the mean. Similarly, Dietz et al. (2007), using the Stern version of PAGE, compared mean results (calculated as the mean of model runs incorporating uncertainty in model parameters) with results calculated using the most likely values of all parameters, and found that mean PAGE results for damages are higher by 7.6 percent. A key reason for such results is the nonlinearities inherent in the climate system and projections of climate impacts that are embodied by the damage function. As discussed above, climate damages increase nonlinearly with temperature, and therefore the incorporation of uncertainty in the climate sensitivity, which opens up the possibility of reaching higher levels of temperature increase for any given emissions pathway, also increases the probability of reaching higher levels of climate damages. This has the effect of increasing calculated SCC, and larger values for SCC are therefore more likely. Incorporation of uncertainty in the parameters of the damage function also generally has a similar effect, opening the possibility of higher levels of climate damage for a given level of temperature increase.

The explicit incorporation of uncertainty generally increases the calculated benefits of climate policy. This is demonstrated by Anthoff et al. (2009), which presents results for FUND3.4 (without carbon cycle feedback) with and without uncertainty in climate response and damage function parameters (although only mean results are presented).[9] Without uncertainty, SCC in 2005 is calculated as \$8.96 per ton of carbon (\$2.44 per ton of CO_2), while with uncertainty SCC in 2005 is \$44.35 per ton of carbon (\$12.1 per ton of CO_2). Demonstrating the importance of equity weighting, the paper also presents results without equity weighting. Without uncertainty, SCC in 2005 is calculated to be -\$1.88 per ton of carbon (-\$0.5 per ton of CO_2), while with uncertainty SCC in 2005 is -\$0.35 per ton of carbon (-\$0.1 per ton of CO_2). In other words, without equity weighting, FUND calculates a slight positive benefit from an addition ton of carbon emitted in 2005, in this analysis. This is consistent with the FUND global damage function described above, which estimates benefits for the first 1-1.5°C of warming. Regional damages vary widely, however,

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[9] Note that these results aggregate over a range of combinations for the pure rate of time preference and the negative of the elasticity of the marginal utility of consumption. See Anthoff et al. (2009) for further details. Note further that this paper employs a utility function that incorporates risk aversion. Given this, these estimates include a risk premium over the simple mean of damage estimates.

with negative impacts at all levels of warming in some (including poorer) regions. Equity weighting, therefore, gives more emphasis to these negative impacts.

Tol (2009) presents a set of deterministic (i.e., not accounting for uncertainty) results employing FUND3.5, the version including carbon cycle feedbacks. Table 3 displays these results for different values of the pure rate of time preference (the negative of the elasticity of the marginal utility of consumption is not reported) and the climate sensitivity, and different strengths for the carbon cycle feedbacks, including no feedback. Even without carbon cycle feedback, negative values for SCC (i.e. net positive benefits of climate change) appear only if the pure rate of time preference is high and the climate sensitivity is low. Increasing the strength of the carbon cycle feedback increases the calculated SCC, with a larger effect at lower values of the pure rate of time preference, since the feedback becomes more important further in the future.

Table 3.

Pure rate of time preference	Climate Sensitivity	Climate feedback terrestrial biosphere			
%	°C	None	Low	Mid	High
3	2.5	1.93	2.03	2.30	2.87
1	2.5	16.44	17.32	19.49	22.52
0	2.5	56.86	60.73	68.28	74.55
3	1.5	-3.69	-3.71	-3.79	-4.02
3	4.5	20.34	21.14	23.15	25.47

Finally, there is a critical distinction between two different types of SCC comparisons. The sensitivity analyses discussed here and in the previous section (e.g., the confidence intervals for PAGE results presented above and the FUND results in Table 2) represent the variation of SCC calculations under one pathway for socioeconomic (e.g., economic and population) growth as parameter values are changed. The DICE results presented above reflect SCC calculations under different economic and emission scenarios (where a new optimal solution for emissions reductions and a new economic growth scenario is calculated under each assumption set). As discussed above, socioeconomic growth is prescribed externally in FUND and PAGE, but it is calculated internally in DICE. Therefore, different levels of emissions in DICE imply different levels of economic growth. Unlike DICE, PAGE and FUND can examine different levels of emissions under the same scenario for economic growth.

PAGE calculates very similar values for SCC across a wide range of possible future emissions, and Hope (2006b; 2009) suggests an explanation. Under each case, a ton of carbon has a different influence on temperature increase and on climate damages, differences that appear to roughly offset. As carbon dioxide concentrations increase, each additional ton of carbon emitted has a smaller influence on temperature increase, because of the physics of the climate system. At the same time, because of the nonlinearity of the damage function, smaller and smaller increases in temperature are equivalent to the same increase in damages. Therefore, under a lower emissions scenario, each ton of carbon has a larger influence on temperature, but a smaller influence on damages, compared to a higher emissions scenario. This is not the case, however, when socioeconomic assumptions (e.g., economic growth or discounting) are varied, as demonstrated by the differing PAGE results described above. Varying these assumptions changes the valuation of climate damages over time and/or across regions and thus significantly affects the magnitude of SCC.

Conclusions and Recommendations

This paper has examined a number of assumptions in IAMs that affect the benefits of climate policy, SCC estimates, and optimal emissions pathways calculated by such models, and discussed their consistency with current research. Several recommendations emerge:

1. *Uncertainty in key assumptions can significantly affect model results, and this sensitivity should be communicated when results are presented.* Critical uncertainties to which results are sensitive, in scientific understanding of the climate system, in the impacts of climate change, and in our ability to cope with those impacts, will not be eliminated in the near future, and may never be fully removed. Different choices about discounting and equity weighting reflect continuing ethical and economic debates. Transparent presentation of model assumptions and the contribution of different sources of uncertainty to model results is an important feature that should

be included in IAMs, and provides an improved basis from which to interpret specific findings.

2. *Systematic model comparisons are an effective tool for examining spread of model results and the consistency of model behavior with more complex representations of climate and socioeconomic systems.* Comparisons such as those described in the Climate Response section above can reveal important differences between IAMs, and provide an evaluation of the consistency of their behavior with projections of more complex models. Moreover, they can be used to evaluate whether existing uncertainty is sufficiently captured.
3. *Expanding and updating economic assessments of climate impacts can improve damage estimates incorporated into IAMs, but it is very difficult to fully represent the impacts of climate change solely in monetary terms.* No IAM currently accounts for all identified climate impacts and all therefore are likely to underestimate the magnitude of damages from climate change. Explicit incorporation of (i) a broader set of climate impacts (e.g., non-market impacts), (ii) new advances in scientific understanding of climate impacts (e.g., impacts from extreme weather events and ocean acidification), and (iii) existing uncertainty in the severity of climate impacts (e.g., a probabilistic representation rather than a deterministic

representation), will generally increase climate damages in IAMs. An alternative approach is the explicit consideration of multiple metrics by which to measure climate risks.

4. *Given the need for concurrent adaptation and mitigation policy, incorporation of adaptation is an area where IAMs can improve considerably.* Adaptation and mitigation decisions will affect each other, and can have both positive and negative synergies. Significant uncertainties exist regarding the limits to and efficacy of adaptation, as well as its costs, and current treatment of adaptation may overestimate the capacity of adaptation to offset damages and underestimate adaptation costs. New information is emerging as adaptation strategies begin to be implemented around the world in response to climate change that is already occurring, which can provide a basis for improving treatment. Adaptation has often been treated in IAMs as an implicit or explicit influence on the damage function, although it also has been considered as a decision variable. Regardless of the mechanism, inclusion of adaptation in IAMs is important, and its influence on damages and other model aspects should be clearly presented.

References

Ackerman, F. et al. 2008a. "The Cost of Climate Change: What We'll Pay if Global Warming Continues Unchecked." NRDC Report.

Ackerman, F., E.A. Stanton, C. Hope, and S. Alberth. 2008b. "Climate Change and the U.S. Economy: The Costs of Inaction." NRDC Report.

Ackerman, F., S.J. DeCanio, R.B. Howarth, and K. Sheeran. 2009a. "Limitations of integrated assessment models of climate change." *Climatic Change* (in press).

Ackerman, F., E.A. Stanton, C. Hope, and S. Alberth. 2009b. "Did the Stern Review Underestimate U.S. and Global Climate Damages?" *Energy Policy* (in press).

Adger, W.N. et al. 2009. "Are There Social Limits to Adaptation to Climate Change?" *Climatic Change* **93**: 335-354.

Adger, W.N. and J. Barnett. 2009. "Four Reasons for Concern About Adaptation to Climate Change." *Environment and Planning A* (in press).

Anthoff, D. and R.S.J. Tol. 2008. "FUND Technical Description." Available at http://www.fnu.zmaw.de/fileadmin/fnu-files/staff/tol/FundTechnicalDescription.pdf.

Anthoff, D., R.S.J. Tol, and G.W. Yohe. 2009. "Discounting for Climate Change." *Economics: The Open-Access, Open-Assessment E-Journal* **3**:2009-24.

Brander, L.M., K. Rehdanz, R.S.J. Tol, and P.J.H. van Beukering. 2009. "The Economic Impact of Ocean Acidification on Coral Reefs." ESRI Working Paper 282.

Climate Risk Management Limited. 2005. *The Financial Risks of Climate Change.* Nottinghamshire, United Kingdom, Climate Risk Management Limited.

Core Writing Team, R.K. Pachauri, and A. Reisinger, eds. 2007. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, United Kingdom and New York.

Daily, G.C., et al. 2000. "The Value of Nature and the Nature of Value." *Science* **289**: 395-396.

Daily, G.C. and P.A. Matson. 2008. "Ecosystem Services: From Theory to Implementation." *Proceedings of the National Academy of Sciences* **105**: 9455-9456.

de Bruin, K.C., R.B. Dellink, and R.S.J. Tol. 2009. "AD-DICE: An Implementation of Adaptation in the DICE Model ." *Climatic Change* **95**: 63-81.

De La Chesnaye, F.C. and J.P. Weyant, 2006. "EMF 21 Multi-Greenhouse Gas Mitigation and Climate Policy." *Energy Policy* Special Issue.

Dietz S., D. Anderson, N. Stern, C. Taylor, D. Zenghelis. 2007. “Right for the Right Reasons: A Final Rejoinder on the Stern Review.” *World Economics* **8**: 229–258.

Fankhauser, S. 1998. “The Costs of Adapting to Climate Change.” GEF Working Paper Series 16, Global Environmental Facility, ISBN 1-884122-14-0.

Friedlingstein, P. et al. 2006. “Climate–Carbon Cycle Feedback Analysis: Results from the C4MIP Model Intercomparison.” *Journal of Climate* **19**: 3337-3353

Hall, D.C. and R.J. Behl. 2006. “Integrating Economic Analysis and the Science of Climate Instability.” *Ecological Economics* **57**: 442-465.

Hayhoe, K. et al. 2004. “Emissions pathways, climate change, and impacts on California.” *Proceedings of the National Academy of Sciences* **101**: 12422-12427.

Hof, A., M.G.J den Elzen, D.P. van Vuuren. 2008. “Analyzing the Costs and Benefits of Climate Policy: Value Judgments and Scientific Uncertainties.” *Global Environmental Change* **18**: 412-424.

Hope, C. 2006a. “The Marginal Impact of CO_2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern.” *Integrated Assessment* **6**: 19-56.

Hope, C., 2006b. “The social cost of carbon: what does it actually depend on?” *Climate Policy* **6**: 566-572.

Hope, C. 2008. “Optimal Carbon Emissions and the Social Cost of Carbon over Time Under Uncertainty.” *The Integrated Assessment Journal* **8**: 107-122.

Hope, C. 2009. "How Deep Should the Deep Cuts Be? Optimal CO_2 Emissions Over Time Under Uncertainty", *Climate Policy* **9**: 3-8.

Karl, T.R., J.M. Melillo, and T.C. Peterson, eds. 2009. *Global Climate Change Impacts in the United States.* Cambridge University Press, United Kingdom and New York.

Lenton, T.M. et al. 2008. “Tipping Elements in the Earth's Climate System.” *Proceedings of the National Academy of Sciences* **105**: 1786-1793.

Link, P.M. and R.S.J. Tol. 2006. “The Economic Impact of a Shutdown of the Thermohaline Circulation: An Application of FUND.” FNU-103.

Mäler, K.-G., S. Aniyar, A. Jansson. 2008. “Accounting for Ecosystem Services as a Way to Understand the Requirements for Sustainable Development.” *Proceedings of the National Academy of Sciences* **105**: 9501-9506.

Mastrandrea, M.D. and S.H. Schneider. 2004. “Probabilistic Integrated Assessment of ‘Dangerous’ Climate Change.” *Science* **304**: 571-575.

Meehl, G.A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J.F. B. Mitchell, R.J. Stouffer, and K.E. Taylor. 2007a. "The WCRP CMIP3 Multimodel Dataset: A New Era in Climate Change Research." *Bulletin of the American Meteorological Society* **88**, 1383-1394.

Meehl, G.A. et al. 2007. "Global Climate Projections." In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon S., et al., eds. Cambridge University Press, United Kingdom and New York, 747–785.

Mendelsohn, R., W. Morrison, M. Schlesinger, and N. Andronova. 2000. "Country-Specific Market Impacts of Climate Change." *Climatic Change* **45**: 553–569.

Mendelsohn, R. 2000. "Efficient Adaptation to Climate Change." *Climatic Change* **45**: 583-600.

Mote, T. L. 2007. "Greenland Surface Melt Trends 1973–2007: Evidence of a Large Increase in 2007." *Geophysical Research Letters* **34**: L22507, doi:10.1029/2007GL031976.

Narita, D., R. S. J. Tol, and D. Anthoff. 2009a. "Damage Costs of Climate Change Through Intensification of Tropical Cyclone Activities: An Application of FUND." Climate Research **39**(2): 87-97.

Narita, D. R.S.J. Tol, and D. Anthoff. 2009b. "Economic Costs of Extratropical Storms Under Climate Change: An Application of FUND." ESRI Working Paper 274.

Newbold S. and A. Daigneaut. 2009. "Climate Response Uncertainty and the Benefits of Greenhouse Gas Emissions Reductions." NCEE Working Paper. http://yosemite.epa.gov/EE/epa/eed.nsf/WPNumberNew/2008-06?OpenDocument.

Nicholls, R.J., S. Hanson, C. Herweijer, N. Patmore, S. Hallegatte, J. Corfee-Morlot, J. Chateau, and R. Muir-Wood. 2008. "Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes," OECD Working Paper No. 1, available at http://www.oecd.org/document/56/0,3343,en_2649_201185_39718712_1_1_1_1,00.html.

Nordhaus, W.D. and J. Boyer. 2000. *Warming the World. Economic Models of Global Warming*. (MIT Press, Cambridge, MA).

Nordhaus, W.D. 2006. "Geography and Macroeconomics: New Data and New Findings." *Proceedings of the National Academy of Sciences* **103**: 3510-3517.

Nordhaus, W.D. 2007. "Critical Assumptions in the Stern Review on Climate Change." *Science* **317**: 201-202.

Nordhaus, W.D. 2008. *A Question of Balance: Economic Modeling of Global Warming*. Yale University Press, New Haven, CT, 234pp.

Department of Energy. 2009. Energy Conservation Program: Energy Conservation Standards for Refrigerated Bottled or Canned Beverage Vending Machines, Final Rule, 74 Fed. Reg. 44913, 44947 (Aug. 31, 2009). http://www1.eere.energy.gov/buildings/appliance_standards/commercial/pdfs/bvm_final_rule_notice.pdf.

Orr, J.C. et al. 2005. "Anthropogenic Ocean Acidification Over the Twenty-First Century and its Impact on Calcifying Organisms." *Nature* **437**: 681–686.

Parry, M.L., T.R. Carter, and N.T. Konijn, eds. 1998a. *The impact of Climate Variations on Agriculture* Kluwer Academic Publishers, Germany.

Parry, M.L., N.W. Arnell, M. Hulme, R.J. Nicholls, and M. Livermore. 1998b. "Adapting to the Inevitable." *Nature* **395**: 741.

Parry, M.L., J. Lowe, and C. Hanson. 2009a. "Overshoot, Adapt, and Recover." *Nature* **458**: 1102-1103.

Parry, M.L., N. Arnell, P. Berry, D. Dodman, S. Fankhauser, C. Hope, S. Kovats, R. Nicholls, D. Satterthwaite, R. Tiffin, and T. Wheeler. 2009b. "Assessing the Costs of Adaptation to Climate Change." International Institute for Environment and Development and Grantham Institute for Climate Change, London.

Pfeffer, W.T., J.T. Harper, and S. O'Neel. 2008. "Kinematic Constraints on Glacier Contributions to 21st-Century Sea-Level Rise." *Science* **321**: 1340-1343

Rahmstorf, S., A. Cazenave, J.A. Church, J.E. Hansen, R.F. Keeling, D.E. Parker, R.C.J. Somerville. 2007. "Recent Climate Observations Compared to Projections." *Science* **316**: 709.

Ramsey, F. 1928. "A Mathematical Theory of Saving." *Economic Journal* **38**: 543-549.

Rosenzweig, C., F.N. Tubiello, R. Goldberg, E. Mills, and J. Bloomfield. 2002. "Increased Crop Damage in the U.S. from Excess Precipitation Under Climate Change." *Global Environmental Change* **12**: 197-202.

Smith, J.B. et al. 2009. "Dangerous Climate Change: An Update of the IPCC Reasons for Concern." in press, *Proceedings of the National Academy of Sciences* **106**: 4133-4137.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller, eds. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Stern, N. 2007. *The Economics of Climate Change: The Stern Review.* Cambridge Univ. Press, Cambridge.

Stone, G.W., J.M. Grymes III, J.R. Dingler and D.A. Pepper. 1997. Overview and significance of hurricanes on the Louisiana Coast, U.S.A. Journal of Coastal Research **13**:656-669.

Tol, R.S.J. 1997. “On the Optimal Control of Carbon Dioxide Emissions: An Application of FUND.” *Environmental Modeling and Assessment* **2**: 151-163.

Tol, R.S.J. 1999. “Spatial and Temporal Efficiency in Climate Policy: Applications of FUND.” *Environmental and Resource Economics* **14**: 33-49.

Tol, R.S.J. 2002a. “Welfare Specification and Optimal Control of Climate Change: An Application of FUND.” *Energy Economics* **24**: 367-376.

Tol, R.S.J. 2002b. “New Estimates of the Damage Costs of Climate Change, Part I: Benchmark Estimates.” *Environmental and Resource Economics* **21**: 47–73.

Tol, R.S.J. 2002b. “New Estimates of the Damage Costs of Climate Change, Part II: Dynamic Estimates.” *Environmental and Resource Economics* **21**: 135–160.

Tol, R.S.J. 2005. “Adaptation and Mitigation: Trade-offs in Substance and Methods.” *Environmental Science and Policy* **8**: 572-578.

Tol, R.S.J. 2007a. “The Social Cost of Carbon: Trends, Outliers, and Catastrophes.” *Economics Discussion Papers,* Working Paper FNU-144. http://www.economics-ejournal.org/economics/discussionpapers.

Tol, R.S.J. 2007b. “The Double Trade-Off between Adaptation and Mitigation for Sea Level Rise: An Application of FUND.” *Mitigation and Adaptation Strategies for Global Change* **12**: 741-753.

Tol, R.S.J. 2008. “Why worry about climate change? A research agenda.” *Environmental Values* **17**: 437–470.

Tol, R.S.J. 2009. “Climate Feedbacks on the Terrestrial Biosphere and the Economics of Climate Policy: An Application of FUND.” ESRI Working Paper 288.

Tol, R.S.J. and G.W. Yohe. 2006. “A Review of the Stern Review” *World Economics* 7: 233–250.

van Vuuren, D.P. et al. 2009. “How Well Do Integrated Assessment Models Simulate Climate Change?” *Climatic Change* (in press).

Warren, R., C. Hope, M.D. Mastrandrea, R.S.J. Tol, N. Adger, and I. Lorenzoni. 2007. “Spotlighting Impacts in Integrated Assessment.” Research report prepared for the Stern Review on the Economics of Climate Change.” Tyndall Working Paper 91, www.tyndall.ac.uk.

Warren, R. et al. 2008. “Development and Illustrative Outputs of the Community Integrated Assessment System (CIAS), a Multi-Institutional modular Integrated Assessment Approach for Modeling Climate Change.” *Environmental Modeling & Software* **23**: 592-610.

Warren, R., M.D. Mastrandrea, C. Hope, and A. Hof. 2009. “Variation in the Climatic Response to SRES Emissions Scenarios in Integrated Assessment Models.” *Climatic Change* (in press).

Weitzman, M.L. 2009. “On Modeling and Interpreting the Economics of Catastrophic Climate Change.” *The Review of Economics and Statistics* **91**: 1-19.

Yohe, G. and D. Tirpak (2008), “A Research Agenda to Improve Economic Estimates of the Benefits of Climate Change Policies”, *Integrated Assessment Journal,* 8: 1-17, 2008.