WORKSHOP PROCEEDINGS

Assessing the Benefits of Avoided Climate Change: Cost-Benefit Analysis and Beyond

Representation of Climate Impacts in Integrated Assessment Models

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Representation of Climate Impacts in Integrated Assessment Models

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Abstract

Integrated Assessment Models (IAMs) of climate change are broadly employed to examine alternative climate policy scenarios. Policy evaluation models quantify the consequences of specific scenarios in terms of a suite of environmental, economic, and social performance measures. Policy optimization models calculate the "best" scenario that optimizes a single performance measure, and are often used for formal cost-benefit analysis (CBA) of climate mitigation policies. IAMs, by necessity, incorporate simplified representations of climate impacts. This paper provides a brief overview of IAMs and an examination of the modeling of climate impacts in prominent IAMs employed for CBA. Over time, these representations are updated by model developers to reflect advancing research, but they generally lag behind current scientific understanding of climate impacts. Moreover, IAMs employed for CBA require translation of economic and non-economic impacts into monetary damages, a key source of uncertainty to which model results are sensitive. Explicit incorporation of non-market impacts, new categories of impacts identified in the scientific literature, and uncertainty in the severity of climate impacts generally will increase climate damages in IAMs and the stringency of recommended emissions reductions.

Introduction

Integrated Assessment Models (IAMs) of climate change combine natural and social scientific information to examine the key interactions between the climate system and society. Their primary purpose is to inform policy decisions on climate mitigation (greenhouse gas emissions reduction). IAMs couple simplified representations of relevant systems to model climate change, its impacts, and the costs of policy measures to reduce those impacts. Those models that attempt to translate climate impacts into monetary damages are often used for social cost of carbon calculations (monetary estimates of the benefit of cutting one ton of carbon emissions today) and cost-benefit analyses (CBAs) to determine "optimal" policy. The purpose of this short paper is to provide a brief overview of IAMs and an examination of the modeling of climate impacts in IAMs employed for CBA. A more detailed scholarly review of IAMs is provided by Goodess et al. (2003).

Categories of IAMs

Existing IAMs reflect a range of modeling approaches to provide policy-relevant information, and most can be summarized by two general categories: policy optimization and policy evaluation. IAMs of all types must make choices about how to account for critical uncertainties in climate and social systems and their interactions. Different assumptions about these parameters create significantly different modeled outcomes and associated policy implications.

Policy Optimization

Policy optimization models are designed to calculate the "best" trajectory for future emission reductions based on a specific performance measure, such as minimizing the sum of mitigation costs and monetized damages from climate impacts.[1] The complexity of optimization models is limited by the numerical algorithms required in optimization calculations. Climate and economic systems are generally represented by a small number of equations, with a limited number of geographic regions (~1-16). 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 (e.g., Mastrandrea and Schneider, 2004). See Ackerman et al. (this volume) for further discussion of such critical issues.

Policy optimization models are used in two main applications. In CBAs, the preferences of climate policymakers are represented by a mathematical "utility function" for social welfare, generally expressed in terms of economic wealth, which is then maximized. In

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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.

cost-effectiveness analyses, the optimization is subject to a constraint, such as avoiding a specific level of global temperature increase. Examples of policy optimization models include DICE/RICE (Nordhaus and Boyer, 2000; Nordhaus, 2008), FUND (Tol, 2002; Tol, 2005), PAGE (Hope, 2006; Hope, 2009), and MERGE (Manne et al., 1995).

Policy Evaluation

Policy evaluation models are designed to calculate the consequences of specific climate policy strategies in terms of a suite of environmental, economic, and social performance measures. These models are not subject to the constraints of optimization models, and therefore can incorporate greater complexity in their representations of natural and social processes and regional detail. Thus, they are generally applied to comparisons of the consequences (e.g., regional economic and environmental impacts) of alternative emissions scenarios. Examples of policy evaluation models include AIM (Kainuma et al., 2002), MESSAGE (Messner and Strubegger, 1995), IMAGE (Alcamo et al., 1998), and the new CIAS (Warren et al., 2008). Some policy optimization models (e.g., DICE/RICE, FUND, PAGE) are also applied to evaluation (e.g., CBAs) of specific scenarios, but their relative lack of complexity and geographic resolution limits the range of questions they can address.

Treatment of Uncertainty

As mentioned above, model results are highly sensitive to critical uncertainties in climate and social systems and their interactions, and different IAMs take different approaches to incorporating uncertainty (see the paper by Hope in this volume for more information on parameter uncertainty). *Deterministic analyses* employ “best-guess” (or expected) values for all model parameters (e.g., parameters determining the sensitivity of the climate to increasing greenhouse gas concentrations, the translation of climate impacts into monetary terms, and the costs of emission reductions). The effect of alternative parameter choices on model outputs and the importance of uncertainty in specific parameters can be determined through sensitivity analyses, which examine differences in model outputs across runs varying 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 and this volume; Warren 2008). *Adaptive or hedging analyses* combine aspects of the two to examine implications of future learning about key scientific and policy uncertainties, such as calculating near-term strategies given current uncertainties, but with specific assumptions about the resolution of those uncertainties in the future (O’Neill, 2008).

IAMs and Climate Impacts in CBA

This paper focuses on how simple IAMs in CBA estimate damages from climate change impacts. Deterministic policy optimization models have primarily been used in CBAs to date. The optimal solutions for these models generally suggest implementing low levels of climate policy controls, which gradually increase over time, but are much less stringent than current policy proposals. These solutions allow significant continued increases in atmospheric greenhouse gas concentrations and temperature. For example, the optimal solution of the most recent version of the DICE model, DICE-2007 (Nordhaus, 2008), allows increasing global carbon emissions throughout the 21st century, increasing from 7.4 GtC/year (Gigatons of carbon per year) in 2005 to 11.3 GtC/year in 2105. These emissions are 16 percent below baseline (no policy) emissions calculated by the model by 2025, 26 percent below baseline by 2050, and 43 percent below by 2105 (but again, all above current emissions levels). Atmospheric CO_2 concentrations reach 586 ppm (not including other greenhouse gases) by the end of the century, compared to 686 ppm in the baseline scenario.

An exception is the probabilistic model PAGE, which was also applied recently in an optimization analysis (Hope, 2008; for more information see the paper by Hope in this volume). Global carbon emissions initially increase from 7.7 GtC/year in 2000, peak in 2010 at 11 GtC, and decrease significantly thereafter, particularly in the second half of the century. Annual carbon emissions roughly return to 2000 levels (8 GtC) by 2050, and are 88 percent lower than 2000 levels (0.9 GtC) by the end of the century. These emissions are 15 percent below baseline emissions in 2020, 60 percent below in 2060, and 93 percent below at the end of the century. Atmospheric CO_2 concentrations are 495-597 ppm by the end of the century (including other greenhouse gases in CO_2 equivalent units), compared to 638-792 ppm in the baseline scenario.[2]

These two optimal solutions differ markedly in annual emissions, particularly in the second half of the century. Figure 1 displays annual carbon emissions for the two models' optimal solutions and baseline scenarios (which also differ). A broader discussion of the reasons for large variations in "optimal" outcomes for emissions reductions (e.g., discounting choices) can be found in Ackerman et al. (this volume).[3] One key determinant, however, is the differing representation of climate impacts in these IAMs. As described above, IAMs by necessity employ simplified and incomplete representations of climate change and resulting climate impacts. MacCracken (this volume) presents a detailed discussion of the general challenges of estimating the environmental and social impacts of climate change in monetary terms, a topic also addressed by Ackerman et al. and Yohe in this volume. Here, the focus is an overview of how climate impacts are represented in particular IAMs employed for CBA. The following section briefly examines the categories of impacts

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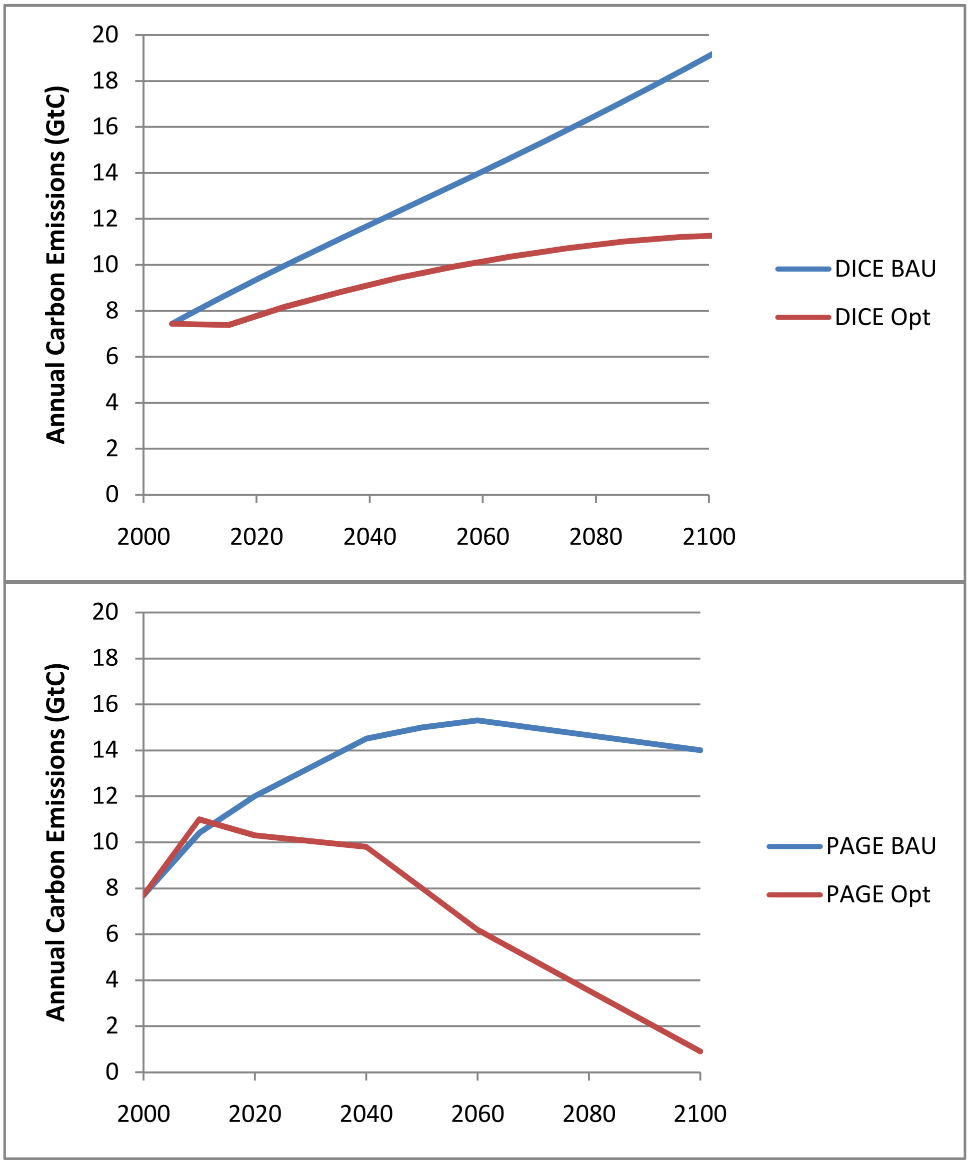
[2] These concentrations are ranges because of the probabilistic structure of PAGE.

[3] "Optimal" solutions are particularly sensitive to the choice of discount rate, as in general, large magnitudes of climate impacts accumulate farther in the future, while costs of emissions reductions to avoid those impacts are incurred earlier. "Optimal" solutions under lower rates of discounting are significantly more stringent (e.g., Nordhaus, 2008; Hope, 2009).

incorporated in three prominent optimizing IAMs: DICE, FUND, and PAGE. A more detailed discussion of impacts in versions of these models can be found in Warren et al. (2006).

Figure 1. Comparison of DICE and PAGE baseline scenarios and optimal solutions. The optimal solutions differ significantly, in part due to differences in the representation of climate impacts between the two models. See Ackerman et al. (this volume) for a broader discussion of the reasons for such differences.



Unpacking Impacts in IAMs

Climate change in IAMs is generally represented by an increase of global or regional average temperature as a proxy for the full range of changes to the climate system. Impacts are quantified through one or more *climate damage functions* for each model region. These damage functions provide monetary estimates of climate impacts associated with different levels of temperature increase, often expressed in terms of percentage loss of GDP. Functions are either specified for specific 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. However, different models assume different curvature and steepness of the rising damage function.

FUND includes sector and region-specific impact functions for agriculture, forestry, water resources, energy consumption, sea level rise, ecosystems, and health (split into functions for diarrhea, vector-borne diseases, and cardiovascular and respiratory illnesses affected by heat and cold). These functions are described in FUND's technical description (Anthoff and Tol, 2008).

DICE uses a single global aggregate damage function based on impact estimates for a similar list of sectors: 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 the shutdown of ocean currents, large-scale melting of ice sheets, or release of methane from permafrost. These damage functions are derived from a climate impact analysis most completely described by Nordhaus and Boyer (2000), Chapter 4.

PAGE2002 simulates region-specific aggregate economic and non-economic damages, as well as damages from abrupt climate changes (discontinuities). Total economic and non-economic damages are calibrated to be consistent with impact estimates summarized in the Intergovernmental Panel on Climate Change (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 (2006). Among optimizing IAMs, only PAGE explicitly incorporates uncertainty in impact estimates through probability distributions for the parameters of its climate damage functions (Hope, this volume), although 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 in FUND (Tol, 2005).

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 U.S. 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, see below) 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, and only for the agricultural and ecosystem sectors. Only PAGE incorporates a potentially significant contribution from non-market damages to overall damage estimates. 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 used 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 2 displays global damage estimates from recent versions of these three IAMs: DICE-2007, FUND2.9, and PAGE2002, respectively. Panels a and c represent damages in terms of percentage loss of global GDP (with losses as positive values) as a function of global temperature increase above preindustrial levels. In Panel c, from PAGE2002, the probabilistic structure of the model generates a range of relationships between temperature and damages, which are displayed separately for economic, non-economic, and discontinuity damages. Panel b, from FUND2.9, 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 b displays damage functions based on several growth scenarios consistent with storylines from four IPCC Special Report on Emissions Scenarios (SRES). For comparison, GDP growth rates in PAGE2002 are those of the SRES A2 scenario, and GDP growth is determined endogenously in the DICE-2007 model.[4]

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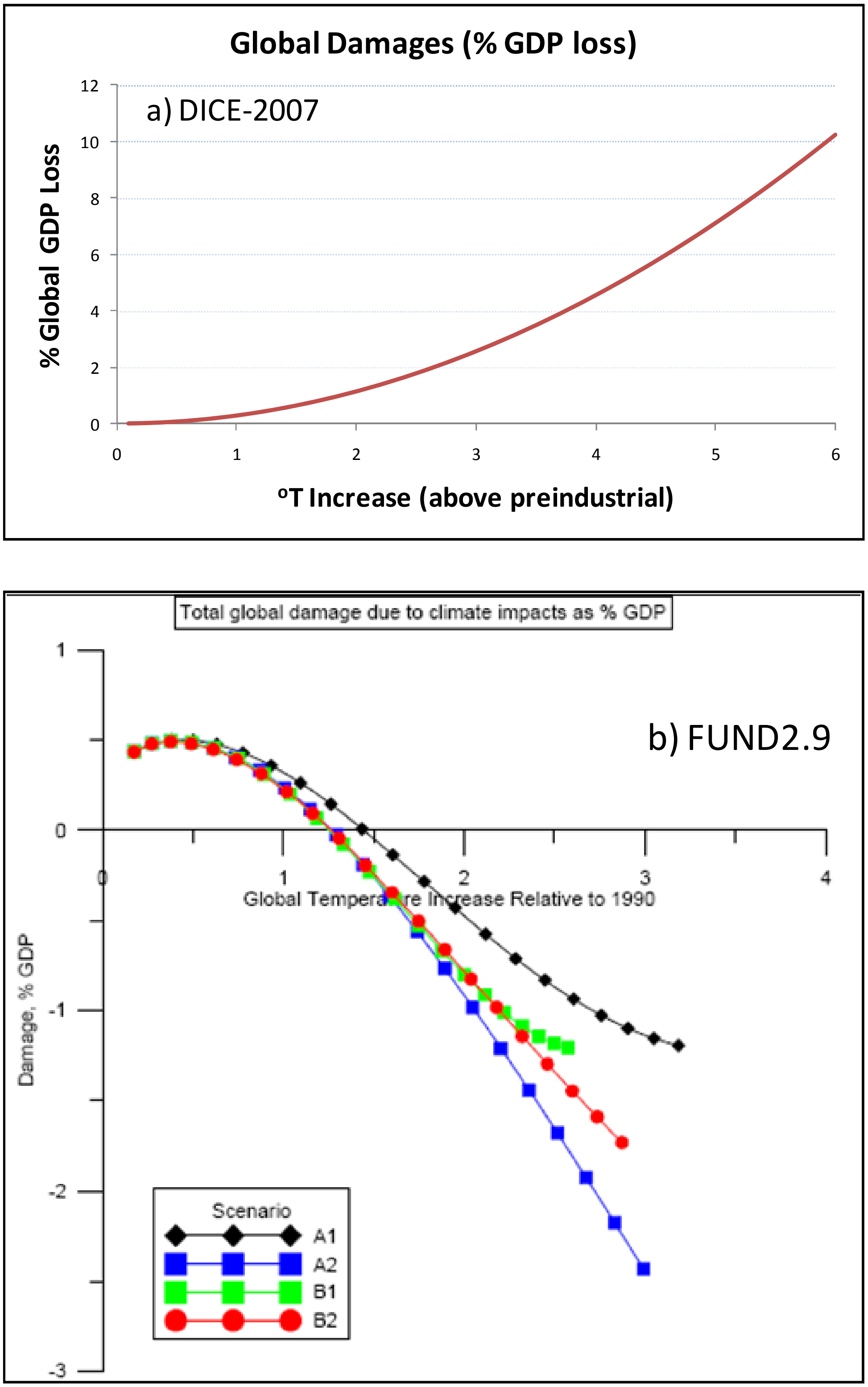
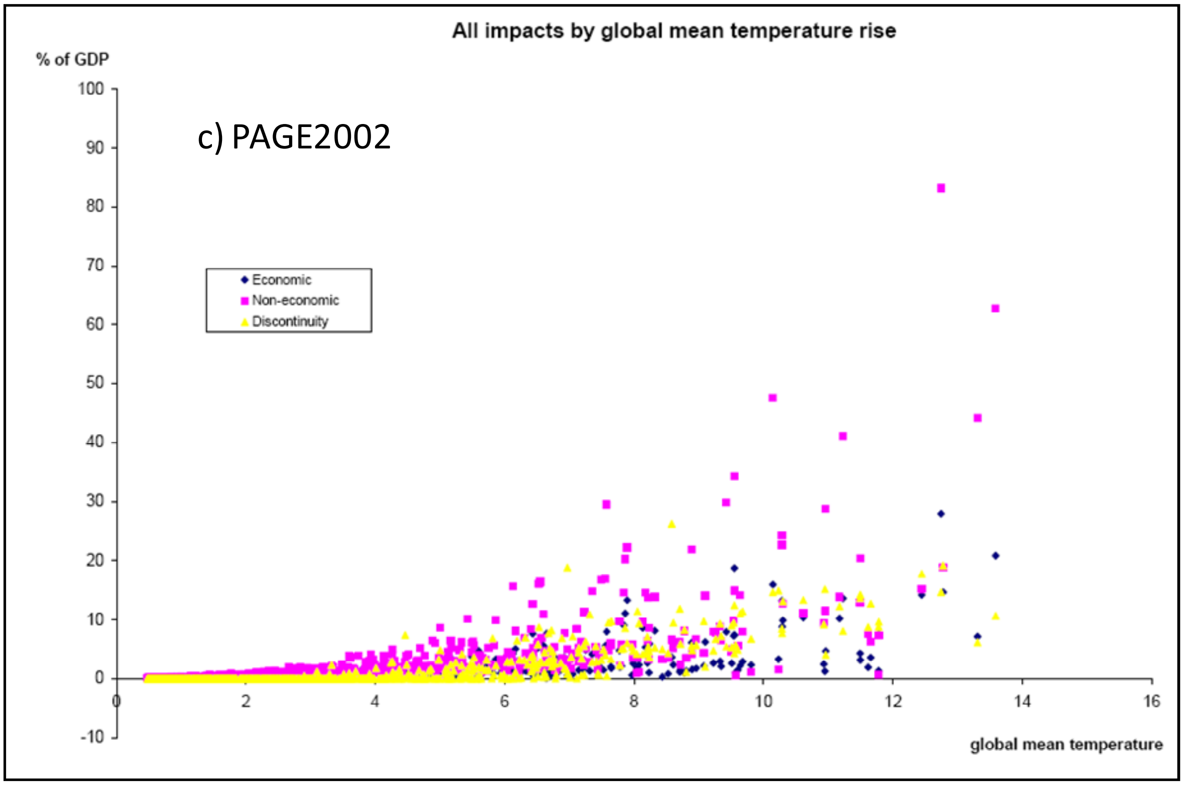
[4] Global GDP growth rates are also affected by the choice of aggregation across regions—generally using either market exchange rates (MERs) or purchasing power parity (PPP) calculations. Choice of aggregation method varies across models, though most recent models use PPP. Aggregation across regions also involves implicit or explicit equity weighting. See papers by Ackerman, et al. and Ebi in this volume for further discussion.

Figure 2. Global damage estimates in terms of percentage loss of global gross domestic product (percent GDP) as a function of global average temperature increase, for a) DICE-2007, b) FUND2.9, and c) PAGE2002.





Although the panels of Figure 2 do not represent a perfectly analogous comparison, it is clear that the relationship between temperature increase and climate damages varies 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 in 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. However, impacts from the energy sector then sharply decrease and become the largest contribution to negative impacts at higher levels of warming, due to increased air conditioning needs. In DICE, impacts are always negative, increasing nonlinearly as temperature increases, and estimates are higher than those found in FUND. In this application, 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 include 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). PAGE2002's probabilistic results indicate that damages from market and non-market sectors, as well as abrupt climate change are of similar magnitude, and in total are somewhat higher than DICE damages, with the possibility of much higher estimates (those estimates, particularly for non-market impacts, spreading above the main clustering in Figure 1c).

Consistency of IAM Damage Functions with Current Science

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. Since that time, scientific understanding of climate impacts has advanced, leading to, in general, the association of greater risks with smaller temperature increases (see, e.g., Smith et al., 2009).

For example, there is now higher confidence in projections of increases in the occurrence of extreme events (e.g., droughts, heat waves 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. There is now greater attention on the risk of sea level rise from melting of the Greenland and West Antarctic ice sheets, which may be more rapid than previously thought and 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 Team et al., 2007; Mote, 2007; Pfeffer et al., 2008, Rahmstorf 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). 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 broadly 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).

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 in 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., 2007), 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, 2007).

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.

IAM developers, of course, update their models over time in an attempt to reflect the latest science. Updates to the DICE-2007 model are described above. The most recent version of FUND updates model estimates of ecosystem impacts (Anthoff and Tol, 2008). The probabilistic structure of PAGE generates a range of relationships between temperature and damages, and this distribution can be adjusted as new information emerges. See, for example, the application of PAGE in the Stern Review (Stern, 2007), where greater inclusion of non-market impacts results in estimates of higher net damages (also see Hope, this volume).

Nevertheless, not all problematic elements can be addressed in this way. As mentioned above, MacCracken (this volume) presents a detailed discussion of the challenges involved in quantifying the environmental and social impacts of climate change in economic terms, topics discussed more abstractly by Ackerman et al. and Yohe (this volume).

The Bottom Line (Recommendations to Decision Makers)

IAMs are powerful tools that, as is the case for any model, must contend with an ever-changing body of underlying literature. Estimates of climate impacts incorporated into IAMs necessarily lag behind the scientific literature on climate impacts. This is one of many sources of uncertainty in IAMs that significantly affect model results, particularly when IAMs are employed in an optimization framework for CBA. This sensitivity is illustrated by the very different optimization results among IAMs described here. Different IAMs make different assumptions about many key scientific uncertainties and aspects of socioeconomic development. There is no one “correct” set of choices, just as there is no one “optimal” solution for a pathway of future emissions.

Thus, it is very important to understand these sources of uncertainty and the limitations of such modeling exercises when considering CBA results and IAM results in general as a source for policy guidance. The most important information to be gleaned from IAM efforts is not the specific numerical results of a particular modeling analysis, but broader insights into the general structure of the policy challenge posed by climate change that come from examining results across models and understanding the relative importance of differences in assumptions that drive the results. The papers in this volume by Hope, Anthoff, and

Newbold provide useful examples of the appropriate use of the PAGE(2002), FUND, and DICE models, respectively, to generate key insights.

In the context of the representation of climate impacts in IAMs, the following conclusions can be drawn:

- 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 as in PAGE, rather than a deterministic representation as in DICE), will generally increase climate damages in IAMs.
- No IAM currently accounts for all of these factors and all therefore are likely to underestimate the magnitude of damages from climate change. Thus, when employed for CBA, they are likely to underestimate optimal emissions reductions.

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