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Integrated Assessment Modeling of Global Climate Change: Much Has Been Learned—Still a Long and Bumpy Road Ahead

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Abstract

This paper presents a history of integrated assessment modeling of climate change, discussing many relevant modeling studies produced over the last few decades. It identifies the era following the release of the Intergovernmental Panel on Climate Change's Third Assessment Report as a new phase in integrated assessment modeling and describes pioneering studies undertaken since that time. The paper then pinpoints challenges and initiatives in integrated assessment modeling, both in terms of the models themselves and in terms of communicating model results to policy makers and the general public. It emphasizes that improved modeling will produce results more relevant to policy makers, but these results must be a collaborative effort between scientists and laypeople, and must be communicated effectively in order to have any impact on the decision-making process.

Keywords: Integrated Assessment, Climate Change, Modeling, Climate Policy, IPCC

1 Introduction

For more than a century, scientists have been considering the greenhouse phenomenon, and asking questions and performing experiments related to it. However, it is only in the last few decades, as climate change has been recognized

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as a more pressing issue, that attempts have been made to consider economic, political, institutional, and other issues in conjunction with climate science. Climate scientists, economists, and other experts are gradually moving away from approaches that are multidisciplinary, involving the use of ideas and methods from many disciplines that remain unintegrated, to approaches that are interdisciplinary, involving the use of an original combination of multidisciplinary ideas or methods integrated in such a way that they allow for explanations or assessments not possible with unintegrated ideas (Schneider, 1997). This practice has come to be known as integrated assessment (IA), and it is applicable not just to climate change, but to many problems of global change disturbance.

IAs typically involve end-to-end analyses of relationships and data from the physical, biological, and social sciences (e.g., see the reviews and references in IPCC, 1996*b*; Morgan & Dowlatabadi, 1996; Rotmans & van Asselt, 1996; Parson, 1996; Rothman & Robinson, 1997; Schneider, 1997). The Intergovernmental Panel on Climate Change (IPCC) takes this definition a step farther in its Third Assessment Report (TAR), calling IA "an interdisciplinary process of combining, interpreting, and communicating knowledge from diverse scientific disciplines in such a way that the whole set of cause-effect interactions of a problem can be evaluated" (IPCC, 2001*b*). The IPCC has identified four approaches to IA of climate change:

- Computer-aided modeling in which interrelationships and feedbacks are mathematically represented, sometimes with uncertainties incorporated explicitly
- Scenario analyses that work within representations of how the future might unfold
- Simulation gaming and participatory integrated assessment, including policy
- Qualitative assessments that are based on limited and heterogeneous data and built from existing experience and expertise (Source: IPCC, 2001*b*).

We will focus here on integrated assessment models (IAMs—what the IPCC calls "computer-aided modeling", above), which have become one of the key mathematical tools used in the integrated assessment of environmental science, technology, and policy problems. Each model is created to answer a specific question or series of questions. IAMs are made up of sub-models from a variety of disciplines, and they produce results that allow scientists (and hopefully policy makers as well) to study the interconnected physical, biological, and social elements of global change problems using common language and metrics. In the case of climate change, sub-models may cover all or part of the boxes shown in Figure 1, from IPCC (1996*b*).

The IPCC defines a full-scale IAM as one that includes sub-models for simulating:

- Activities that give rise to greenhouse gas (GHG) emissions

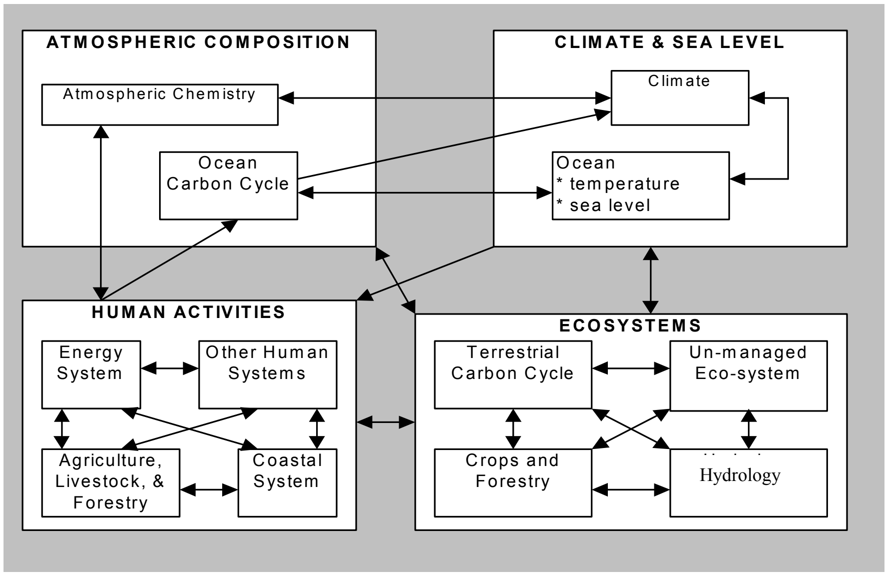


Figure 1: Representation of a generalized integrated assessment model (IAM) for climate change, displaying the interactions between subcomponents of the coupled social-natural system. An IAM may include all or some of these submodels. (From IPCC, 1996*b*).

- The carbon cycle and other processes that determine atmospheric GHG concentrations
- Climate system responses to changes in atmospheric GHG concentrations
- Environmental and economic system responses to changes in key climate-related variables. (Source: IPCC, 2001*b*)

For modelers, IAMs are beneficial in that they are able to incorporate scientific knowledge in very different areas and with very different degrees of certainty; manage the huge amounts of data required for varying temporal and spatial scales; maintain consistent definitions and identities, even over large areas and time periods and at varying levels of aggregation; and allow for computation and reproduction of “solutions” based on specific assumptions, which can be varied (Barker, 2003).

The outcomes produced by such IAMs, however, are not meant to simply be ingested by the modelers who created them. On the contrary, they should be used first and foremost in elucidating the decision-making process. Like any analytic method, IAMs should show policy makers how different policy choices could change the costs and likelihoods associated with various opinions and/or consequences. By assessing specific climate change policies, IAMs provide valuable information to policy analysts and decision makers, who are, as Schneider (1997) puts it, “In search for rational enlightenment in the bewilderingly complex global climate change policy debate." Specifically, IAMs should help policy makers evaluate the costs involved in meeting emissions targets and the best ways in which to implement emissions cuts over time. In the future, it is also hoped that they will better describe the socio-economic impacts of climate change, which are generally assumed to be more uncertain than the costs of mitigation. In more recent years, IAMs have been used increasingly frequently by members of the media as well, who have become more important as translators and disseminators of scientific conclusions. As an ancillary benefit, IAMs may also give scientists new information and insights into the intricacies of integrated systems and the interactions between natural and social systems, providing data and ideas on which additional modeling and research can be based.

2 Integrated assessment modeling—We've come a long way in the last few decades

2.1 Classifying IAMs

In its infancy, integrated assessment modeling seemed to serve its ancillary purpose (providing scientists with new information) better than its primary one (enlightening policy makers)(Grobecker et al., 1974), but in retrospect, it seems to have been a natural course of evolution. As scientists ran their IAMs and viewed the computer-generated data they produced, and as more information on climate science and other disciplines represented in sub-models improved, better IAMs were produced. There is still much to do—both in terms of modeling and outreach—to make sure that IAMs penetrate the policy community to the extent they should, but we've come a long way since the 1980s.

Climate change modeling entered a new phase in the 1960s and 1970s, when the first papers on General Circulation Models (GCMs) of the climate were published (e.g., SMIC, 1971). Climate policy became a growing concern in the 1980s, thanks in part to organizations like the World Meteorological Organization (WMO) and the World Commission on Environment and Development (WCED). At that time, climate change was often linked to the broader concerns of sustainable development and global change (see World Meterological Organization, 1988; Bruntland, 1987). Early IAMs were developed in this era, including the RAINS model, which proposed solutions for the acid rain problem in Europe (Alcamo et al., 1990; Hordijk, 1991). Then, in 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was ratified, with an aim of preventing "dangerous anthropogenic change to the climate system." The period since ratification has been marked by a dramatic increase in the quantity and quality IAMs.

Schneider (1997) provides a "generational" classification scheme for IAMs based on the components they include:

Integrated assessment modeling of global climate changes: Hierarchy of climatic impact and policy assessment components

1. Premethodological (essentially unintegrated) assessments
    - Climatic determinism (naive association of regional climatic and social factors)
    - Case studies in which climatic variations in a region are associated with environmental or societal "responses" (e.g., 1846 potato blight in Europe or 1970s Sahelian drought and its suspected impacts)
    - Direct cause and effect links without feedbacks (e.g., value of coastal damage made equal to inundated property market values with no adaptation)
2. Second generation (some integration) climate impact and policy assessments
    - $2 \times CO_2$ equilibrium snapshot (or simple time-varying CO_2) GCM scenarios
    - no aerosols or other heterogeneous radiative forcings
    - no realistic transient climate change scenarios
    - simple (or no) landscape changes
    - simple (or no) endogenous adaptation/technological change
    - time and space variations in climate and impact sectors assumed substitutable
    - no stochastic variability of weather, economy or technology variables
    - simple (or no) representation of non-market impacts
    - may be multi-sector, multi-biome, and multi-regional, but limited subsets of species, sectors or regions
    - conventional discounting applied equally to impacts and mitigation costs
    - simple (or no) representation of uncertainty via probability distributions
3. Third generation (partly integrated) climatic impact and policy assessment
    - Includes more realistic transient scenarios of heterogeneous radiative forcing driving coupled Earth systems models
    - stochastic variability explicitly included
    - adaptation/technological change endogenized
    - land use changes (including urbanization) endogenized
    - individual species and communities may be simply represented
    - alternative discounting assumptions explored

   - subjective opinions from decision analytic surveys endogenized and uncertainties explicitly treated via probability distributions

4. Fourth generation (more integrated) climatic impact and policy assessments
   - synergism among habitat fragmentation, exotic species invasions, chemical releases and climate change explicitly treated
   - biodiversity and ecosystem services (i.e., "non-market" nature) endogenously treated
   - plausible biogeophysical surprises explicitly considered
   - alternative demographic, political and macroeconomic processes endogenously considered (i.e., inclusion of changes in human behavior at various levels)
5. Fifth generation (largely integrated) climate impact and policy assessments
   - Changing value systems explicitly considered
   - Surprises to social systems and values explored

An example of a first generation, or premethodological (type I), assessment can be found in some of the studies mentioned above and in Schneider & Chen (1980). The authors' self-labeled "integrated climatic impact assessment" consisted of calculating the cost of a sea level rise scenario by summing discounted values of lost property in flooded areas, without considering depreciation, reinvestment, relocation, or other types of adaptation. It did not quantify potential losses in non-market damage categories (i.e., biodiversity loss, loss of heritage sites), and it was more of a "consciousness-raising" exercise than a true integrated assessment. Later papers introduced more advanced models that fell into the second and third generations of Schneider's classification scheme, as detailed in the rest of this paper.

In retrospect, if we were to rewrite the Schneider (1997) generational classification scheme now, we would put more weight on the following: stakeholder involvement, power relationships, multiple numeraires, robust strategies, tolerable windows, probabilistic assessment, and overshoots (e.g., Schneider & Mastrandrea, 2005).

2.2 DICE and RICE

One of the most well known IAMs, and one that continues to be used to this day, is the Dynamic Integrated model of Climate and the Economy (the DICE model), produced by William Nordhaus in 1990 (but see Nordhaus, 1994*b*, for a fuller description). Nordhaus, an economist by training, considered the climate change problem to be an economic problem which required shrinking (relative to a business-as-usual baseline) our use of goods and services over time in order to reduce climate change damages in the long term: "By taking costly steps to slow emissions of GHGs today, the economy reduces the amount of output that can be devoted to consumption and productive investment. The return for this 'climate investment' is lower damages and therefore higher consumption in the future" (Nordhaus & Boyer, 2000).

The DICE model is designed as a simple optimal growth model that, when given a set of explicit value judgments and assumptions, generates an optimal future forecast for a number of economic and environmental variables. It does this through maximizing discounted utility (satisfaction from consumption), by balancing the costs to the economy of GHG emissions abatement (a loss in a portion of GDP caused by higher carbon energy prices) against the costs of damages from the build-up of atmospheric GHG concentrations. This build-up affects the climate, which in turn causes "climate damage," a reduction in GDP determined by the rise in globally averaged surface temperature due to GHG emissions. In some sectors and regions, such climate damages could be negative—i.e., benefits—but DICE aggregates across all sectors and regions (see, for example, the discussions in Chapters 1 and 19 of IPCC, 2001*a*) and therefore assumes that this aggregate measure of damage is always a positive cost.

Critics of the DICE model claimed that the damage function Nordhaus used underestimated the impacts of climate change on non-market entities. This led Nordhaus to conduct a survey of conventional economists, environmental economists, atmospheric scientists, and ecologists to assess expert opinion on estimated climate damages (Nordhaus, 1994*a*). Interestingly, the survey reveals a striking cultural divide between natural and social scientists. The most conspicuous difference is that conventional economists believed that even extreme climate change (i.e., 6°C of warming by 2090) would not impose severe economic losses and hence considered it cheaper to emit more in the near term and worry about cutting back later, using the extra wealth generated from delayed abatement to adapt later on. Natural scientists estimated the economic impact of extreme climate change to be 20 to 30 times higher than conventional economists did and often advocated immediate actions to abate emissions. This brings up many questions regarding how damages should be assessed and whether damage estimates in IAMs are reasonable, even to an order of magnitude!

Despite the difference in magnitude of damage estimates between economists and ecologists, the shape of the damage estimate curve was similar. All respondents indicated accelerating costs with more climate changes. Most respondents—economists and natural scientists alike—offered subjective probability distributions that were "right skewed." That is, most of the respondents considered the probability of severe climate damage, or "nasty surprises," to be higher than the probability of moderate benefits, or "pleasant surprises" (Schneider, 2004).

Roughgarden & Schneider (1999) put the data from Nordhaus' (1994*a*) survey into subjective probability distributions, which they used to recalculate "optimal" carbon taxes in the DICE model. They demonstrate that adopting a "right-skewed" probability distribution in a simple integrated assessment model (DICE) produces optimal carbon taxes several times higher than "point estimates."

After introducing the DICE model, Nordhaus went on to create the RICE model, which was similar to the DICE model but was meant to be used at a regional, rather than a global, scale (Nordhaus & Yang, 1996). The original RICE and DICE models are similar to a multitude of other IAMs that, like RICE and DICE, are essentially benefit-cost analyses (i.e., that find the emissions pathway that minimizes mitigation costs plus climate change damages). These include Peck & Teisberg (1992, 1994, 1995); Chattopadhyay & Parikh (1993); Parikh & Gokarn (1993); Maddison (1995); Manne et al. (1995); Manne & Richels (1995); Yohe (1996); Edmonds et al. (1997); Tol (1997, 2002*a*,*b*).

In 1999, Nordhaus and Boyer came out with improved versions of both DICE and RICE, termed DICE-99 and RICE-99. The main improvements are:

1. Whereas the earlier DICE and RICE models used a parameterized emissions/cost relationship, the new models use a three factor production function in capital, labor, and carbon-energy, develop a new technique for representing the demand for carbon fuels and use existing energy-demand studies for calibration.

2. The new models change the treatment of energy supply to incorporate the exhaustion of fossil fuels and hence a depletable supply of carbon fuels, with the marginal cost of extraction rising steeply after 6 trillion tons of carbon emissions. With limited supplies, fossil fuel prices will eventually rise in the marketplace to choke off consumption of fossil fuels.

3. Model data were updated to reflect data for 1994-98. The output growth in the models is driven off of regional economic, energy, and population data and forecasts. The new models project significantly lower reference CO_2 emissions over the next century than the earlier DICE and RICE models because of slower projected growth and a higher rate of decarbonization of the world economy.

4. The RICE/DICE-99 carbon cycle model is now a 3-box model, with carbon flows among the atmosphere, upper biosphere/shallow oceans, and deep oceans. (In earlier versions, carbon simply disappeared at a constant rate from the atmosphere.) Forcings from non-CO_2 GHGs and aerosols have been updated to reflect more recent projections. The projected global temperature change in the reference case turns out to be significantly lower in the current version of RICE. This is due to the inclusion of negative forcings from sulfates in RICE-99, the lower forcings from the chlorofluorocarbons, and the slower growth in CO_2 concentrations.

5. The impacts of climate change have been revised significantly in the new models. The global impact is derived from regional impact estimates. These estimates are derived from an analysis that considers market, nonmarket, and potential catastrophic impacts. The resulting temperature damage function is more pessimistic than that of the original DICE model (Nordhaus & Boyer, 2000).

RICE-99 and DICE-99 examine economic and ecological implications of achieving a given emissions target, starting from a specific emissions baseline. Other studies that work in this manner include Alcamo (1994); Edmonds et al. (1997); Morita et al. (1997); Murty et al. (1997); Yohe et al. (1998); Jacoby & Wing (1999); Tol (1999); Yohe et al. (1999).

2.3 Strategic Cyclical Scaling

Root & Schneider (1995) suggested advancements in IAMs of climate change not by introducing a new model, but by calling for Strategic Cyclical Scaling (SCS) in integrated assessment. The authors focused on a well-known major problem confronting modeling and other IA attempts: mismatch in scales. For example, how can a conservation biologist interested in the impacts of climate change on a mountaintop-restricted species downscale climate change projections from a climate model whose smallest resolved element is a grid square (the smallest unit in most models) that is 200 kilometers on a side? How can a climate modeler scale up knowledge of evapotranspiration through the sub-millimeter-sized stomata of forest leaves into the hydrological cycle of the climate model, which is resolved at hundreds of kilometers? The former problem is known as downscaling (Easterling et al., 2001), the latter, upscaling (Harvey, 2000). Root & Schneider conclude that top-down associations among variables believed to be cause and effect and bottom-up mechanistic models run to predict associations (but for which there is no large-scale data time series to confirm), are not by themselves sufficient to provide high confidence in the cause-and-effect relationships embedded in integrated assessments. Rather, a cycling between top-down associations and bottom-up models is needed. SCS should help to provide better explanatory capabilities for multi-scale, multi-component interlinked environmental models; more reliable impact assessments and problem-solving capabilities, as has been requested by the policy community; and more well-rounded modeling, as neither bottom-up nor top-down approaches are sufficient by themselves. Root & Schneider (2003) expanded on the SCS paradigm by exploring how one might search for convergence in the scaling cycles.

2.4 IPCC Second Assessment Report (SAR)

The IPCC's Second Assessment Report (IPCC, 1996*b*) championed IAMs as the principal tool of integrated assessment of climate change because their energy and emissions model components enabled simulations of different emission paths resulting from a range of possible energy policies. The SAR compared 23 IAMs designed to address mitigation.

In addition, the SAR spurred further development of IAMs due to its statement that human activities were indeed linked to climate change, and its projection that average global surface temperatures would rise by 1 to 3.5°C by 2100 (IPCC, 1996*a*).

2.5 “Inverse” methods

Following the SAR, various “inverse methods” of integrated assessment modeling were developed. Wigley et al. (1996) were one of the first, following on the work of Richels & Edmonds (1995). In their IAM, they begin with atmospheric CO_2 concentrations and consider a range of stabilization targets (IPCC, 2001*b*). They use inverse methods on each target to find the implications for global CO_2 emissions. Because a long-term concentration target can be reached through many pathways and impacts may be path-dependent, they show the implications of the emissions pathway chosen on temperature change and sea level rise.

Both the “tolerable windows” approach (Toth et al., 1997; Petschel-Held et al., 1999; Yohe & Toth, 2000) and “safe corridors” approach (Alcamo et al., 1998) are considered inverse methods as well. These approaches focus on the level of emissions that would allow the costs of emissions reductions and the impacts of climate change to stay within limits deemed “acceptable,” as defined by policy makers. In a more recent paper, Toth et al. (2003) introduce their ICLIPS (Integrated Assessment of Climate Protection Strategies) IAM and provide an excellent description of how the “tolerable windows” approach functions: The ICLIPS IAM finds its starting point in impact analysis (to define acceptable climate change impacts) and in cost estimates (to determine acceptable mitigation costs). The inverse approach is thus formulated as a kind of extended and generalized cost-benefit analysis for which two types of normative inputs are required. The first type of input is based on the use of climate impact response functions (CIRFs) that depict reactions of climate-sensitive socioeconomic and natural systems to climate change forcing. As users of the ICLIPS model, social actors can specify their willingness to accept a certain amount of climate change impacts in important sectors in their own jurisdiction. Second, the same social actors can reveal their perceptions about their society’s willingness to pay for climate change mitigation in terms of acceptable burden sharing principles and implementation schemes internationally, as well as in terms of the acceptable social costs for their nations. The ICLIPS IAM can then determine whether there exists a corridor of emission paths over time that keeps the climate system within the permitted domain without exceeding the specified social costs.

In addition to finding an impacts corridor, ICLIPS can explore situations in which impact and mitigation cost constraints cause emissions corridors to disappear altogether. However, Toth et al. (2003) remind readers that ICLIPS cannot replace human sentiment about acceptable risks and costs and the feasibility of transfers of resources to facilitate adaptation.

2.6 Induced Technological Change (ITC)

Goulder & Schneider (1999) explored incorporating the concept that climate policies can spur additional, or “induced,” technological change, into IAMs. Building on the work of Grubb et al. (1994), they engaged in the first attempt to model the implications of ITC for climate change policy. Their model found that a noticeable carbon tax would likely dramatically redistribute energy research and development (R&D) investments from conventional to non-conventional sectors, thereby producing ITCs that lower long-term abatement costs.

Sanstad concurred with Goulder and Schneider's ITC work, finding that policies promoting climate-related R&D may simultaneously encourage R&D in other sectors (see Sanstad, 2000). Sanstad attributes this phenomenon to the fact that the economy's initial equilibrium may allocate too few resources to R&D, so that when a policy arises that calls for a specific sort of innovation, overall economic efficiency may be improved (not just efficiency in a specific sector). In addition, Sanstad emphasized that ITC is not exogenous but endogenous, and hence is strongly influenced by market incentives. There is clear potential for positive policy initiatives in this area.

Since Sanstad's 2000 report, some IAMs have begun treating ITC as an endogenous factor. Goulder (2004) studied such IAMs and found that ITC can significantly lower the cost of achieving GHG reductions; it is especially cost-effective when policies are announced in advance so that actors have time to prepare for them. Schneider & Goulder (1997) found that reducing GHG emissions in the most cost-effective manner requires both technology-push and emissions reduction policies. While different studies show different effects of ITC on the overall timing of climate policy, most of them conclude that abatement policies (or at minimum, policies to make abatement cheaper in the future) should be put into force now to accelerate the critical process of technological change.

2.7 The discount rate and equity concerns

Discounting is a method used in economic models or IAMs to aggregate costs and benefits over a long time horizon by summing net costs (or benefits), which have been subjected to a discount rate typically greater than zero, across future time periods. If the discount rate equals zero, then each time period is valued equally (case of infinite patience). If the discount rate is infinite, then only the current period is valued (case of extreme myopia). The discount rate chosen in IAMs is critical, since abatement costs will typically be incurred in the relatively near term, but the brunt of climate damages will be realized primarily in the long term. Thus, if the future is sufficiently discounted, present abatement costs, by construction, will outweigh discounted future climate damages, as discounting will eventually reduce future damage costs to negligible present values.

Consider a climate impact that would cost 1 billion dollars 200 years from now. A discount rate of 5% per year would make the present value of that future cost equal to $58,000. At a discount rate of 10% per year, the present value would only be $5. Using a higher discount rate will result in more damaging climatic effects than a lower rate. As Perrings (2003) notes, "The effect of discounting is both to increase the potential for unexpected future costs, and to eliminate those costs from consideration." Discounting using large discount rates helps to explain why some authors (Nordhaus, 1994*b*; Nordhaus & Yang, 1996; Manne & Richels, 1997; Nordhaus & Boyer, 2000) conclude that massive

CO_2 emission increases are socially beneficial—i.e., more economically efficient than significant cuts—whereas others (Cline, 1992; Azar & Sterner, 1996; Hasselmann et al., 1997; Schultz & Kasting, 1997; Mastrandrea & Schneider, 2001, 2004; Lind, 1982) using low or zero discount rates justify substantial emission reductions, even when using similar damage functions (Portney & Weyant, 1999).

It is often claimed that the appropriate discount rate should be a matter of empirical determination, but in reality, choosing a discount rate involves a serious normative debate about how to value the welfare of future generations relative to current ones. Moreover, it requires that this generation estimate what kinds of goods and services future generations will value—e.g., how they will want to make trade-offs between material wealth and environmental services.

In a recent study, Howarth (2000) considers how future generations are treated in IAMs. Most models use a single, simple discount rate when making projections for the next 50 to 300 years. But, over long periods of time, the modeling will span multiple generations, and a single discount rate may not be appropriate. To deal with this, Howarth advocates for the overlapping generations model (OLG), in which a series of differentiated generations replaces the typical convention of the infinitely-lived decision maker, so that more realistic assessments of spending and savings tendencies of generations can be distinguished. (The OLG concept was introduced by Paul Samuelson in the 1950s.) Howarth uses his IAM to compare how three different policy regimes will affect present and future generations and finds in all three cases that climate stabilization policies act as an insurance policy that protects future generations against potential climatic catastrophes and the exorbitant costs they would likely bring. In addition, Howarth concludes that emissions control is consistent with maintaining long-term economic well-being, even if climate damages turn out to be only moderate.

Other approaches to discounting include Weitzman's gamma discounting (see Weitzman, 2001) and Heal's time-varying hyperbolic discounting (see Heal, 1997).

2.8 Special Report on Emissions Scenarios (SRES), IPCC Third Assessment Report (TAR)

Both the SRES and the TAR provided new information and challenges for integrated assessment modeling teams. The SRES provided "storylines" of future human demographic, economic, political, and technological futures from which a range of emissions scenarios were described. These storylines and scenario families provided valuable input for IAMs. The TAR gave an overview of integrated assessment analyses to-date, and concluded, based in part on a review by Parson & Fisher-Vanden (1997), that "IAMs have contributed to the establishment of important new insights to the policy debate, in particular regarding the evaluation of policies and responses, structuring knowledge, and prioritizing uncertainties. They have also contributed to the basic knowledge about the climate system as a whole" (IPCC, 2001*b*). The TAR also presented two major challenges for IAMs: "managing their relationship to research and disciplinary knowledge, and managing their relationship to other assessment processes and to policymaking" (IPCC, 2001*b*). In addition, the TAR provided modelers with new information on temperature changes to 2100 (a range of 1.4 to 5.8°C), new warnings about the possibility of "abrupt" and "dangerous" climate change, and new calls to address uncertainty explicitly (e.g., Moss & Schneider, 2000).

3 The new wave of integrated assessment modeling

3.1 Incorporating "dangerous" climate change

The IPCC TAR led to a sea change in integrated assessment modeling. One example of work inspired by the IPCC's suggested risk-management framework for climate policy was Mastrandrea and Schneider's "Integrated assessment of abrupt climate changes" (Mastrandrea & Schneider, 2001). They recognized that climate change assessments rarely consider low-probability, high-consequence extreme events. Instead, they typically consider scenarios thought to "bracket the uncertainty." Another problem arises because of the fact that each sub-model within an IAM is complex in and of itself, but when coupled with other sub-models, the interactions can create even more complex behaviors known as "emergent properties" that are not necessarily evident when studying only one or two of the subsystems in isolation. Therefore, omitting extreme events in an IAM produces results that likely overestimate the capacity of humans to adapt to climate change and underestimate the optimal control rate for GHG emissions.

In an attempt to incorporate extreme events in their modeling, Mastrandrea & Schneider (2001), building on the ICLIPS model work done by Toth et al. (1997), developed a modified version of Nordhaus' DICE model called E-DICE, which contains an enhanced damage function that reflects the likely higher damages that would result when abrupt climate changes occur. E-DICE uses the Simple Climate Demonstrator (SCD), developed by Schneider & Thompson (2000), as a sub-model. The SCD is used to simulate catastrophe behaviour of the Thermohaline Current (THC). It incorporates a straightforward density-driven set of Atlantic Ocean boxes that mimic the results of complex models, but the model is still sufficiently computationally efficient and is able to facilitate sensitivity analysis of key parameters and generate a domain of scenarios that show abrupt collapse of THC.

Due to the abrupt non-linear behaviour of the SCD model, the EDICE model produces a result that is qualitatively different from DICE, which lacks internal abrupt non-linear dynamics. An "optimal" solution of conventional DICE can produce an emissions profile that triggers a collapse of THC, whereas this abrupt non-linear event can be prevented when the damage function in DICE is modified (as in EDICE) to account for enhanced damages created by this THC collapse and THC behaviour is incorporated into the coupled climate-economy model.

The coupled system contains feedback mechanisms that allow the profile of carbon taxes to increase sufficiently in response to the enhanced damages so as to lower emissions enough to prevent the THC collapse in an optimization run of EDICE. The enhanced carbon tax actually “works” to lower emissions and thus avoid future damages from an abrupt event.

Previous IAM work by Keller et al. (2000) obtained similar results with different models. They found that significantly reducing carbon dioxide emissions to prevent or delay potential damages from an uncertain and irreversible future climate change, such as a THC collapse, may be cost-effective. But the amount of near-term mitigation the DICE and EDICE models “recommend” to reduce future damages is critically dependent on the discount rate. For low discount rates, the present value of future damages creates a carbon tax large enough to keep emissions below the trigger level for the abrupt non-linear collapse of the THC a century later. A higher discount rate sufficiently reduces the present value of even catastrophic long-term damages so that abrupt non-linear THC collapse becomes an emergent property (e.g., Mastrandrea & Schneider, 2001) of the coupled socio-natural system. The discount rate is therefore the parameter that most influences the 22nd century behaviour of the modeled climate.

A further attempt at modeling dangerous climate change and providing meaningful policy implications has been performed by Mastrandrea & Schneider (2004). They begin with the concept of “dangerous anthropogenic interference” (DAI), taken from Article 2 of the UNFCCC. In defining their metric for DAI, Mastrandrea and Schneider estimate a cumulative density function (CDF) based on the IPCC’s “burning embers” diagram by marking each transition-to-red threshold and assuming that the probability of “dangerous” change increases cumulatively at each threshold temperature by a quintile, as shown by the thick black line in Figure 2. This can be used as a starting point for analyzing “dangerous” climate change.

From this figure, Mastrandrea and Schneider identify 2.85°C as their median threshold for “dangerous” climate change, which may still be conservative. They apply this median 2.85°C threshold to three key parameters—climate sensitivity, climate damages, and the discount rate—all of which carry high degrees of uncertainty and are crucial factors in determining the policy implications of global climate change. To perform these calculations, they use Nordhaus’ (1994*b*) DICE model because it is well-known and is a relatively simple and transparent integrated assessment model (IAM), despite its well-known limitations. Using an IAM allows for exploration of the impacts of a wide range of mitigation levels on the potential for exceeding a policy-relevant threshold such as DAI. Mastrandrea and Schneider focus on two types of model output: i) global average surface temperature change in 2100, which is used to evaluate the potential for DAI; and ii) “optimal” carbon taxes.

They begin with climate sensitivity, typically defined as the amount that global average temperature is expected to rise for a doubling of CO_2 from pre-industrial levels. The IPCC estimated up through the TAR that climate sensitivity ranges between 1.5°C and 4.5°C, but it has not assigned subjective probabilities to the values within or outside of this range, making risk analysis

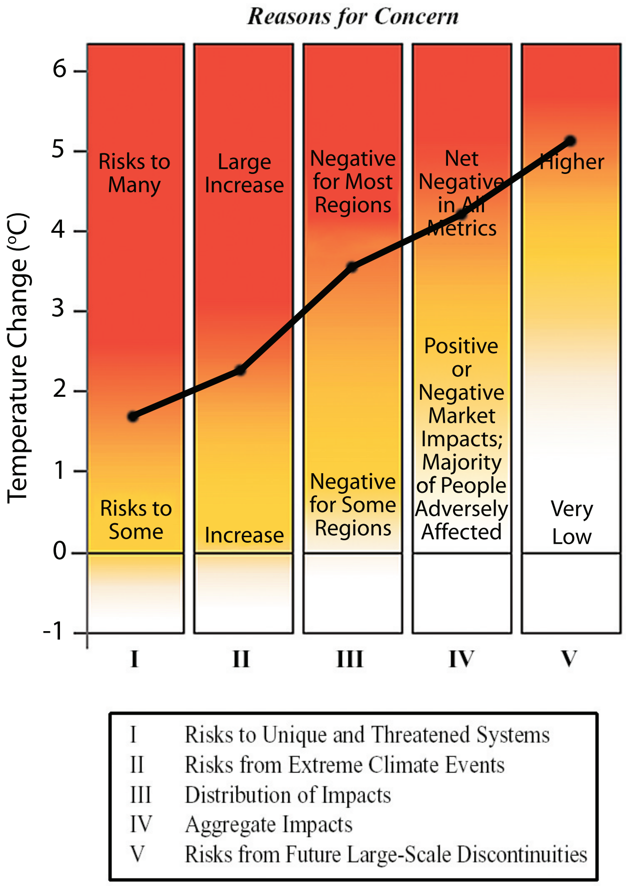


Figure 2: An adaptation of the IPCC "burning embers" diagram, with the thresholds used to generate the CDF for DAI from Mastrandrea & Schneider (2004). The IPCC figure conceptualizes five reasons for concern, mapped against climate change through 2100. As temperature increases, colors become redder: White indicates neutral or small negative or positive impacts or risks, yellow indicates negative impacts for some systems, and red means negative impacts or risks that are more widespread and/or greater in magnitude. The risks of adverse impacts from climate change increase with the magnitude of change, involving more of the reasons for concern. The authors used the transition-to-red thresholds for each reason for concern to construct a CDF for DAI, assuming the probability of DAI increases by a quintile as each threshold is reached. (From Mastrandrea & Schneider, 2004).

difficult. However, recent studies, many of which produce climate sensitivity distributions wider than the IPCC's 1.5°C to 4.5°C range, with significant probability of climate sensitivity above 4.5°C, are now available. Mastrandrea & Schneider (2004) use three such probability distributions: the combined distribution from Andronova & Schlesinger (2001), and the expert prior (F Exp) and uniform prior (F Uni) distributions from Forest et al. (2002). They perform a Monte Carlo analysis sampling from each climate sensitivity probability distribution separately, without applying any mitigation policy, so that all variation in results will be solely from variation in climate sensitivity. The probability distributions they produce show the percentage of outcomes resulting in temperature increases above their 2.85°C "dangerous" threshold (A in Figure 3).

Mastrandrea and Schneider's next simulation is a joint Monte Carlo analysis looking at temperature increase in 2100 with climate policy, varying both climate sensitivity and the climate damage function, their second parameter (B in Figure 3). For climate damages, they sample from the distributions of Roughgarden & Schneider (1999), which produce a range of climate damage functions both stronger and weaker than the original DICE function. As shown, aside from the Andronova and Schlesinger climate sensitivity distribution, which gives a lower probability of DAI under the single (climate sensitivity-only) Monte Carlo analysis, the joint runs show lower chances of dangerous climate change as a result of the more stringent climate policy controls generated by the model due to the inclusion of climate damages. Time-varying median carbon taxes are over \$50/Ton C by 2010, and over \$100/Ton C by 2050 in each joint analysis. Low temperature increases and reduced probability of DAI are achieved if carbon taxes are high, but because this analysis only considers one possible threshold for DAI (the median threshold of 2.85°C) and assumes a relatively low discount rate (about 1%), these results cannot remotely account for the range of interactions between climate policy controls and the potential for "dangerous" climate change. They are given to demonstrate a framework for probabilistic analysis, and the highly model-dependent results are not intended to be taken literally.

Because the analysis above only considers Mastrandrea and Schneider's median threshold (DAI[50‰]) of 2.85°C, Mastrandrea and Schneider continue their attempt to characterize the relationship between climate policy controls and the potential for "dangerous" climate change by calculating a series of single Monte Carlo analyses varying climate sensitivity and using a range of fixed damage functions. For each damage function, they perform a Monte Carlo analysis sampling from each of the three climate sensitivity distributions discussed above. They then average the results for each damage function, which gives the probability of DAI at a given 2050 carbon tax under the assumptions described above, as shown in Figure 4. Each band in the figure corresponds to optimisation around a different percentile range for the "dangerous" threshold CDF, with a lower percentile from the CDF representing a lower temperature threshold for DAI. At any DAI threshold, climate policy "works": higher carbon taxes lower the probability of future temperature increase, and thus reduce the probability of DAI. For example, if climate sensitivity turns out to be on the high

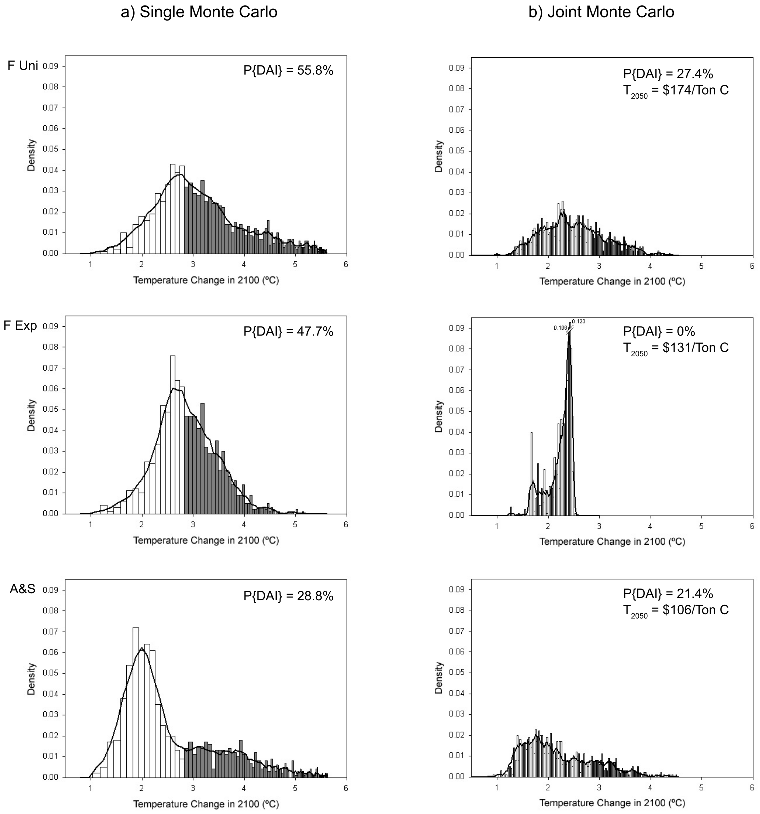


Figure 3: Panel A displays probability distributions for each climate sensitivity distribution for the climate sensitivity only—that is, Monte Carlo analyses with zero damages. Panel B displays probability distributions for the joint (climate sensitivity and climate damage) Monte Carlo analyses. All distributions indicate a 3-bin running mean and the percentage of outcomes above the median threshold of 2.85°C for "dangerous" climate change (P[DAI]), and the joint distributions display carbon taxes calculated in 2050 (T2050) by the DICE model using the median climate sensitivity from each climate sensitivity distribution and the median climate damage function for the joint Monte Carlo cases. Comparing the joint cases with climate policy controls, B, to the climate sensitivity-only cases with negligible climate policy controls, A, high carbon taxes reduce the potential (significantly in two out of three cases) for DAI. (However, this case uses a PRTP of 0%, implying a discount rate of about 1%. With a 3% PRTP—a discount rate of about 6%—this carbon tax is an order of magnitude less, and the reduction in DAI is on the order of 10%. See the supplementary online materials of Mastrandrea & Schneider (2004) for a full discussion.)

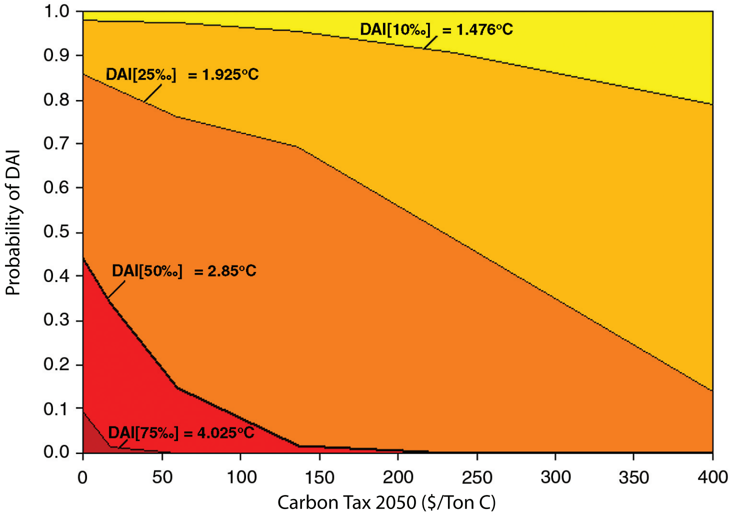


Figure 4: Each band represents a different percentile range for the DAI threshold CDF—a lower percentile from the CDF representing a lower temperature threshold for DAI. At any threshold, climate policy controls significantly reduce the probability of DAI. At the median DAI threshold of 2.85°C (the thicker black line on the figure), a 2050 carbon tax of ∼\$150/Ton C is necessary to virtually eliminate the probability of DAI.

end and DAI occurs at a relatively low temperature like 1.476°C (DAI[10‰]), then there is nearly a 100% chance that DAI will occur in the absence of carbon taxes and about an 80% chance it will occur even if carbon taxes were \$400/ton, the top end of Mastrandrea and Schneider's range. If we inspect the median (DAI[50‰]) threshold for DAI (the thicker black line in Figure 4), we see that a carbon tax by 2050 of \$150-\$200/Ton C will reduce the probability of DAI to nearly zero, from 45% without climate policy controls (for a 0% PRTP, equivalent to a discount rate of about 1%). Incidentally, the European Union has endorsed a do-not-exceed threshold for global warming (i.e., a form of DAI) of 2°C above pre-industrial temperatures—about 1.3°C above today's temperatures, and close to the Mastrandrea & Schneider (2004) 10th percentile DAI estimate.

Lastly, Mastrandrea and Schneider run Monte Carlo analyses varying climate sensitivity at different values for the PRTP, which illustrates the relationship between the discount rate and the probability of DAI at different temperature threshold values, as shown in Figure 5. As expected, increasing the discount rate shifts the probability distribution of future temperature increase upwards; a lower level of climate policy controls becomes "optimal" and thus increases the probability of DAI. At the median threshold of 2.85°C for DAI (the thicker black line in Figure 5), the probability of DAI rises from near zero with a 0%

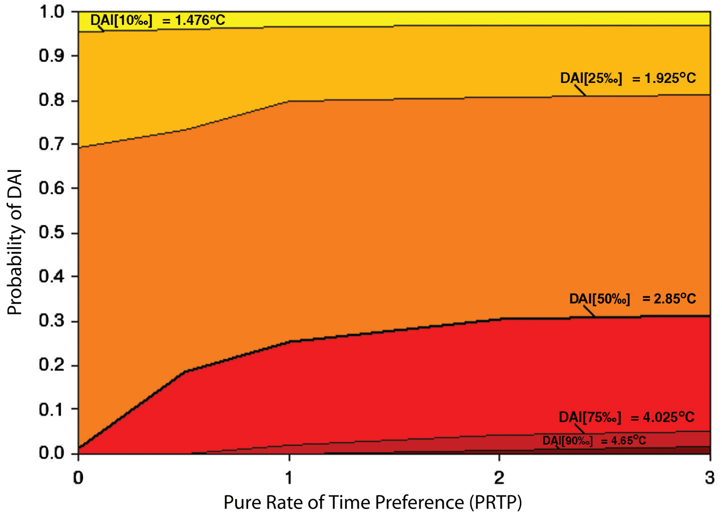
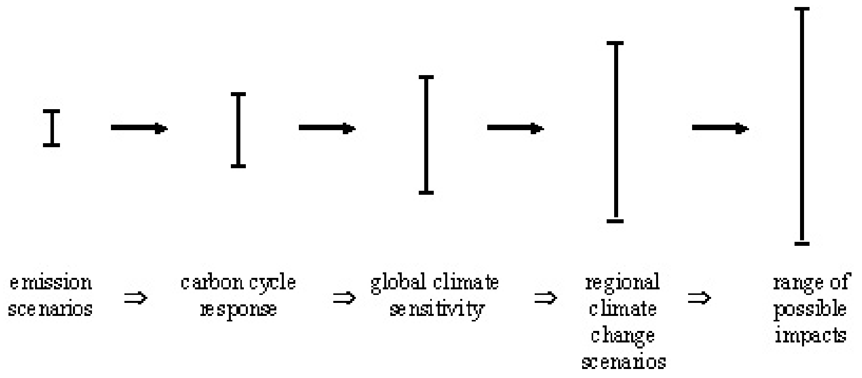


Figure 5: Increasing the PRTP (and hence the discount rate) reduces the present value of future climate damages and increases the probability of "DAI." At the median threshold of 2.85°C for DAI (thicker black line), the probability of DAI rises from near zero with a 0% PRTP to 30% with a 3% PRTP, as originally specified in the DICE model.

PRTP to 30% with a 3% PRTP. A PRTP of 3% is the value originally specified in Nordhaus' DICE model. At PRTP values greater than 1%, the "optimal" outcome becomes increasingly insensitive to variation in future climate damages driven by variation in climate sensitivity.

While Mastrandrea and Schneider's model-dependent results using the DICE model do not provide us with confident quantitative answers, they still demonstrate three very important issues: (1) that DAI can vary significantly, depending on its definition; (2) that parameter uncertainty will be critical for all future climate projections; and, most importantly for this volume on integrated assessment, (3) that climate policy controls (i.e., "optimal" carbon taxes) can significantly reduce the probability of dangerous anthropogenic interference. This last finding has considerable implications for introducing climate information to policymakers. We agree with Mastrandrea and Schneider that presenting climate modeling results and arguing for the benefits of climate policy can be graphically displayed for decision makers in terms of the potential for climate policy to reduce the likelihood of exceeding a DAI threshold.

Other recent studies focused on incorporating "dangerous" climate change into IAMs have been performed by Azar & Lindgren (2003); Bruckner & Zickfeld (2004) and others.



Source: Modified after Jones, 2000, and the "cascading pyramid of uncertainties" in Schneider, 1983.

Figure 6: The "cascade of uncertainties" from emissions scenarios to impacts. Uncertainty grows at each step of the causal chain. Modified after Jones (2000) and the "cascading pyramid of uncertainties" in Schneider (1983).

3.2 Dealing with uncertainty

There is a cascade of uncertainty that results from coupling the separate probability distributions for emissions, biogeochemical cycles, climate sensitivity, climate impacts, and the valuation of such impacts into climate damage functions, as depicted schematically in Figure 6 (modified after Jones (2000) and the "cascading pyramid of uncertainties" in Schneider (1983)). These uncertainties have yet to be fully dissected in climate-change literature, but Webster et al. (2003) provide a pioneering attempt (although in some ways this type of analysis was first demonstrated in Morgan & Dowlatabadi, 1996). Webster et al. (2002) comment that their study differs from other studies attempting to address uncertainty in three ways: (1) they use explicit probabilities for different emissions projections, based on judgments about the uncertainty in future economic growth and technological change (Webster et al., 2002) and on documented uncertainty in current levels of emissions (Olivier et al., 1996); (2) they use observations to constrain the joint distributions of uncertain climate parameters so that simulated climate change for the 21st century is consistent with observations of surface, upper-air, and deep ocean temperatures over the 20th century (Forest et al., 2000, 2001, 2002); and (3), they estimate uncertainty under a policy constraint as well as a no policy case, to show how much uncertainty remains even after a relatively certain cap on emissions is put in place.

Although their IAM doesn't incorporate abrupt changes, it does consider uncertainty in five specific areas: 1) anthropogenic emissions of greenhouse gases; 2) anthropogenic emissions of short-lived climate-relevant air pollutants; 3) climate sensitivity; 4) oceanic heat uptake; and 5) specific aerosol forcing. The results of the IAM are "probability distributions of future climate projections based on current uncertainty in underlying scientific and socioeconomic parameters" (Webster et al., 2003). While some line up with projections used in the IPCC TAR, others (especially for SO_2 concentrations) do not, showing how in-depth analysis of uncertainties can produce differing results. In the case of temperature, Webster et al. find that:

> Without policy, our estimated mean for the global mean surface temperature increase is 1.1°C in 2050 and 2.4°C in 2100. The corresponding means for the policy case are 0.93°C in 2050 and 1.7°C in 2100. The mean outcomes tend to be somewhat higher than the modes of the distribution, reflecting the skewed distribution - the mean outcome of the Monte Carlo analysis is higher than if one were to run a single scenario with mean estimates from all the parameter distributions. One can also contrast the distribution for the no policy case with the IPCC range for 2100 of 1.4 to 5.8°C (IPCC, 2001a). Although the IPCC provided no estimate of the probability of this range, our 95% probability range for 2100 is 1.0 to 4.9°C. So, while the width of the IPCC range turns out to be very similar to our estimate of a 95% confidence limit, both their lower and upper bounds are somewhat higher. When compared to our no-policy case, our policy case produces a narrower pdf and lower mean value for the 1990-2100 warming. But, even with the reduced emissions uncertainty in the policy case, the climate outcomes are still quite uncertain. There remains a one in forty chance that temperatures in 2100 could be greater than 3.2 C and a one in seven chance that temperatures could rise by more than 2.4 C, which is the mean of our no policy case. Hence, climate policies can reduce the risks of large increases in global temperature, but they cannot eliminate the risk.

3.3 Other models

Numerous other IAMs exist, including IAMs that comprise global vegetation models to assess shifts in ecosystems caused by climate change (Fssel & van Minnen, 2001; Fssel, 2003; Leemans & Eickhout, 2004) and models that incorporate land use change (ICAM—Brown & Rosenberg, 1999; AIM—Matsuoka et al., 1995; IMAGE—Alcamo et al., 1998; and TARGETS—Rotmans & de Vries, 1997) The latter authors explored "cultural theory"—a set of values which would lead to very different policy choices depending on the value system picked—but it is beyond the scope of this paper to discuss every one in detail. Suffice it to say that undoubtedly, other IAMs include some unique elements that are valuable in learning more about climate change and making coherent policy decisions and lack other elements that could help to clarify their results.

4 Current challenges, future possibilities: the long, bumpy road ahead

4.1 Uncertainties in climate science, and model-related challenges

In 1997, when Schneider published the above IAM classification scheme, he opined that IAMs had progressed to the second and third generations. Many scientists believe that, eight years later, most IAMs are still in the second and third generations, with the exception of a few that have penetrated the fourth generation. Even those "advanced" models that have moved up the hierarchy don't always do a full job of dealing with elements of earlier generational classifications on the table. In essence, they skip some steps in their progression upward and emphasize special features. (Thus, to get an overview of the landscape of integrated assessment means more than looking at only the most recent or most comprehensive models; rather, an integrated look at both current and historic works is necessary to have a broad overview.) Hence, there is much work that remains to be done in climate science and impacts, within the models themselves, and in how the information models generate is presented to the policy community—assuming it is presented at all.

Many difficulties in integrated assessment modeling are not a result of inherent uncertainty within the models themselves, but a result of uncertainties in the climate debate, as illustrated by the cascade of uncertainties (see Figure 6). In order to arrive at reasonable conclusions on global warming, scientists must estimate future populations, levels of economic development, and potential technological props spurring that economic development, all of which will influence the radiative forcing of the atmosphere via emissions of greenhouse gases and other radiatively active constituents. This is no small task, and it will only be advanced by improving scientific research over time. The necessity of doing so is great, as it will provide better information for use in IAMs, and hence may improve accuracy, and as importantly, transparency. As stated by Webster et al. (2003), discussed above, "If it were possible to significantly resolve climate science over the next few years, about one-third of the uncertainty, as measured by the standard deviation, could be reduced."

As Webster et al. (2003) suggest, the uncertainties in climate science and impacts translate into uncertainties in IAMs. The questions these uncertainties have elicited in modeling include:

- How do we estimate climate damages and the discount rate? The IPCC (2001*a*) worries that some damage metrics may not fully capture the value of some impacts. Nonmarket impacts of climate change are of particular concern. How do we account for cultural differences across different professional or social groups that may influence damage estimates?
- On a similar note, how do we gain understanding of the damage function, particularly the part addressing the response of developing countries and

natural ecosystems to climate change (Nordhaus & Boyer, 2000)? The damage function is very uncertain, yet it can't be eliminated, because it is fundamental in helping models generate inferences on climate change policy and suggest what measures may need to be taken to prevent "dangerous" climate change.

- How do we incorporate structural changes in political or economic systems and regime shifts, such as public consciousness on climate change (See also Dessai et al., 2004)?
- Can we find a way in which to include ITC in IAMs in a manner that is not ad hoc (Goulder & Schneider, 1999)? Currently, most models don't include a formulation for ITC, which reduces the credibility of insights they produce about costs and timing of abatement policy.
- How can we assure the structural integrity of an IAM's sub-models? Should there be protocols for procedures that should be followed in linking submodels together to form IAMs and in identifying and correcting for overlaps and gaps (Barker, 2003)?
- In considering abrupt climate events, how do we create IAMs that credibly evaluate the probabilities of currently imaginable surprises (Schneider, 1997)?
- How do we resolve the mismatch in geographic and time scales between emissions, climate science, and climate impacts (Root & Schneider, 2003; IPCC, 1996*b*)? Scientists assign different levels of confidence to different components of the earth system, and we are still unsure how to aggregate that in integrated assessment modeling.
- What is the proper trade-off between detail and accuracy in IAMs?
- Can models be made to mimic a dynamic world, rather than being static in nature (IPCC, 2001*a*)?
- Is it possible to effectively manage the repeated updating of IAMs (Barker, 2003)?
- Can cultural theory or some other classifications of differing value sets be incorporated in IAMs to examine the sensitivity of conclusions to value changes and/or differences?
- Are these the right questions to be asking? We know a lot more now than a couple decades ago, but not yet enough to be confident that we even know all the important questions to be asking, let alone how to answer them (IPCC, 1996*b*)!

IAMs can only provide "answers" that are as good as the assumptions that underlie them and the structural fidelity they exhibit (Schneider, 1997). It is the hope of the authors that IAMs will improve in lock step with any improvement in climate science and impacts. As modelers learn more, it is also our hope that peer review of IAMs is bettered; at present, the interdisciplinary community experienced in working at the intersections of knowledge from the many subdisciplines that comprise IA is small. Until peer review of IAMs becomes more mainstream, the following validation protocols may help in determining model legitimacy: 1) Inter-comparisons of highly aggregated models with a limited set of highly resolved test runs or special field experiments; 2) Inter-comparisons of such hybrid models with different designs against each other; 3) Tests of the ability of such models' simulations to capture known and salient features of the actual natural/social systems, and, for example, the ability of all models to demonstrate reasonable sensitivity responses to known forcing events (e.g., physical sub-models should respond reasonably to volcanic dust veils or changes in the Earth's orbital elements and the impact of price shocks or trade policy changes on societal models should bear resemblance to actual societal impacts) (Schneider, 1997). (In addition, Schneider notes that model results should be compared to empirical data at the scale of the smallest model elements, not necessarily at the scale at which the empirical data was originally collected.)

Much emphasis has been placed on this concept of assuring that IAMs can accurately reproduce historical data, but given that the world is changing rapidly and will continue to do so, how much does it matter whether a model is calibrated to historical data? Until we have a better method for gauging model accuracy, it is the belief of the authors that a model that can reproduce past trends over time is preferable to a model that can only reproduce historical data for a single point in time or to a purely theoretical model, but with the caveat that if the model is only tuned to reproduce past events, its credibility for projections is severely compromised.

While the concerns above are ones that hopefully will be reduced slowly with time, modelers should not despair. Acknowledging that IAMs are, in some respects, limited in scope, is not synonymous with dismissing the usefulness of their insights altogether. There are some steps that modelers can take in the near term to improve their assessments. First, more effort must be put into full integration. Individual component models feeding into an IAM must be as reliable as state of the art disciplinary science allows, of course, but in order for the overall model to produce valuable results, the integration across disciplinary sub-models must be good as well (IPCC, 1996*b*). More ideas for making integration flexible, consistent, and meaningful will undoubtedly improve results. Morgan & Dowlatabadi (1996) offer additional invaluable guidelines:

1. The characterization and analysis of uncertainty should be a central focus of all assessments.

2. The approach should be iterative. The focus of attention should be permitted to shift over time depending on what has been learned and which parts of the problem are found to be critical to answer the questions being asked.

3. Parts of the problem about which we have little knowledge must not be

ignored. Order-of-magnitude analysis, bounding analysis, and carefully elicited expert judgment should be used when formal models are not possible.

4. Treatment of values should be explicit, and when possible parametric, so that many different actors can all make use of results from the same assessment.
5. To provide proper perspective, climate impacts should be placed in the context of other natural and human background stochastic variation and secular trends. Where possible, relevant historical data should be used.
6. A successful assessment is likely to consist of a set of coordinated analyses that span the problem...not a single model. Different parts of this set will probably need to adopt different analytical strategies.
7. There should be multiple assessments
    - Different actors and problems will require different formulations; and
    - No one project will get everything right. Nor are results from any one project likely to be persuasive on their own.

Second, IA modelers must think beyond the paradigm of neo-classical economics, which has provided the base for IAMs to date (DeCanio et al., 2000). If integrated assessment modeling is to mature, it needs to broaden its scope by adding more cutting-edge ideas not just from economics, but other fields as well. Third, and perhaps most importantly, modelers must be aware of their own biases, which can lead to three serious pitfalls: 1) Picking a model structure without having a set of applications firmly in mind, and not modifying the model in response to new problems; 2) Mistaking the model for reality, and assuming that if something is not included in the model, it doesn't matter; testing alternative assumptions only against the model; and assuming that restrictions in the model reflect restrictions inherent in the real world; 3) Poor communication of results; overstating the strength of model results; and omitting key assumptions/qualifications (IPCC, 1996*b*).

Other biases exist as well. By definition, science with policy content is socially constructed; there is no such thing as purely "objective" policy. The IAM community has already adopted a common set of values, and indeed, some important communities (i.e., the coal industry, Saudi Arabia, some developing nations) have been left out or pushed to the fringe of the debate—sometimes by their own doing. A first step in dealing with this issue would be for assessment reports to clearly describe their values. Next, groups with different societal values must be brought together so that they can at least air their varying viewpoints. In the future, it is our belief that modelers should aim to represent some important phenomena that are absent from, or poorly communicated in, most IAMs available today, including power relationships in a society, short-term interests, equity, and even corruption and black markets when they are a significant component of reality.

4.2 Penetrating the policy community

Weyant's third concern, poor communication of results, leads to the next conundrum of integrated assessment modeling: how can results be better communicated to decision makers? However, if communication of results is poor, then IAMs can do more harm than good:

> To the extent that IAMs inform that value-laden process of decision making, they can educate our intuitions and make our decisions more rational. To the extent that, in a haze of analytic complexity, IAMs obscure values or make implicit cultural assumptions about how nature or society works, IAMs can thus diminish the openness of the decision-making process. And, to the extent that openness is proportional to rationality, diminished openness would render policy making even "less rational" (Schneider, 1997).

This is clearly contradictory to the purpose of IAMs, and thus, scientists must learn to effectively communicate their results. This often requires the building of personal relationships, and thus credibility, with stakeholder communities. When speaking to policy makers and citizens, scientists must make it evident that any quantitative answers generated by IAMs are not to be taken literally, but should be used more as tools to generate insights into the decision-making process; they are not "truth machines," but general guideposts. Scientists must open and conclude their presentations to policy makers and laypeople on IAM results with clear, concise statements about assumptions and uncertainties, and should avoid overloading a presentation with numerical data, keeping in mind that communicating with decision makers and the public requires very different skills and language than communicating with scientific colleagues. It will be necessary for scientists to find the appropriate balance between transparency and completeness. Perhaps this is less a challenge of choosing a model and more one of interpreting its results in a manner comprehensible to non-scientists. Schneider (1997) suggests guidelines for communicating results:

1. Specify clearly at the outset and in the conclusions of presentations or publications the limited context of each particular IAM exercise.

2. Cite alternative approaches and contrast them to your approach, stressing how each treats uncertainty and deals with the many value-laden components of the analysis.

3. Provide as many menu options as practical, especially for those choices which deal with culturally-dependent components or "imaginable surprises".

4. Perform as many "validation" tests as possible, and when not practical, discuss, based on qualitative reasoning, the credibility of the structural assumptions, input data, and model parameters, and their relevance to policy issues that are being considered.

5. Stress the likelihood that this generation of IAM results will change as "rolling assessments" provide an evolving picture of climatic effects, impacts and the efficacy of policy instruments and societal values.

6. Note components of the IAM which are particularly sensitive (or insensitive) to aspects of the problem that are controversial and thus likely to change with evolving research.

In addition, modelers must overcome one enormous bias and realize that integrated assessment modeling is not the only component of IA. In reality, there is a chance that, if the results of IAM are communicated poorly, stakeholders will not use them at all when considering their options when faced with climate change (Cohen, 1996). For this reason, not only must scientists learn proper and effective ways of communication with the public, but integrated assessment modeling must be complemented by other integrated assessment approaches that may attract a broader range of stakeholders. If IA in general, and IAMs specifically, are to become the best option for informing decision making on climate change, they cannot be performed in isolation from policy analysts and decision makers. Therefore, Cohen (1996) suggests a "new paradigm" for IAMs: a) consideration of regional impacts and adaptation, b) linkage with existing resource management instruments and policies, c) identification of indirect impacts when the focus is on places, rather than sectors, and d) incorporation of local knowledge into the analysis. More focus should be placed on outreach programs that train decision makers and citizens in helping design, test, and implement IAMs so that the best interests and perceptions of the public are reflected in assessment, and those assessments are used by the very public for which they are meant. Scientists should direct policy makers toward the specific IAMs that answer the questions they want to ask, rather than allow them to become overwhelmed and discouraged as they attempt to sort through IAM data themselves. To avoid these steps is to "make IAMs at best irrelevant to policy-makers, and at worst misleading" (Schneider, 1997).

Even if all these steps are followed, it is not possible to predict the interactions and/or influence that scientists will have with different audiences (although understanding various actors' culture and value systems may help scientists to do so). Oftentimes, policy formation occurs in an emergency situation, and policy makers will suddenly request available results and knowledge from scientists' dealings with IAMs. This may happen at a speed to which an academic, who has been working on interpreting the results of IAMs for years, is unaccustomed. Nevertheless, it is useful to have a strong foundation in communicating the results of IAMs to the public. Such training cannot lead to the avoidance of emergency situations, but it can help guide scientists in any interaction.

5 Conclusion

After decades of work on integrated assessment modeling of climate change, we have indeed come a long way, but the road ahead promises to be lined with challenges. In order to further progress in integrated assessment modeling, scientists must address as well as they can the challenges that remain in both the models themselves and in relaying information to policy makers and laypeople. It is only in this way that the seeds of integrated assessment modeling will bear fruit and truly contribute to policy action on climate change.

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