Annu. Rev. Energy Environ. 1997. 22:589–628

INTEGRATED ASSESSMENT MODELS OF GLOBAL CLIMATE CHANGE

Edward A. Parson and Karen Fisher-Vanden
Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, Cambridge, Massachusetts 02138

KEY WORDS: modeling, emissions, assessment, climate, impacts, policy

ABSTRACT

We review recent work in the integrated assessment modeling of global climate change. This field has grown rapidly since 1990. Integrated assessment models seek to combine knowledge from multiple disciplines in formal integrated representations; inform policy-making, structure knowledge, and prioritize key uncertainties; and advance knowledge of broad system linkages and feedbacks, particularly between socioeconomic and biophysical processes. They may combine simplified representations of the socioeconomic determinants of greenhouse gas emissions, the atmosphere and oceans, impacts on human activities and ecosystems, and potential policies and responses. We summarize current projects, grouping them according to whether they emphasize the dynamics of emissions control and optimal policy-making, uncertainty, or spatial detail. We review the few significant insights that have been claimed from work to date and identify important challenges for integrated assessment modeling in its relationships to disciplinary knowledge and to broader assessment seeking to inform policy- and decision-making.

CONTENTS

1056-3466/97/1022-0589$08.00

1. INTEGRATED ASSESSMENT MODELS OF GLOBAL CLIMATE CHANGE: CONTEXT, SCOPE, AND BACKGROUND

We review recent work in integrated assessment (IA) modeling of global climate change. To bound the discussion and place it in context, we first briefly discuss assessment, then integrated assessment, then alternative methods of conducting integrated assessment including formal modeling, the focus of this review. Assessment consists of social processes that bridge the domains of knowledge and decision-making, assembling and synthesizing expert scientific or technical knowledge to advise policy or decision-making (1, 2). Assessment processes might seek to mine current knowledge to answer specific policy-relevant questions, to identify policy-relevant implications, or to help policy-makers understand what questions they should be asking. Assessment has been practiced for three decades in particular policy domains under such titles as environmental impact assessment, risk assessment, and technology assessment (3, 4), and for longer under such less systematic processes as National Research Council committees or other advisory bodies.

Assessment is integrated according to the breadth of the expert knowledge it synthesizes in advising the issue at hand (1, 2, 5, 6). It is plausible that most useful assessment is integrated to some degree, since few real policy issues or decisions can be usefully advised by drawing only on the knowledge of a single research community. Practitioners and critics of integrated assessment differ over the precise conditions that make an assessment integrated, but we contend that this debate mistakenly treats integration as a binary characteristic and mistakes the means for the end. Assessments can be more or less integrated. And assessment activities should be judged by their contribution to advising policy issues or decisions and perhaps to the advancement of knowledge. Being more or less integrated is a means toward these ends. Below we discuss some specific issues of integration that arise in integrated assessment (IA) models.

Two methods of assessment have dominated practice and research for more than 20 years: deliberation by interdisciplinary expert panels and formal modeling. Deliberation of interdisciplinary panels has been the main method of delivering official assessment to policy-making bodies through this period, and it remains predominant in such bodies as the Intergovernmental Panel on Climate Change (IPCC) and the Assessment Panels of the Montreal Protocol. Formal integrated modeling as an assessment method has been a primary interest of independent researchers and analysts over a similar period and has experienced a surge of activity since approximately 1990 for global climate change. Other approaches that have recently been advocated combine and extend the distinct strengths of panels and models (7, 8).

A landmark early integrated assessment of a global environmental issue was the Climatic Impacts Assessment Program (CIAP), which assessed impacts of stratospheric supersonic flight (9). CIAP comprised six parallel interdisciplinary expert teams, which each examined one link of a causal chain stretching from scenarios of supersonic flight and jet engine design, through atmospheric chemistry and radiation, to biological, economic, and social impacts. While its immediate contribution to policy was limited, CIAP made a major contribution to developing an interdisciplinary atmospheric research community (10). Although several other climate assessments conducted through the late 1970s and early 1980s used interdisciplinary expert panels (11–13), no assessment since CIAP has attempted such ambitious integration of any global environmental issue without using a formal integrated model.

While panels are a *deliberative* approach to assessment, integrated modeling is a *representational* approach: It seeks to advance understanding by constructing a formal representation of the issue to be studied. Current integrated assessment models of global climate descend from two streams of work. The representational components that they integrate draw, often in highly simplified form, on models of energy systems and economies, of atmospheric chemistry and climate, and of ecosystems developed in various disciplines, whereas their bold pursuit of integrated representation descends from the global models of the 1970s (15–18).

The most prominent heritage of many current IA climate models lies in the energy-economic models of the 1970s (19). From these, an early step toward climate integration was the addition of fuel-specific CO_2 emissions coefficients, which allowed the emissions paths associated with particular energy scenarios (20–22) or the cost of meeting emission constraints (23) to be calculated. But the first assessment model of a global environmental issue that pursued integration from sources to impacts did not examine climate but rather the more analytically tractable issue of acid rain. The RAINS model of acidification in Europe integrates national emissions, a previously developed model of atmospheric transport and chemistry, and maximum permissible deposition levels, called critical loads (24). RAINS can calculate deposition on a 50-km grid resulting from specified growth scenarios and control measures or calculate cost-minimizing controls to meet specified deposition limits. The modelers sought close relations with European policy-makers, and RAINS was used extensively in negotiations for a 1994 agreement to limit sulfur emissions. Similar integrated modeling projects elsewhere appear to have been less used in policy-making (25–28).

Beginning in the late 1980s, several modeling projects began to seek broader integration in climate assessments, first by adding non-CO_2 greenhouse gases and simple atmospheric representations. Mintzer projected emissions and concentrations of multiple greenhouse gases, combining a widely used energy model with exogenous scenarios, and added simple radiative-forcing equations to project equilibrium, or "committed" global temperature change (20, 29). The Atmospheric Stabilization Framework (ASF) refined the projection of emissions, particularly from land-use and agriculture, and added a simple calculation of realized global temperature change (30). The IMAGE 1 model (Integrated Model for the Assessment of the Greenhouse Effect) added a simple calculation of sea-level rise, its impact on the Netherlands, and optimal coastal defense (31, 32). ASF and IMAGE 1 were used to generate the IPCC's 1990 scenarios of greenhouse gas emissions and concentrations (33).

In this article, we review the rapid surge of IA modeling activity for climate change that has taken place since 1990, increasing the number of projects from 3 to approximately 40 (2, 34). This surge of activity has reflected the combined influence of several factors, including the sudden political prominence of climate change; widespread belief that understanding and managing it requires integrating knowledge from a broad set of biophysical and socioeconomic domains; advances in computing power and in sectoral modeling of energy systems, the atmosphere, and ecosystems; the increasing availability of consistent global data sets; and the activity of research entrepreneurs building interdisciplinary projects, responding to general interest in the field and the availability of funding. The past two years show increasing signs of maturation of the field—the first review articles and conferences, and published contributions summarizing cumulative results, critiquing current practice, and calling for development of a more connected professional community (2, 35–38).

Section 2 summarizes the purposes that have been claimed for IA models and the meaning of the two primary dimensions of integration in IA models, "vertical" and "horizontal." Section 3 follows the structure of IA models defined by vertical integration, following a causal chain from emissions to impacts, and summarizes the range of approaches that IA models have taken to represent each component. Section 4 summarizes major IA modeling projects, sorting them according to differences in emphasis and apparent purpose into three categories—models that stress dynamics and optimization, uncertainty, and spatial detail, respectively. Section 5 summarizes and evaluates the significant results and insights claimed for IA models so far. Section 6 offers concluding observations on the current state, and contributions to date, of IA modeling of global climate change.

2. PURPOSES OF INTEGRATED ASSESSMENT MODELING AND MODES OF INTEGRATION

Four broad contributions have been claimed for integrated assessment (IA) modeling: evaluating potential responses to climate change; structuring knowledge and characterizing uncertainty; contributing to broad comparative risk assessment; and contributing to scientific research. In principle, IA models can make any of these contributions; in practice, work to date has served these purposes to different degrees, and basic elements of structure and design of any particular IA model strongly influence which of these purposes it can serve and how well. We elaborate on each of these four contributions below.

First, IA models can help evaluate potential responses to climate change in several ways: by characterizing potential climate impacts; by describing the cost, effect, and other consequences of specific responses or of alternative means of attaining a specific environmental goal; or by balancing costs and benefits of particular responses. Any of these contributions require that IA models be able to compare future projections of relevant aspects of the climate issue, under alternative assumptions and alternative specified responses. While responsible IA modeling will make clear that these projections are appropriately qualified, contingent on a host of assumptions, and responsibly reflect currently understood uncertainties, this use of IA modeling is a predictive endeavor and subject to all the usual risks of predicting the future.

Second, by their very nature as tools to integrate knowledge coherently from multiple relevant domains, IA models can provide a framework for structuring present knowledge about climate change. Having such a framework can serve several purposes. It can assist in keeping the whole problem in view, hence supporting systematic search for responses and resistance to premature closure on a few options. It can help organize and interpret advances in relevant knowledge as they occur. Perhaps most importantly, such a framework can help identify and characterize the magnitude of key uncertainties and their importance for key impacts and decisions.

Third, by constructing broad characterizations of future development of the climate issue, IA models can help put climate in the context of other environmental stresses and other social and economic changes that might occur over the same time, to give insight into the broadest of policy questions—How important is climate change?

Finally, IA models can be research tools independent of any direct assessment function, serving to advance basic knowledge and understanding. In part this purpose is closely related to the use of IA models in identifying key uncertainties, which can help research communities identify priority directions for investigation. But in addition, IA models may seek to represent linked system behavior across domains, including biosphere-atmosphere feedbacks and linkages between biophysical and socioeconomic aspects of the system. To the extent that such broad integration captures quantitatively important linkages and feedbacks, IA modeling can contribute to basic understanding of system behavior.

Assessment can be integrated on many dimensions, including such political and managerial dimensions as participation, process, and oversight, which may be important in explaining how effectively assessment contributes to policy or decision. Questions of integration in IA modeling are more narrow and substantive, concerned with what knowledge domains are included and what questions are posed. These substantive aspects of integration have conventionally been grouped into two dimensions, vertical and horizontal integration.

Vertical integration is integration along the primary causal chain that links the causes and consequences of climate change: emissions and their sources; atmospheric and biogeochemical processes; physical and ecological impacts; social and economic impacts; and response options at various points in this chain. An IA model that seeks to provide benefit-cost evaluation of responses, weighing the impacts of climate change against measures to reduce it or adapt to it, must include at least simple representations of all major components of this chain.

Two kinds of integration have been described as horizontal. The term has been used to refer to expanding each link of the causal chain laid out by vertical integration, i.e. integrating more source activities and emissions, more atmospheric and biotic processes, or more forms of impact or response. But increasingly, horizontal integration describes an IA model's representation of linkages between climate change and other issues, including both other atmospheric issues such as ozone depletion, acidification, or photochemical air pollution, and linked social issues such as health and development. While these issues have causal links of various strengths, they are conventionally identified and managed separately. The IA models that are making preliminary attempts at such horizontal integration are consequently not strictly IA models of climate change. Rather, they are moving some distance ahead of current structures of decision-making to sketch an integrated conception of sustainable development (39–41).

3. BUILDING BLOCKS: COMPONENTS OF VERTICALLY INTEGRATED CLIMATE-ASSESSMENT MODELS

This section summarizes the component domains of IA models, while the next section summarizes complete IA modeling projects. Here, we follow the structure of vertical integration to summarize the approaches IA models have taken to representing particular components of the causal chain. A vertically integrated IA model combines representations of some or all of the following: emissions and their socioeconomic determinants, the atmosphere-ocean-climate system, ecosystems, socioeconomic impacts, and policy and responses. IA models have differed in the prominence and detail they give to particular components, reflecting the project's disciplinary heritage, the interests and skills of team members, and the intended purpose. Many attempts at vertical integration in IA modeling, including all early attempts, treated these components as links in a single straight causal chain, as shown in Figure 1. More recent work in IA modeling has begun to enrich this structure with more complex linkages and feedbacks, such as direct human modification of ecosystems and CO_2 fertilization, yielding more complex structures as illustrated in Figure 2.

3.1 *Representation of Emissions and Their Socioeconomic Determinants*

Climate change will depend on the future path of world emissions, which any integrated assessment study must project. IA models have employed three related methods, alone or in combination, to project emissions: externally specified emission scenarios, detailed bottom-up representation of technologies, and aggregate economic modeling. All these methods involve speculative projections about future events but differ in the detail and explicitness of different components of the projections. The biggest challenges for any of these methods are integrating multiple source gases and activities and credibly projecting the two most basic drivers of emissions trends—population growth and technological change.

Scenarios are exogenously specified time paths of key variables, which are used as inputs to drive other parts of an assessment. Scenarios may provide time paths of emissions directly or of population, economic, and technological trends from which emissions paths are calculated. Scenarios may be estimated through prior analysis or modeling or through disciplined, consistent guesswork. Scenarios provide input values for parts of a model that are not represented directly, e.g. for emissions in a model that focuses primarily on atmospheric dynamics and impacts. Scenarios drawn from an authoritative source such as the IPCC can facilitate standardization and controlled comparison between models, relieving each of the need to select and defend its own inputs.

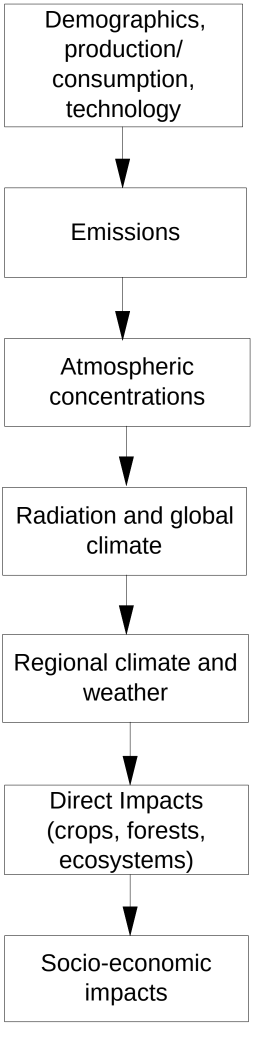

Figure 1 Vertical integration: simple end-to-end form.

Emission scenarios permit only limited investigation of effects of alternative assumptions or policies, which must be specified as departures from a scenario-defined baseline. Scenarios normally come in groups, which are claimed only to illustrate plausible future emission trends but are often treated as if they span the entire plausible (or possible) relevant range. They are hence subject to misinterpretation. They may imply subtle biases toward continuance of recent trends, particularly by excluding possible surprise or discontinuity

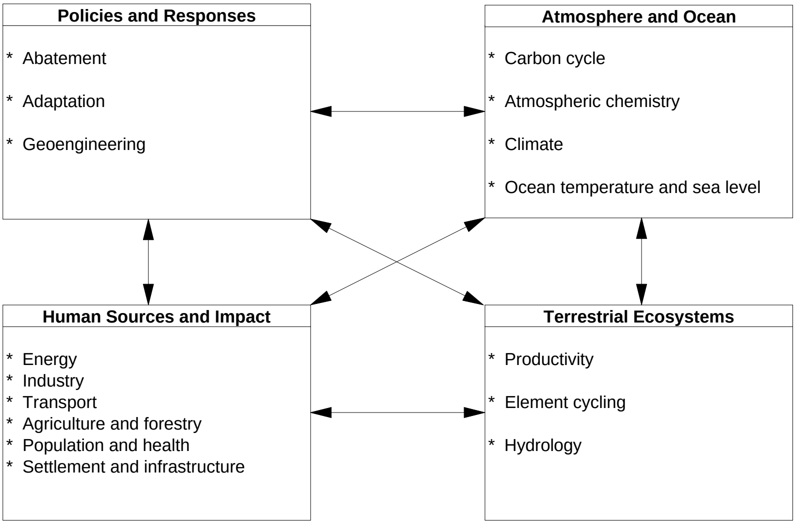

Figure 2 Vertical integration: fully linked form.

that may dominate historical change. They may also embed unstated policy presumptions or undetected contradiction or incoherence (42–44).

The second approach is detailed bottom-up specification of the technologies that generate emissions. The mix of technologies in each region at each time is described by its costs, inputs, and outputs, including emissions. This approach allows precise specification of known or projected innovations, e.g. that an advanced gas turbine with specified cost and efficiency will be available in 2005. But the approach can require specifying time paths of huge numbers of technical coefficients, risking arbitrariness and spurious precision.

The third approach is aggregate economic modeling with embedded emission coefficients, projecting future emissions as the outcome of specified production relationships, preferences, and economic growth. Such models can project unconstrained emissions growth paths, estimate the cost of specified emissions constraints, or assess the stringency of taxes or other policies needed to meet a specified emissions limit. The models can range from those of simple aggregate economies with embedded abatement-cost functions (45), to macro-models coupled to a detailed energy sector (20, 46), to full dynamic general equilibrium models (47, 48). Basic design choices include the kind of optimizing behavior represented (e.g. meeting specified final energy demands at minimum cost, or maximizing the present value of consumption or of some utility function); whether agents have foresight and what choices they can make (labor-leisure and consumption-saving decisions, or only consumption decisions); how capital is structured and vintaged, and whether it is malleable once invested; and the degree of disaggregation among world regions and how they interact through flows of capital, people, and goods. A problem common to all such models, which is particularly acute when they are applied to developing or transitional economies, is the use of common equilibrium assumptions and determinants of behavior worldwide. Stanford University's Energy Modeling Forum has compared 14 such models under various scenarios of population, resource availability, technology, and emissions abatement (49).

Combinations of the three approaches are most common in projecting emissions of multiple gases. Detailed atmospheric modeling can require specifying emissions of multiple gases and aerosols at fine spatial resolution. While fossil-CO_2 emissions can be well modeled through either energy-economic or technology representations, other emissions are more difficult to measure and model. Consequently, many IA modeling projects have combined modeled emissions of CO_2 and sometimes other gases from fossil combustion with fixed scenarios for other emissions. Weak representation of multiple emissions in present IA models limits their ability to evaluate abatement measures that affect multiple gases.

Land use is both a significant emissions source—as a result of clearing, burning, cultivation, and other activities—and an important route for climate impacts, both direct and those mediated by the effect of demand for food, fiber, and possibly biofuels on land resources. The approach of early IA models to land use has been primitive. Either global land-use emissions are assumed to be balanced by terrestrial carbon uptake (the "neutral biosphere" assumption) or fixed scenarios of land-use emissions with no feedbacks are used. Further advances require detailed spatial disaggregation. Current work seeks to improve understanding of socioeconomic processes driving land use and its change, including competing uses for land, and to investigate land-related feedbacks between biophysical and socioeconomic processes. Attempts thus far to integrate land use into IA models have stressed either the biophysical or the economic side, with limited treatment of linkages (50–52).

Over multi-decade periods, population and technological change are crucial drivers of emissions but pose sharp challenges to IA models because understanding of their determinants is weak. Most IA models use exogenous population scenarios, while a few include demographic accounting modules that allow regional age-specific fertility, mortality, and migration to be specified. Models of social and economic determinants of fertility have been constructed, but these are purely illustrative, as knowledge of these relations remains very weak (53). Future technological change will also strongly influence emissions and the costs of abatement (54, 55). While aggregate technological trends are evident in the long-term record, such as substitution of major primary energy sources and economy-wide decarbonization (56, 57), knowledge of their determinants—and hence of the magnitude and even direction of technology's effect on future emissions—is very limited. Most IA models make exogenous assumptions of technological change, represented as specific technologies including backstops or as economy-wide parameters such as input-output coefficients or autonomous rates of efficiency increase. Attempts to endogenize technological change, through statistically estimated learning-curve effects (58–60) or as functions of investment or fossil energy prices (61, 62), demonstrate that the magnitude of such effects is large, but the foundation for any particular representation remains weak.

3.2 *Representation of the Atmosphere and Oceans*

Any attempt to assess environmental consequences of climate change requires an IA model to represent atmospheric and oceanic processes. Three basic processes must be represented: the carbon cycle, atmospheric chemistry, and climate. The level of detail in a representation of the atmosphere and ocean is a basic design choice for an IA model. Scientifically credible models of atmospheric chemistry and climate impose very large computational burdens, which can limit an IA model's accessibility and use in policy settings as well as the extent of uncertainty analysis that can be conducted. In addition, research and understanding in these areas is rapidly progressing, so IA models that seek to include scientifically current models must decide how to treat disparities among available models.

Moving from carbon emissions to atmospheric concentrations requires a carbon-cycle model to represent how carbon moves among the reservoirs of the atmosphere, the terrestrial biota, and the surface and deep oceans. Approaches of widely varying complexity have been used. The simplest are airborne-fraction models, in which a specified fraction of each year's emissions is retained in the atmosphere indefinitely (29). Most widely used are impulse-response functions that partition emissions into shares, each of which decays exponentially with a distinct lifetime. Such functions can be fitted statistically to results of more detailed carbon-cycle models or to observed historical concentrations and emissions (63–65). Some IA modelers have developed their own simple carbon-cycle models, statistically refitting data series on atmospheric concentrations and historical emissions and land-clearing (45, 66, 67). Various alternative specifications are consistent with the historical record. One IA model has used a more complex carbon cycle (68, 69). The enrichments captured by detailed carbon-cycle models may be important for understanding regional-scale biosphere-atmosphere feedbacks, but their importance for global-scale IA modeling has not yet been determined (70, 71).

Non-CO_2 greenhouse gases react chemically in the atmosphere, so modeling the relationship between emissions and concentrations requires representing atmospheric photochemistry. Some IA models exclude other emissions or represent them in carbon-equivalent terms and do not model their atmospheric fate explicitly. Those that do project non-CO_2 emissions most commonly represent their fate as a fixed global atmospheric lifetime for each species, ignoring nonlinearities, photochemical feedbacks, and dependence on fine-scale processes. IA models that stress spatial detail must represent atmospheric chemistry explicitly. Present IA models have resolved chemically coherent regions such as hemispheres and land vs ocean (72–74). One IA modeling project is sponsoring development of a two-dimensional, land-ocean resolving atmospheric chemistry model.

Changed trace-gas concentrations change climate by altering the atmosphere's radiative properties and hence its temperature distribution. The most detailed representations of these physical processes in the atmosphere are General Circulation Models (GCMs) with coupled oceans, which divide the atmosphere into cells of a few degrees and a dozen-odd vertical layers and calculate numerical approximations to the properties of these cells and the flows of mass and energy between them (75). No IA model uses a full GCM; rather, less computationally demanding reduced-form models are used, which can be calibrated to results of full GCMs or to specified regional climate sensitivities.

The simplest approach, used by many IA models, treats the entire lower atmosphere together. A single equation represents the incremental contribution of each trace gas to radiative forcing and hence to equilibrium global-average temperature change (76, 77). These temperature equations can be scaled to match a specified value of climate sensitivity (e.g. 1.5–4.5°C)—the equilibrium global temperature change from doubled CO_2 concentration—which summarizes assumed effects of feedbacks (e.g. clouds) not captured in such an aggregate representation. Realized temperature change at any time also depends on lags in the system, which many IA models estimate using simple zero or one-dimensional models of ocean-atmosphere heat transfer (78–80). The most spatially detailed IA models include two-dimensional atmosphere-ocean climate models (81, 82).

Calculated global-average temperature can be used directly to estimate global sea-level rise (74, 83). To obtain projections of regional climate change without running a GCM, the most common approach is statistical downscaling, which fits higher-dimension or finer-scale data calculated by a GCM to a latitudinal or global average provided by a simple model (84, 85). Such techniques allow reduced-form models to replicate the behavior of full GCMs quite well. Meaningful studies of ecosystem, agricultural, or other impacts require climate variables specified at finer resolution than GCM grid-cells. Consequently, IA models that pursue spatially detailed impacts must also downscale climate projections from the few-degree grid-cell size typical of GCMs to the roughly half-degree resolution of ecosystem models. Various statistical smoothing techniques are used, which match historically observed local weather patterns to GCM grid-cell averages (86, 87). The validity of GCM results and of these statistical techniques for impact studies is controversial (88–90). Basic problems include uncertainty over whether observed correlations between large- and small-scale climate will persist under changed global climate and the importance in impacts of changes in precipitation, for which GCM projections in many regions differ even in sign, and of extreme events as well as means. In view of these difficulties, many detailed sectoral climate-impact studies have used analog climates derived from other locations, observed extremes, or historical or paleo records, instead of, or in addition to, GCM results (91–93).

3.3 *Representation of the Biosphere*

Changed climate can affect ecosystems, as can changes in atmospheric trace gases directly. While many climate impacts will occur through effects on markets, highly managed ecosystems, or human structures and settlements, some will occur through changes in less-managed ecosystems. Climate change might shift the location or functioning of ecosystem types, affecting human welfare through changes in such environmental services as water retention, productivity, or nutrient cycling or via direct preferences for particular landscapes. Imperfectly understood feedbacks between the atmosphere and either the terrestrial or oceanic biosphere may be important for understanding the entire climate system (94, 95).

While work in modeling terrestrial ecosystems is proceeding rapidly, there is yet no dynamic global model of terrestrial ecosystem response to changes in climate and atmospheric trace gases. Consequently, while biosphere-atmosphere interactions may be key components for understanding climate change, their representation is presently limited by underlying knowledge of ecosystem dynamics. IA models have taken two approaches to this situation. Many ignore ecosystems, treating socioeconomic impacts as direct functions of climate change, as discussed in the next section. A few are incorporating spatially detailed ecosystem models that draw on active, rapidly developing work in terrestrial ecology (68, 69, 96). This work is attempting to represent climate and CO_2 effects on production and nutrient cycling processes of specific plant types; to represent dynamics of ecosystem response; and to introduce stochasticity to the climate dependence of biome types (97–104). While this is a key field in IA modeling, advances here depend on advances in underlying knowledge, and IA models that link climate and ecosystem change to socioeconomic feedbacks and impacts are far from realization.

3.4 *Representation and Valuation of Impacts*

Most IA projects seek to characterize and evaluate the social and economic impacts of climate change. Impacts are likely to be of diverse character, to depend on different aspects of climate, and to require different bodies of knowledge to inform them. Salient impacts may occur through agriculture or forestry, storm damage, sea-level rise or other aspects of coastal management, water management, transport, construction, health, or other sectors. Some may be mediated by changes in unmanaged terrestrial ecosystems, but many likely will not be. All are likely to depend in complex ways on other social and economic trends (e.g. on population and economic growth, consumption patterns, and settlement patterns) and on management changes or adaptive measures taken by individuals, communities, and nations. Impacts may interact or propagate across sectors or regions through economic or other linkages.

To date, the most common approach to representing impacts in IA models has been to avoid all details, linking monetized measures of projected impacts directly to aggregate climate variables. This approach originated with a review of climate-sensitive sectors of the US economy that estimated losses from a 3° equilibrium global temperature change as a 0.25% GNP loss, then judgmentally adjusted upward to 1–2% to reflect cross-sectoral linkages or other overlooked damages (105, 106). Subsequent similar analyses reviewed by the IPCC have yielded estimates of 1–1.5% for industrialized countries and 2–9% for developing countries (107). Many IA models have used such point estimates to calibrate simple (linear or quadratic) climate-damage functions of global temperature change. Such damage functions can be used to calculate the marginal social damage of a unit emission over time (45, 108, 109) or to construct impact-based measures of the relative damage caused by emissions of different gases (110–112). These functions can be enriched by introducing variation between regions or by dependence on time, wealth, or other climate variables such as precipitation or the rate of temperature change. Increasingly, IA models also define separate damage functions for market and nonmarket impacts, which may be driven by different processes and mitigated by different adaptive possibilities.

While it is widely acknowledged that these damage functions are unsatisfactory, they remain widely used because specifying impacts in more detail requires disaggregation that may be limited by underlying process understanding, computational power, and particularly in developing countries, availability of data. Disaggregating specific impacts, particularly in nonmarket sectors, while retaining a common metric for evaluation, has posed severe problems. Even if contingent valuation methods are accepted as measures of present damages, valuing environmental changes over long periods is much more problematic, as memories fade and tastes, behavior, and technology change in unknown ways.

In contrast with the aggregated approach to impacts, many studies have investigated direct impacts of climate change in such sectors as agriculture, sea level, water, biological diversity, and health, and some IA models include a few such first-order sectoral impacts (113–119). The principal challenges to more effectively integrating such studies into IA models are representing adaptive responses and characterizing linkages across sectors and regions to permit aggregation. Adaptation has been studied for agriculture and sea-level rise, more effectively at the level of individual decision makers than of communities or markets (114, 120–122). Impacts have been aggregated across sectors by simple summing (i.e. assuming no cross-sectoral linkages), input-output modeling, and models of general equilibrium and international trade (92, 124; R Mendelsohn & J Neumann, manuscript submitted). Neither of these enrichments has yet adequately been incorporated into IA models. An alternative to aggregating impacts, proposed but not yet implemented, is to present vectors of multiple valued environmental and social consequences. These could be used to define multi-attribute utility functions, to investigate the effect of constraining one consequence on others, or to provide multidimensional output projections to provoke policy debate.

Recent reviews of impact studies are increasingly identifying low-cost adaptation measures, and in some regions off-setting benefits, that reduce or in some cases eliminate estimated market impacts of doubled-CO_2 climate change, particularly in OECD countries (107, 109, 125; R Mendelsohn & J Neumann, manuscript submitted). These results are increasingly directing attention to the less well–studied areas of nonmarket impacts, extreme events, cross-sectoral linkages, and multiple environmental stresses. There is as yet no consensus on the likely magnitude of these impacts, even for the OECD countries. A finding that they are also small would highlight the interregional distributional aspects of climate change.

3.5 *Representation of Responses*

A primary purpose claimed for IA models is to assess potential response options. Potential responses include abatement (reducing emissions), adaptation (reducing the harm caused by a changed climate), and geoengineering (altering the climate system directly to compensate for changes caused by increased emissions). In both policy and assessment, abatement has received the most attention, adaptation less, and geoengineering the least. In principle, IA models may represent any of these forms of response, but to date representation of all forms has been weak. How well each can be represented in a particular IA model depends on the model's representational detail in the corresponding domain: emissions and their socioeconomic determinants for abatement responses, impacts for adaptation responses, and specific elements of the atmosphere or biosphere for geoengineering. Assessing any of these responses is difficult under the long time horizon of climate change, for any response would be undertaken against a background of other changes likely to be large, but whose character and effects cannot be anticipated.

Abatement measures can be represented either as directly specified changes in emissions, population, production, or technology from a baseline case—though this begs the question of what feasible policies might bring about such changes—or as policies such as taxes or other economic measures, regulation, or direct investment intended to effect such changes. Representing either form requires that emissions be modeled with substantial technological or economic detail. IA models have been used to study the effects of broad generic abatement policies, such as national emission caps, economy-wide carbon taxes, or uniform international systems of tradable emission permits, though such studies do not require vertical integration beyond modeling of the determinants of emissions (49, 126). In addition, IA models with regional detail have examined simple bargaining outcomes for international allocation of abatement effort, e.g. comparing globally optimal distributions of abatement with cases in which certain regions abate either less or more than this optimal level. These studies have found large savings from cooperative international abatement, half or more of the cost of abatement through separate regional efforts (108, 127–129).

But the utility of IA models' representation of any specific abatement policies is presently limited by their coarse regional and sectoral resolution; by their inability to represent details of realistic policies and their implementation; by the difficulty of disentangling proposed policy interventions from baseline projections; and by limitations in knowledge about the effects of near-term policy choices on such long-term drivers as rates of investment, research, and technological innovation and diffusion.

Adaptation measures are even more difficult to represent within IA models than abatement, in part because of the diversity of adaptive responses and the agents who undertake them. Most IA models have excluded explicit adaptation, in effect embedding assumed adaptation within impact functions, so explicit adaptive responses cannot be considered. Detailed sectoral impact studies have increasingly included adaptive responses, and IA models have examined adaptation to sea-level rise through large infrastructure investments (32, 92), but in general the representation of adaptive response remains a particularly weak area of IA modeling. Geoengineering measures, which seek to alter aggregate parameters of the climate system such as the earth's albedo or the rate of ocean carbon uptake, may be easier to represent in IA models than either abatement or adaptation. But the assessment of geoengineering measures depends first on detailed process and technical studies of the potential effect, cost, and risks of specific proposed interventions (130–133). IA models may contribute to this assessment by identifying potential feedbacks or impacts and by comparing and studying interactions among multiple forms of policy response.

4. SUMMARY OF INTEGRATED ASSESSMENT PROJECTS

This section summarizes recent and continuing projects in IA modeling, sorting them according to differences in their emphasis and purpose. Section 4.1 summarizes projects that emphasize the characterization of optimal responses to climate change, considering dynamics inherent in economic growth and abatement and in atmospheric accumulation. Section 4.2 summarizes projects that emphasize uncertainty, including some that highlight both dynamic optimization and uncertainty through sequential and adaptive decision formulations. Section 4.3 summarizes projects that emphasize fine spatial detail in the characterization of atmospheric change, impacts, and feedbacks.

Previous attempts to categorize IA models have found it difficult to draw clean boundaries (2, 5, 134), and this scheme is likely to be no exception. Some IA projects incorporate more than one of these aspects to a limited extent or use them in diverse ways; others aspire to provide a sophisticated representation of all these aspects. But given the constraints of resources, underlying knowledge, and computational power, IA models that are simultaneously strong on all these aspects will not be realized soon. We contend that this categorization highlights basic differences in disciplinary heritage and emphasis of IA models—differences that have long-lived effects on the directions of enquiry and the kinds of questions for which each is best suited.

4.1 *Projects that Emphasize Emission Dynamics and Optimization*

One major theme of IA modeling has been investigating alternative paths of global emissions over time, considering their linked effects on economic growth and atmospheric accumulation of greenhouse gases. Several projects have sought to identify dynamically optimal emission paths that balance, over time, the costs of emissions abatement and damages from climate change. Others have assessed differences in abatement cost of broadly different emission paths that meet specified atmospheric-concentration constraints, or they have identified emission corridors that simultaneously meet several constraints on allowed atmospheric change and on maximum rates of emission reduction.

The projects that calculate dynamically optimal emission time paths show several common features that reflect the conceptual and computational requirements of dynamic optimization. They all must postulate a single long-lived representative producer-consumer, either for the world or for each region, on whose behalf the optimization is performed. They all require that abatement costs and climate damages be specified in a common metric and therefore must represent regional or global climate damages by simple aggregate functions of global temperature change. These functions are usually calibrated to Nordhaus's point estimates for equilibrium doubled-CO_2 and are sometimes presented in a few alternative forms. They all require that these costs be comparable over long time horizons, so they require—and typically are highly sensitive to—specification of a discount rate.

Nordhaus presents a dynamically integrated climate-economy model (DICE) that extends his earlier comparative-static analysis of optimal greenhouse abatement (45, 105). A single global producer-consumer chooses between current consumption, investment, and reducing greenhouse emissions, so as to maximize the present value of utility. The basic framework is of a neoclassical optimal-growth model (135), with production losses introduced by emission abatement and climate damages. No energy-sector detail is represented. Rather, an abatement cost function is fitted statistically to the collection of point estimates from prior studies, such that reducing emissions by half from their unconstrained level at any time costs about 1% of output. Simple statistically fitted carbon-cycle and climate models, and a damage function, complete DICE. A fixed fraction of each period's carbon emissions adds to atmospheric concentrations, while realized temperature change is represented by a three-box model including the atmosphere, mixed-layer upper ocean, and deep ocean. Climate damage is a quadratic function of realized temperature, in which a 3° rise reduces output by 1.3%.

DICE has been used to calculate the marginal damage of a ton of carbon emissions over time (equivalent to the optimal emissions tax to impose), to evaluate abatement policies, and to identify optimal emissions time paths. Marginal damages are calculated at a few dollars per ton, rising to $20 per ton over the next century. Optimal emission paths involve only very modest reduction from unconstrained emissions growth, while stabilizing emissions or concentrations is estimated to cost as much as 3–9% of output. Adding uncertainty to the formulation doubles to triples the optimal emission taxes. A regionally disaggregated form of DICE has been developed (129), and a stochastic form is under development.

Two projects sponsored by the Electric Power Research Institute (EPRI) have constructed dynamic-optimization IA models around prior energy-economic models developed by EPRI. Peck & Teisberg have built CETA (Carbon Emissions Trajectory Assessment model), extending the Global 2100 macroeconomic-energy model by adding simple models of the carbon cycle and global-average temperature change, and a damage function (46, 136). Energy CO_2 emissions are modeled by embedding an energy sector with substantial technical detail within the production function, while other emissions follow fixed scenarios similar to the IPCC's. Doubled-CO_2 sensitivity is tuned to 3°, while damage estimates are calibrated to 2% GNP loss from 3° equilibrium temperature change. The model is driven by a single global consumer-producer who maximizes the present value of utility of consumption, net of climate-change damages, over the period from the present to the year 2200.

CETA has been used to study the effects of alternative forms of climate-damage function, including dependence on the rate of global temperature change, as well as uncertainty about climate damages and global cooperation in a two-region world. As in Nordhaus's analysis, estimated emission damages and optimal abatements are small, \$10–\$20 per tonne of carbon, increasing modestly with nonlinear or rate-dependent damages (137). The value of information about damage severity is high relative to current research budgets, but the cost of a 20-year delay in gaining this information is modest (138). A study introducing large stochastic climate losses (139), using subjective expert probabilities, found that optimal abatement was highly sensitive to probability of loss, which natural scientists put an order of magnitude higher than social scientists (140, 141).

MERGE (Model for Evaluating Regional and Global Effects), like CETA, combines a detailed energy-economy model with simple carbon and climate models and a damage function. MERGE uses Global 2200, a five-region dynamic general equilibrium model with a detailed energy sector. New technologies, fossil resource depletion, technological change, and emissions coefficients are specified exogenously. A single agent in each region makes consumption and savings/investment decisions to maximize the present-value of utility of consumption. Energy-related emissions of CO_2, CH_4, and N_2O are modeled, while exogenous scenarios are used for other emissions (48). A simple impulse-response function represents the carbon cycle, while CH_4 and N_2O have fixed atmospheric lifetimes. Radiative forcing functions and a lagged adjustment model for realized global temperature are drawn from the IPCC. Regional temperature change over land is assumed to be equal to the global mean in temperate latitudes and half as large in the tropics. Simple regional damage functions separate market and nonmarket damages. Both are quadratic in temperature, and nonmarket damages also depend on regional income. Policy studies with MERGE, both comparing specified abatement policies and incorporating climate damages into the dynamic optimization, found that delaying abatement was preferable (48, 142). A similar dynamic optimization study by Maddison, assessing specified levels of abatement relative to a baseline emissions scenario drawn from the IPCC and EMF 12, yielded similar results: Optimal abatement levels are small, roughly 10–20% from unconstrained baseline growth paths, with minimal costs to a 20-year delay in implementing controls (66).

These studies stress the dynamics of economic growth and investment and of atmospheric accumulation. Grubb et al report a simple model that instead studies dynamics of technological change, in which abatement cost depends both on the level of abatement and on its rate of change. When the second, adaptive component of abatement cost dominates, they obtain results that contradict the preceding studies: High abatement is preferred even if climate damages are small, and delays of a few decades in starting abatement effort are very costly (55). Hourcade & Chapuis find similar benefits to early abatement activity in a dynamic formulation that combines positive feedbacks in abatement with nonlinear climate damage functions (143).

The arbitrary climate-damage functions used in these dynamic optimization studies have been problematic and contentious (38). An alternative approach replaces these damage functions by environmental constraints, in effect replacing a cost-benefit approach by a cost-effectiveness approach. In this approach, a specified environmental constraint is imposed (e.g. a limit on atmospheric concentrations or temperature in an endpoint year), and the costs of alternative specified emissions trajectories that meet the constraint are calculated or cost-minimizing trajectories are determined. This replacement of a climate-damage function with an atmospheric constraint has different effects on preferred abatement levels in the near and the long term: In the near term, because damages below the constraint are treated as zero, the approach favors smaller abatement effort; but in the long term, because damages above the constraint are treated as infinite, the approach favors larger abatement (144, 145).

Recent applications of this approach have compared the costs of alternative emissions paths to stabilize atmospheric concentrations at specified levels between 350 and 750 ppm, finding that trajectories in which global emissions climb through 2050 and then decline sharply reduce present-value abatement costs by as much as half relative to trajectories with near-term emissions stabilization or reduction. The lower costs reflect four factors—technological change, avoiding premature capital retirement, exploiting natural carbon absorption, and discounting—and optimal trajectories depend strongly on the discount rate (146–148).

An approach that goes further in replacing hypothesized cost functions by constraints is the "safe emissions corridor" approach, which calculates emission trajectories that simultaneously meet several externally specified environmental and economic constraints such as maximum limits on total global temperature increase and its rate and limits on the maximum rate of emission reduction attainable per year (149, 150). The safe emission corridors calculated by these approaches involve larger near-term reductions than either those that calculate dynamically optimal emissions paths or those that impose only environmental constraints in a future year.

4.2 *Projects that Emphasize Uncertainty*

Uncertainty is central to climate change, and many IA modeling projects include it to at least some degree. Indeed, characterizing key policy-relevant uncertainties to help guide inquiry is a central purpose for IA. But rich treatment of uncertainty imposes heavy computational demands, so stronger treatment of uncertainty is associated with weaker dynamics and less spatial detail.

Nearly all IA modeling projects have addressed uncertainty at least to the extent of conducting sensitivity analyses, either on a few key parameters or between discrete clusters of related parameter choices representing broad alternative scenarios. For those projects that make uncertainty central to their analysis, the primary approach has been stochastic simulation with sampling over distributions of many uncertain input parameters. Such sampling generates probability distributions of outputs that reflect both the sensitivity of outputs to particular inputs and the uncertainty in the inputs. Other approaches to uncertainty have included evaluating adaptive decision strategies that can respond to progressive resolution of uncertainty over time, investigating the implications of low-probability climatic catastrophes, and representing uncertainty as subjective, consisting of correlated sets of preferences plus beliefs about uncertain parameters and model structure.

The first probabilistic IA model was PAGE (Policy Analysis of the Greenhouse Effect), in which roughly 80 parameters describing emissions, atmosphere, and impacts were represented by user-definable triangular probability distributions, with uncertainty propagated through the model. Costs of abatement were calculated relative to assumed regional baseline emissions scenarios for four world regions, centered on Europe (151).

The Integrated Climate Assessment Model (ICAM) has been developed within the integrated assessment project of Carnegie Mellon University, using a specialized system for probabilistic modeling (152). ICAM derives regional emissions of CO_2, N_2O, CH_4, and sulfate aerosols from exogenous assumptions by a demographic and economic accounting framework. Simple linear atmospheric models yield concentrations and changes in radiative forcing, while regional impact functions combine direct dependence on regional climatic variables with explicit representation of a few specific impacts, including sea-level rise and changes in terrestrial ecosystems. Certain specific forms of abatement and geoengineering measures can be represented explicitly.

Representation of uncertainty is the central goal of ICAM: Successive versions of the model have included hundreds to thousands of uncertain parameters and some experimentation with sampling over uncertainties in model structure (37, 153, 154). The project has also included various detailed sectoral analyses, which all stress uncertainty but of which only reduced forms are incorporated in

ICAM. These have included analyses of expert judgment of climate uncertainties, stochastic modeling of ecosystem change under climate change, coastal impacts, trace-gas indexes, geoengineering policy, and value-of-information calculations (37, 111, 120, 131, 141). A consistent result of many analyses with ICAM has been that socioeconomic uncertainties and variation in preferences are more important than biophysical uncertainties in determining uncertainty in impacts or preferred policy responses (37, 155).

Tol has presented a nine-region IA model that combines exogenous emission scenarios with moderately detailed endogenous abatement costs and climate damages, including quantified, highly illustrative impacts in particular sectors, defined as functions of temperature change and income—agricultural and coastal effects, flooding, storm damage, deaths from heat stress and malaria, migration, and hurricanes. Optimal regional abatement from baseline emissions is calculated to be modest, with or without global interregional cooperation and financial transfers, while a stochastic simulation with 13 uncertain parameters increases optimal abatement to roughly 10–20% of baseline emissions (156, 157). Other IA projects have conducted stochastic simulations with uncertain inputs, using submodels when the complete IA model is too complex to permit the required replication (158, 159).

As an alternative to stochastic simulation, a decision-analytic approach can be taken to uncertainty, assuming that uncertainties will be resolved at a specified future date. Studies taking this approach combine optimal decision-making and uncertainty. In contrast with the dynamically optimizing analyses discussed in Section 4.1, these studies normally only compare a few near-term policy strategies. In contrast with the stochastic simulation studies discussed in this section, they normally consider only a few key uncertainties. But by combining these two elements, they allow study of adaptive decision strategies that can hedge against uncertainty and respond to new information; how uncertainty alters preferred or optimal policy choices in the near term; and the value of information and the costs of waiting to obtain more information.

Yohe & Wallace sample nine uncertain parameters to develop a set of probabilistic scenarios. With these they examine optimal near-term response to the chance that a binding atmospheric-concentration limit will be revealed in the year 2020. Under a wide variety of scenarios, they find that optimal near-term abatement is small, even if the probability of subsequent imposition of a concentration constraint is high (160).

Hammitt et al present an IA model of two-period sequential choice between two levels of abatement effort, each based on a moderately detailed energy-sector model. Two parameters, climate sensitivity and a global temperature target, are uncertain in the first period but revealed in the second. Damages can be represented either as a function of temperature or by imposing a limit on global temperature change. They find that moderate near-term abatement is preferred under most parameter values, and adding risks of abrupt climate change does not alter the qualitative conclusion (161, 162). A game-theoretic application of the model to a two-region world finds that uncertainty reduces the benefits of cooperation and that delaying action for 20 years can eliminate them (128).

In other uncertainty-based analyses, Kolstad introduced irreversibilities and learning into Nordhaus's DICE model and found that irreversibility of abatement investment, which reduced preferred abatement levels, had a larger effect than environmental irreversibility (163). Chao represented climate damages not as a smooth function but as a temperature-dependent Poisson process generating climatic catastrophes, and found a higher optimal carbon tax but a lower discount rate, yielding an ambiguous aggregate effect (164).

A novel and controversial approach to uncertainty has been presented in the TARGETS project, which is not an IA model of climate change but a broad horizontally integrated IA model of sustainable development that links multiple environmental, social, and economic issues (39). The project has used heuristic representations of uncertainty inspired by the three social types of Cultural Theory (165) to define scenarios that cluster linked subjective beliefs about uncertainties with policy preferences (166). Defining such scenarios can reveal previously unobserved subjectivity in models and provides one solution to the operational problem of handling correlations among many uncertain inputs. But the particular structuring of subjective beliefs employed is arbitrary, absent a better empirical and conceptual foundation for the particular social types employed.

In summary, IA models take diverse approaches to uncertainty. Some combine probability distributions of uncertain inputs or model structures to project distributions of consequences, while others integrate limited uncertainty into optimal choice frameworks. No IA modeling project performs full stochastic dynamic optimization.

4.3 *Projects that Emphasize Spatial Detail*

Several IA models stress the characterization of global climate change at fine spatial scale. This approach tends to emphasize the biophysical over the socioeconomic aspects of climate change. A fine spatial scale allows more explicit treatment of the atmospheric chemistry of multiple emissions and the radiative effect of aerosols, though parameterizations of these are also available at larger scales. This approach also allows explicit treatment of biosphere-atmosphere feedbacks and of multiple linked global-change issues. It allows examination of the spatial variability of impacts, one often-sought component of policy relevance. Finally, it allows linking IA models with global, spatially referenced data sets, principally from remote-sensing but also from field campaigns, increasing the tools available for validating IA models.

The practical obstacles to this approach to IA modeling, however, are severe. Neither the climate nor the ecosystem models used in IA models yet offer either transient or well-validated representations at fine spatial scales. Limits to underlying process knowledge, as well as massive computational demands, have thus far limited spatially disaggregated IA models to illustrative projections, which lack realistic behavior or socioeconomic feedbacks and which admit very limited uncertainty analysis.

The first spatially detailed IA model, ESCAPE, used technically detailed exogenous scenarios of multiple emissions for four world regions centered on Europe. Simple global-scale atmospheric chemistry and climate models calculated global mean temperature and sea-level rise, while regional changes in temperature and precipitation were estimated at fine spatial resolution over Europe through GCM downscaling. Simple illustrative impacts were calculated in six sectors (74, 167).

The first IA model to include some fine spatial detail globally was IMAGE 2, whose three linked systems represented energy and emissions, the terrestrial environment and land cover, and the atmosphere and oceans, each operating at a different scale (168). Emissions are projected for 13 regions by a bottom-up, technologically detailed model with exogenous energy demand and primary fuel prices, which includes fuelwood demand (169). Land cover, soil type, element fluxes, and direct ecosystem impacts are represented on a global half-degree grid. Land cover is modeled at this fine scale through the interaction of four factors: regional agricultural demands derived from simple income-elasticity relationships; the FAO crop-suitability model, which calculates climate-dependent yields, modified by a local soil factor (170); land conversion as required to meet regional food and fuelwood demands, following a few simple heuristic rules to determine which land is converted; and the BIOME model of potential land cover as a function of climate and soil, which determines the cover of abandoned agricultural land (171). Emissions are calculated from land use and conversion, including climate and CO_2 fertilization feedbacks. Land cover interacts with the atmosphere via emissions and changes in albedo (172). The globally parameterized atmospheric chemistry model and climate-ocean model calculate annual-average temperature and precipitation change for 10° latitude bands, plus ocean circulation and transport of heat and CO_2. Calculated climate over latitude bands is translated to grid-scale by GCM downscaling (72, 81).

The model has been calibrated to reasonably good agreement on 1970–1990 data for regional energy and emissions, deforestation, and atmospheric concentrations. Prospective runs have contrasted a conventional wisdom scenario (similar to the IPCC's IS92a) with three discrete alternatives intended to yield instructively divergent land-use patterns: two that assume very high and very low use, respectively, of modern biofuels; and one that postulates a large shift in ocean circulation (173). The project's detailed treatment of land cover has allowed detailed investigation of direct climate-change impacts and of the effects of large-scale biomass-energy and afforestation responses (133, 174). Its lack of realistic representation of behavior, however, makes it unsuitable for valuing the effects of abatement or impacts or for estimating the emissions effect of other policy instruments.

Three other current IA modeling projects incorporate moderate to high levels of spatial detail. A project at the Massachusetts Institute of Technology has been developing a large IA model with fine spatial detail since 1991. Multiple emissions, including aerosols, are modeled by a dynamic computable general equilibrium (CGE) model that includes 13 sectors and 12 world regions. Technical change is represented through exogenous changes in input-output coefficients and specified backstop technologies (175–177). Newly developed two-dimensional, land-ocean resolving linked chemistry and climate models represent the atmosphere and calculate average temperature, precipitation, cloudiness, and humidity for 23 latitude bands (82, 158). Ecosystems are represented by the Terrestrial Ecosystems Model (TEM), a process-based model that calculates net primary production and nitrogen cycling at half-degree resolution, as functions of changed climate, CO_2 concentration, and nutrient deposition (96, 101). Global models of methane and nitrous oxide flux from natural ecosystems have also been developed, while representations of managed ecosystems, human land use, and impacts are under development.

PGCAM is a spatially detailed IA model under development by Battelle Pacific Northwest National Laboratories, the University Corporation for Atmospheric Research, and Texas A&M University (178). Emissions are represented by a set of computable general-equilibrium models for 13 world regions, developed in collaboration with regional researchers. These models provide substantial technical detail in the energy sectors and vintaged capital stocks, so they permit fairly detailed modeling of policies that influence technological development or investment (179). Land-use emissions are estimated by models that allocate regional land among an unmanaged state and several competing uses, based on prices of biomass energy and agricultural products (51). The MAGICC and SCENGEN models represent atmospheric chemistry and climate, projecting global changes in temperature and sea level and using GCM downscaling to project regional temperature and precipitation at half-degree detail over selected high-resolution windows (presently North America and Europe), and 5° elsewhere (73, 74). Impacts will be projected, first for North America, using the BIOME model for unmanaged ecosystems, and detailed agricultural crop and hydrology models for managed ecosystems (171).

The Asian-Pacific Integrated Model (AIM) is being developed collaboratively by nine institutions in five countries, coordinated by Japan's National Institute of Environmental Studies (180, 181). AIM is designed to investigate regional mitigation and adaptation strategies for the Asia-Pacific region. Emissions of major greenhouse gases and aerosols from energy and deforestation are represented through technologically detailed bottom-up national models for five Asian nations, linked by a global model that maintains equilibrium and represents emissions from the rest of the world. Simple global carbon-cycle and climate models are used, with statistical downscaling to a half-degree spatial scale for the Asia-Pacific region. Sectoral impacts are projected for hydrology, agricultural production, natural ecosystems, and malaria, at fine spatial scale, and integrated with other data sets using a Geographic Information System.

5. RESULTS AND INSIGHTS FROM INTEGRATED ASSESSMENT MODELS

Despite its rapid growth, IA modeling is at an early stage of development, so the significant insights to emerge from it so far are few and tentative. Different kinds of projects permit different kinds of insights. For example, identifying key uncertainties requires rich specification and propagation of uncertainty, while examining alternative international bargaining solutions requires adequate regional resolution and policy detail.

All IA modeling projects have stressed qualitative insights over quantitative predictions, suggesting that these are more robust to uncertainty and hence more persuasive (2, 5). This difference is one of degree, though, not of kind. Qualitative insights depend on underlying quantitative predictions and can be rendered invalid by erroneous underlying assumptions (36, 38). Confirmation by multiple IA models does not eliminate this risk if the models share the relevant assumptions. Claimed insights of IA models should consequently be regarded as consequences of particular assumptions, and both the reasonableness of the assumptions and the possibility of corroboration through dissimilar means should be explicitly considered. It has been argued that contributions of IA models should be evaluated by several criteria: not just the persuasiveness and novelty of the insights, but their robustness, their specificity, and the extent to which the IA model was needed to obtain them (182).

The specific insights that have been claimed from IA models include, first, a cluster of related results that all appear to demonstrate that large near-term abatement is not justified (182). These include results showing that economic climate-change impacts in rich (though not in poor) countries will be small and that ecosystem effects from climate change, agricultural management, and urbanization are all of similar magnitude (2, 125; R Mendelsohn & J Neumann, manuscript submitted); cost-benefit results showing that optimal abatement involves reductions of only a few percent from unconstrained paths, which can be accomplished by carbon taxes of a few dollars per tonne and achieve gains on the order of 1% of world product (45, 48, 183, 184); and the result, obtained from adaptive decision models and from cost-effectiveness analyses of future concentration constraints, that delays of a few decades in controlling emissions are preferred even if we later learn that stringent reductions are needed (146, 147, 160, 161).

These results depend on several levels of assumptions. The analyses showing small climate impacts in rich countries increasingly do incorporate uncertainty, though not low-probability events. More importantly, they are all based on reference doubled-CO_2 scenarios and hence do not admit the highest levels of trace-gas concentrations that aggressive fossil-fuel growth scenarios would generate by late next century. IA models have so far provided no insights on the implications of such scenarios, because they drive atmospheric, ecosystem, and impacts models far out of their validated ranges. These impact results are also based on weak representation of nonmarket impacts, cross-sectoral linkages of impacts, and interactions of multiple environmental stresses such as climate and air pollution. Better consideration of such interactions would likely increase projected impacts, but present IA models offer no insight into whether this increase would be large enough to change the qualitative conclusion and justify more stringent abatement. That climate impacts will be higher in poor countries depends on assumptions of less wealth and infrastructure, which obstruct the adaptation responses largely responsible for estimated rich-country impacts being small. Together, these two results imply that climate is fundamentally a problem of interregional distribution of wealth.

The cost-benefit result that optimal OECD abatement is small depends on the impact results summarized above and their associated assumptions, and also on assumptions that shape the unconstrained path of future emissions (e.g. population and economic growth and technological change, in particular the continuing extent of autonomous decarbonization trends), the cost of abatement, fossil resources, and the basis for balancing costs and benefits, in particular the social discount rate. Plausible alternative formulations of technological change strongly reduce abatement costs and hence shape optimal emission paths (54, 55, 143), though technical change can also increase future emissions (61, 160), while optimal abatement is greatly increased in all formulations by assuming low or zero social discount rates (though such rates would imply high rates of saving that we do not presently observe) (185–187).

The result that it is preferable to delay abatement even if it is ultimately to be done again depends partly on the same assumptions, plus two linked additional ones: that the value of information to be obtained by waiting is high and that the expected cost of waiting to obtain it is low. These are fairly restrictive assumptions about the dynamics of technological change and policy. They presume that the most important uncertainties are scientific rather than economic or social, a presumption at odds with a major claimed insight from uncertainty-based IA modeling (37, 160). They presume that significant resolution of these uncertainties in a few decades is likely and hence that "research" means something other than undertaking immediate abatement activity to climb up technological learning curves (contrast 188); and that positive returns, lock-ins, and learning effects are not dominant in the economy or in policy-making, so large abatement after several decades is consistent with little or none in the near term. If different assumptions hold, then optimal emission paths might rise less and fall sooner, or paths that rise then fall abruptly might be consistent with, or even require, substantial near-term commitment to abatement in the form of research, investment, and policy.

Several other diverse insights have been claimed from IA models to date. One that may be obvious, but which all IA models that have examined the question confirm, is that OECD abatement alone cannot sustain reasonable limits on atmospheric concentrations because global cooperation is required. While back-of-envelope calculations of regional emission growth rates generate the same result, IA models have also permitted calculation of the magnitude of benefits available from various levels and forms of international cooperation.

IA models have elaborated the importance of sulfate aerosols in climate change. While the magnitude of aerosol contributions to radiative forcing can be calculated from atmospheric models alone, identifying their implications for abatement strategies requires detail about spatial patterns of aerosol sources and how economic growth, fuel switching, technological change, and policy will affect them. Similarly, IA models have provided preliminary characterization of the effects of linked demographic, economic, and climatic pressures on land cover, with attendant atmospheric feedbacks; further elaboration of these patterns will require further integrated analyses.

Contributions from IA models can take the form of identification of key uncertainties or research priorities, rather than specific results. These may be particularly significant when IA projects combine models with other forms of analyses. While large uncertainties are present in every component of climate change, one striking result has been that socioeconomic uncertainties—including economic structure, technological change, and social values—contribute more strongly to uncertainties in impacts and in preferred responses than do biophysical uncertainties (21, 37, 155, 160, 189).

6. EVALUATION AND CONCLUSIONS

In conclusion, we review the contributions of IA modeling to date relative to the four purposes stated in Section 2. We then identify a few prominent challenges facing the field, with particular reference to the dual relationships of IA modeling to research and to broader processes of assessment and policy-making.

Four potential contributions have been claimed for IA models: evaluating policies and responses, structuring knowledge and prioritizing uncertainties, contributing to basic knowledge of the whole climate system, and broad comparative risk assessment. We consider these in turn. First, as Section 5 outlines, several important insights relevant to evaluating responses have been drawn from IA models. These have not addressed specific policies but have more broadly characterized generic responses. IA models appear unsuitable for evaluating highly specific policies, as their representations lack necessary sectoral, institutional, and political detail.

A few of these claimed insights, while contentious, have made real contributions to policy debate. That they depend on specific, restrictive assumptions does not negate this contribution, for clarifying these relationships can and has advanced both the agenda for IA investigation (e.g. highlighting the importance of further study of nonmarket effects and linkages) and the relative contributions of different assumptions and political values in associated policy debates (e.g. in controversies provoked by the large savings apparently available from flexibility in the location and timing of abatement effort). The IA models that have claimed these policy-relevant insights, though, have been those that are rich and detailed, if anywhere, in their representation of economies and market impacts, and not in ecosystems, nonmarket impacts, or linkages. Their claims of small impacts and the preferability of modest and delayed abatement should consequently not be taken as definitive, but should focus investigation on these less-understood domains.

Second, IA models have made large contributions to structuring knowledge and identifying uncertainty, principally because the attempt to construct IA models has revealed how extreme and pervasive uncertainties are in every domain of the climate issue. This may be the complement of the more modest contributions IA models have made thus far to evaluating responses: When the gains available from identifying and characterizing uncertainties are large, it may be premature to seek specific policy advice.

The most important component uncertainties for controlling whole-system behavior or for guiding policy and decision might be neither the most important for intrinsic understanding nor the largest in magnitude. Particular IA models have reported rank orderings of specific uncertainties, but these typically depend on the formulation of the model. Indeed, the primary work identifying and investigating uncertainties within particular domains remains the job of disciplinary research, not IA modeling.

As with evaluating responses, IA models' contributions to understanding uncertainties have been, and are likely to remain, at more synoptic scale. IA models are particularly valuable for comparing broad uncertainties across subdomains of the climate issue—comparisons that are necessary for understanding whole-system behavior, valued outcomes, and decisions, but that disciplinary investigations are not motivated or equipped to make. For example, the emerging result that socioeconomic uncertainties dominate biophysical uncertainties in contributing to uncertainty in impacts and preferred responses, if further corroborated, may be an insight of key importance. When decisions must be made under substantial uncertainty, the structuring of available knowledge and ignorance can also be an important, more direct contribution of IA models to policy.

Third, IA models have offered some preliminary contributions to basic knowledge, particularly in characterizing linked socioeconomic and environmental pressures on land cover, and associated feedbacks. But these insights are highly preliminary and depend strongly on advances in extremely incomplete, rapidly developing disciplinary knowledge. While better characterization of these links and feedbacks remains a central goal of both IA modeling and associated disciplinary work, the great majority of this work remains to be acomplished.

Finally, IA models have thus far contributed very little to broad comparative risk assessment. This purpose addresses the most basic policy question: How important is climate change, and for whom, relative to other competing concerns? Significant contributions here would depend on IA models providing consistent comparative representations of multiple trends and issues, and linkages between them, over the relevant periods. This requires very broad horizontal integration rather than precision. IA models with broad horizontal integration could contribute to this task, and it is worth pursuing, but work to date is highly preliminary. Of the four purposes of IA models, this one may most compellingly require that IA models be embedded in broader, more deliberative assessment processes, for while IA models may plausibly contribute to the identification of substantive linkages across multiple environmental issues, it is unlikely that they can contribute to a useful debate about broad priorities in social goals and multiple risks without broader inputs.

For each of these four areas, the contributions of IA models have largely come from models whose particular emphasis and design highlight relevant dimensions—optimal or adaptive decision-making, uncertainty, spatial detail, and horizontal integration, respectively.

At the broadest level, IA modeling faces two challenges: managing its relationship to research and disciplinary knowledge and managing its relationship to other assessment processes and to policy-making. In its relationship with disciplinary knowledge, IA modeling's two challenges are to define appropriate intellectual standards for integrating activity and to balance attempts at integration with advances in component knowledge. IA models supplement and depend on disciplinary inquiry but do not supersede or replace it (36, 38). Consequently, IA results are limited by weaknesses in underlying knowledge. But the attempt to integrate can both challenge and serve the constituent disciplines, both in identifying priority investigations for broader understanding and in clarifying the uncertainties, weaknesses, and limits of pieces of constituent knowledge (35). Serving these purposes inverts the conventional argument that integrated modeling should await adequate understanding in all constituent domains, by requiring that integration attempts proceed ahead of underlying knowledge. Indeed, IA models may make contributions of different kinds depending on their relationship to current knowledge, and it has been persuasively argued that waiting for all component science to be done minimizes the contribution of integrating models (27). Proceeding iteratively between aggregate integrating studies and component disciplinary studies may advance knowledge faster, while also advancing policy relevance. This is likely true of integrated modeling and of other processes of integrated assessment; both qualitative and quantitative approaches to integration can serve in this iterative process.

The direct contributions of IA modeling projects to policy so far have been limited. The difficulties are not surprising and reveal no particular fault of IA modelers. Long-known difficulties continue to obstruct attempts to provide useful scientifically grounded advice to policy-making: failure to converge on the set of things that analysts can assert and policymakers care about; reasonable skepticism about specific claims when limited means are available to engage underlying analyses; and results that are too complex to be accessible or are ineffectively communicated. These difficulties have prompted interest in developing very simple, reduced-form IA models that can be operated in real time by nonexperts, some of them free-standing and some developed in parallel with, or embedding key insights from, more extensive IA modeling projects (41, 190). These may serve a useful didactic function for specific and well-founded insights but are not likely fully to solve the problems of nontransparency or eliminate risks of misunderstanding, hidden assumptions, or bias. For real policy advice, even simple models are likely to require mediation and interpretation (1).

IA modeling is not, and cannot be, all of assessment. There are fundamental limits to any assessment method based entirely (or nearly so) on representation. IA models can contribute best to assessment when embedded in broader assessment processes that introduce more deliberation, criticism, diversity of views, and common sense. When relevant constituent knowledge is highly complex, linked across multiple domains, and uncertain, IA models may be essential in such processes, or nearly so, but they cannot be sufficient. IA models cannot identify what questions to ask; what kinds of responses, risks, or linkages to consider; or make broad evaluative judgements, though they may be able to make valuable contributions to any of these discussions. The use of IA models in the second round of the IPCC was a promising, though limited, start. Their structuring role could be expanded in subsequent IPCC assessments. There may also be substantial promise to developing novel process-based methods such as simulations or policy exercises that embed IA tools or models, and other forms of expert knowledge, into broader processes for investigating options, clarifying values, identifying contingencies, or teaching (7, 8, 191). As with the connection of IA models to underlying knowledge, the longer-term use of IA models in advising policy will likely involve repeated iterations in which IA models serve as one mediating device in the exchange between policy and scientific domains over time.

Beyond these broad challenges, several acute weaknesses particularly limit the policy contributions of IA models at present. While these largely reflect underlying weaknesses in knowledge or data, they make IA models unable now, and perhaps for some time, to advise certain specific high-priority concerns of policy-makers. These include limited understanding of impacts and adaptation; weak or nonexistent representation of social and behavioral processes in developing countries; and extremely limited treatment of major low-probability climatic change.

Despite these current weaknesses and long-term challenges, integrated assessment is necessary for responsible, informed policy-making on issues of global environmental change, and integrated assessment models are likely to play an increasing, perhaps essential, role in broader processes of integrated assessment. IA models can also make important contributions to the development of underlying knowledge. The field is progressing and can make substantial contributions if it avoids misunderstanding or overpromising what it can deliver. Continued diverse activities, in multiple projects with diverse substantive and methodological emphases, with continued attempts to develop appropriately ecumenical but intellectually demanding professional and methodological standards, promise the most useful contribution. Early attempts to bring closure on a single focus, method, or approach should be resisted.

ACKNOWLEDGMENTS

Work on this paper was partially supported by the United States Department of Energy under award No. DE-FG-02-ER-61941 (Parson), by the National Science Foundation through the Harvard University Global Environmental Assessment Project (Fisher-Vanden), and by CIESIN, which also granted permission to revise some material from an earlier review published on their Web site at http://sedac.ciesin.org/mva/iamcc.tg/TGHP.html. Valuable comments on earlier forms of this review were provided by Hadi Dowlatabadi, Henry Jacoby, James Hammitt, Milind Kandlikar, Granger Morgan, Tom Parris, John Robinson, Jan Rotmans, Earl Saxon, Marjolein van Asselt, John Weyant, and four anonymous reviewers. These contributions are gratefully acknowledged.

Literature Cited

1. Parson EA. 1995. Integrated assessment and environmental policy-making: in pursuit of usefulness. *Energy Policy* 23(Apr./May):463–75
2. Weyant J, Davidson O, Dowlatabadi H, Edmonds J, Grubb M, et al. 1996. Integrated assessment of climate change: an overview and comparison of approaches and results. In *Climate Change 1995: Economic and Social Dimensions of Climate Change*, ed. JP Bruce, H Lee, EF Haites. Contrib. Work. Group III to 2nd Assess. Rep. IPCC. Cambridge, UK: Cambridge Univ. Press
3. Brooks H. 1985. Technology assessment and environmental impact assessment. In *Conference Papers, US-China Conference on Science Policy, 1983,* pp. 105–22. Washington, DC: Natl. Acad. Press
4. Porter AL, Rossini FA, Carpenter SR, Roper AT, eds. 1980. *A Guidebook for Technology Assessment and Impact Analysis.* New York: Elsevier-North Holland
5. Rotmans J, Dowlatabadi H. 1998. Integrated assessment of climate change: evaluation of models and other methods. In *Human Choice and Climate Change,* Vol. 3, ed. S Rayner, E Malone. Columbus, OH: Battelle Press. In press
6. Shackley S, Wynne B. 1995. Integrating knowledges for climate change, pyramids, nets and uncertainties. *Glob. Environ. Change* 5(2):113–26
7. Brewer GD. 1986. Methods for synthesis: policy exercises. In *Sustainable Development of the Biosphere*, ed. WC Clark, RE Munn, pp. 455–73. Cambridge: Cambridge Univ. Press
8. Parson EA. 1997. Informing global environmental policy-making: a plea for new methods of assessment and synthesis. *Environ. Modeling Assess.* 2(2): In press
9. Grobecker AJ, Coroniti SC, Cannon RH Jr. 1974. *The Report of Findings: The Effects of Stratospheric Pollution by Aircraft. DOT-TST-75-50.* US Dep. Trans. Clim. Impact Assess. Prog. Springfield, VA: Natl. Tech. Info. Serv.
10. Glantz MH, Robinson J, Krenz ME. 1985. Recent assessments. In *Climate Impact Assessment: Studies of the Interaction of Climate and Society*, ed. RW Kates, JH Ausubel, M Berberian. SCOPE 27. Int. Counc. Sci. Unions. Chichester, UK: Wiley
11. Clark W, ed. 1982. *Carbon Dioxide Review: 1982.* New York: Cambridge Univ. Press
12. US National Research Council. 1979. *Carbon Dioxide and Climate: A Scientific Assessment.* Washington, DC: Natl. Acad. Press
13. Carbon Dioxide Effects Research and Assessment Program. 1980. *Workshop on Environmental and Societal Consequences of a Possible CO_2-Induced Climate Change. Rep. Workshop Am. Assoc. Advance. Sci.,* US Dep. Energy, Annapolis, MD
14. Deleted in proof
15. Forrester JW. 1971. *World Dynamics.* Cambridge, MA: Wright-Allen
16. Mesarovic MD, Pestel E. 1974. *Mankind at the Turning Point.* New York: EP Dutton
17. Meadows D, Richardson J, Bruckmann G. 1982. *Groping in the Dark: The First Decade of Global Modeling.* Chichester: Wiley
18. Greenberger M, Crenson MA, Crissey BL. 1976. *Models in the Policy Process: Public Decision Making in the Computer Era.* New York: Russell Sage Found.
19. Greenberger M, Brewer GD, Hogan WW, Russell M. 1983. *Caught Unawares: The Energy Decade in Retrospect.*

Cambridge, MA: Ballinger
20. Edmonds J, Reilly JM. 1985. *Global Energy: Assessing the Future.* New York: Oxford Univ. Press
21. Nordhaus WD, Yohe GW. 1983. Future carbon dioxide emissions from fossil fuels. In *Changing Climate.* Carbon Dioxide Assess. Comm. Washington, DC: Natl. Acad. Press
22. Wolf H, Anderer J, McDonald A, Nakicenovic N. 1981. *Energy in a Finite World: Paths to a Sustainable Future. Rep. Energy Syst. Prog. Group, IIASA.* Cambridge, MA: Ballinger
23. Manne AS, Richels RG. 1990. CO_2 emission limits: an economic cost analysis for the USA. *Energy J.* 11(Apr.):51–85
24. Alcamo J, Shaw R, Hordijk L, eds. 1990. *The RAINS Model of Acidification: Science and Strategies in Europe.* Dordrecht: Kluwer
25. Levy MA. 1995. International cooperation to combat acid rain. In *Green Globe Yearbook 1995,* pp. 59–68. Oxford: Oxford Univ. Press
26. Hordijk L. 1995. Integrated assessment models as a basis for air pollution negotiations. *Water Air Soil Pollut.* 85:249–60
27. Rubin ES, Lave LB, Morgan MG. 1992. Keeping climate research relevant. *Issues Sci. Technol.* 8(2):47–55
28. Gough CA, Bailey PD, Biewald B, Kuylenstierna JCI, Chadwick MJ. 1994. Environmentally targeted objectives for reducing acidification in Europe. *Energy Policy* 22(12):1055–66
29. Mintzer IS. 1987. *A Matter of Degrees: The Potential for Controlling the Greenhouse Effect.* Washington, DC: World Resourc. Inst.
30. US Environmental Protection Agency. 1989. *Policy Options for Stabilizing Global Climate. Draft Rep. to Congress,* ed. DA Lashof, DA Tirpak. Washington, DC: US EPA Off. Policy Plan. Eval.
31. Rotmans J. 1990. *IMAGE: An Integrated Model to Assess the Greenhouse Effect.* Dordrecht: Kluwer
32. den Elzen MGJ, Rotmans J. 1992. The socio-economic impact of sea-level rise on the Netherlands: a study of possible scenarios. *Clim. Change* 20:169–95
33. Intergovernmental Panel on Climate Change. 1991. *Climate Change: The IPCC Response Strategies.* Washington, DC: Island
34. van der Sluijs JP. 1996. Integrated assessment models and the management of uncertainties. *IIASA Work. Pap. WP-96-119.* Laxenburg, Austria: Int. Inst. Appl. Syst. Anal.
35. Toth FL. 1995. Practice and progress in integrated assessments of climate change: a workshop overview. *Energy Policy* 23(Apr./May):253–67
36. Parson EA. 1996. Three dilemmas in the integrated assessment of climate change. *Clim. Change* 34(3-4):315–26
37. Morgan MG, Dowlatabadi H. 1996. Learning from integrated assessment. *Clim. Change* 34(3-4):337(32)
38. Risbey J, Kandlikar M, Patwardhan A. 1996. Assessing integrated assessments. *Clim. Change* 34(3-4):369–95
39. Rotmans J, van Asselt MBA, de Bruin AJ, den Elzen MGJ, de Greef J, et al. 1994. *Global Change and Sustainable Development: A Modelling Perspective for the Next Decade. RIVM Rep. 461502004,* Natl. Inst. Public Health Environ. Protection. Bilthoven, The Netherlands
40. Groffman PM, Likens GE, eds. 1994. *Integrated Regional Models: Interactions Between Humans and Their Environment.* New York: Chapman Hall
41. Raskin P, Heaps C, Sieber J, Pontius G. 1996. *PoleStar System Manual. PoleStar Ser. Rep. 2.* Boston: Stockholm Environ. Inst.
42. Alcamo J, Bouwman A, Edmonds J, Grubler A, Morita T, Sugandhy A. 1995. An evaluation of the IPCC IS92 emission scenarios. In *Climate Change 1994,* ed. JT Houghton, LG Meira Filho, J Bruce, H Lee, BA Callander, E Haites, N Harris, K Maskell, pp. 247–304. Cambridge: Cambridge Univ. Press
43. Grubler A. 1994. A comparison of global and regional energy emission scenarios. *Work. Pap. WP-94-132.* Laxenburg, Austria: Int. Inst. Appl. Syst. Anal.
44. Leggett J, Pepper WJ, Swart RJ, Edmonds JE, Meira Filho LG, et al. 1992. Emission scenarios for the IPCC: an update. In *Climate Change 1992: The Supplementary Report to the IPCC Assessment,* ed. JT Houghton, BA Callander, SK Varney, pp. 69–96. Cambridge: Cambridge Univ. Press
45. Nordhaus WD. 1994. *Managing the Global Commons: The Economics of Climate Change.* Cambridge, MA: MIT Press
46. Manne AS, Richels RG. 1992. *Buying Greenhouse Insurance: The Economic Costs of CO_2 Emission Limits.* Cambridge, MA: MIT Press
47. Jorgenson DW, Wilcoxen PJ. 1991. Reducing US carbon dioxide emissions: the cost of different goals. In *Energy, Growth, and the Environment,* ed. JR Moronoy. Greenwich, CT: JAI

48. Manne AS, Mendelsohn R, Richels RG. 1993. MERGE: a model for evaluating regional and global effects of GHG reduction policies. *Energy Policy* 23(1):17–34
49. Gaskins DW, Weyant JP. 1993. Model comparisons of the costs of reducing CO_2 emissions. *Am. Econ. Rev., Pap. Proc.* 83(May):318–23
50. Zuidema G, Van Den Born GJ, Alcamo J, Kreileman GJJ. 1994. Simulating changes in global land cover as affected by economic and climatic factors. *Water Air Soil Pollut.* 76(1-2):163-98
51. Edmonds JA, Wise M, Sands R, Brown R, Kheshgi H. 1996. *Agriculture, Land-Use, and Commercial Biomass Energy: A Preliminary Integrated Analysis of the Potential Role of Biomass Energy for Reducing Future Greenhouse Related Emissions, PNNL-11155*. Washington, DC: Battelle Pac. Northwest Lab.
52. Turner BL, Skole D, Sanderson S, Fischer G, Fresco L, Leemans R. 1995. *Land Use and Land-Cover Change: Science/Research Plan. IGBP Rep. 35, HDP Rep. 7*. Stockholm: Int. Geosphere-Biosphere Prog./Human Dimensions Glob. Environ. Change Prog.
53. van Asselt MBA, et al. 1994. *Fertility Change: A Global Integrated Perspective. Rep. 461502008,* RIVM (Natl. Inst. Public Health Environ.), Bilthoven, The Netherlands
54. Edmonds JA, Wise MA, MacCracken CN. 1994. *Advanced Energy Technologies and Climate Change: An Analysis Using the Global Change Assessment Model (GCAM).* Glob. Stud. Prog. Battelle Pac. Northwest Natl. Lab.
55. Grubb M, Chapuis T, Duong MH. 1995. The economics of changing course: implications of adaptability and inertia for optimal climate policy. *Energy Policy* 23(4/5):417–32
56. Nakicenovic N. 1996. Freeing energy from carbon. *Daedalus* 125(3):95–112
57. Ausubel JH. 1995. Technical progress and climate change. *Energy Policy* 23(4/5):411–16
58. de Vries B, van den Wijngaart R. 1995. *The TARGETS/IMAGE Energy (TIME) 1.0 Model. RIVM Rep. 461502016,* RIVM (Natl. Inst. Public Health Environ.), Bilthoven, The Netherlands
59. Messner S. 1995. *Endogenizing Technological Learning in an Energy Systems Model. WP-95-114*. Laxenburg, Austria: Int. Inst. Appl. Syst. Anal.
60. World Energy Council/Int. Inst. Appl. Syst. Anal. (WEC/IIASA). 1995. *Global Energy Perspectives to 2050 and Beyond.* London: World Energy Counc.
61. Hogan WW, Jorgenson DW. 1991. Productivity trends and the cost of reducing CO_2 emissions. *Energy J.* 12(1):67–85
62. Jorgenson DW, Fraumeni BM. 1981. Relative prices and technical change. In *Modeling and Measuring Natural Resources Substitution*, ed. ER Berndt, B Field. Cambridge, MA: MIT Press
63. Maier-reimer E, Hasselmann K. 1987. Transport and storage of CO_2 in the ocean: an inorganic ocean-circulation carbon cycle model. *Clim. Dynam.* 2:63–90
64. Siegenthaler U, Oeschger H. 1987. Biospheric CO_2 emissions during the past 200 years reconstructed by deconvolution of ice-core data. *Tellus* 39:140–54
65. Wigley TML. 1993. Balancing the carbon budget: implications for projections of future carbon dioxide concentration changes. *Tellus B* 45(5):409–25
66. Maddison D. 1995. A cost-benefit analysis of slowing climate change. *Energy Policy* 23(4/5):337–46
67. Tol RSJ. 1996. *A decision-analytic treatise of the enhanced greenhouse effect.* PhD thesis. Free Univ., Amsterdam
68. Klein Goldewijk K, Van Minnen JG, Kreileman GJJ, Vloedbeld M, Leemans R. 1994. Simulating the carbon flux between the terrestrial environment and the atmosphere. *Water Air Soil Pollut.* 76(12):199–230
69. van Minnen JG, Klein Goldewijk K, Leemans R. 1996. The importance of feedback processes and vegetation transition in the terrestrial carbon cycle. *J. Biogeogr.* 22:805–14
70. Schimel D, Alves D, Enting I, Heimann M, Joos F, et al. 1996. Radiative forcing of climate. See Ref. 192, pp. 65–131
71. Wigley TML. 1994. How important are carbon cycle uncertainties? In *Climate Change and the Agenda for Research,* ed. T Hanisch. Boulder, CO: Westview
72. Krol MS, van der Woerd HJ. 1994. Atmospheric composition calculations for evaluation of climate scenarios. *Water Air Soil Pollut.* 76(1–2):259–81
73. Wigley TML. 1994. *MAGICC: User's Guide and Scientific Reference Manual.* Norwich, UK: Clim. Res. Unit, Univ. East Anglia
74. Hulme M, Raper SCB, Wigley TML. 1995. An integrated framework to address climate change (ESCAPE), and further developments of the global and regional climate modules (MAGICC). *Energy Policy* 23(4/5):347–56

75. Henderson-Sellers A, McGuffie K. 1990. *A Climate Modelling Primer.* Chichester, UK: Wiley
76. Ramanathan V, Cicerone RJ, Singh HB, Kiehl JT. 1985. Trace gas trends and their potential role in climate change. *J. Geophys. Res.* 90:5547–66
77. Dickinson RE, Cicerone RJ. 1986. Future global warming from atmospheric trace gases. *Nature* 319:109–15
78. Shine KP, Derwent RG, Wuebbles DJ, Morcrette J-J. 1990. Radiative forcing of climate. In *Climate Change: The IPCC Scientific Assessment,* ed. JT Houghton, GJ Jenkins, JJ Ephraums, pp. 49–68. Cambridge: Cambridge Univ. Press
79. Schneider SH, Thompson SL. 1981. Atmospheric CO_2 and climate: importance of the transient response. *J. Geophys. Res.* 86(C4):3135–47
80. Schlesinger ME, Jiang X. 1990. Simple model representation of atmosphere-ocean GCMs and estimation of the time scale of CO_2-induced climate change. *J. Clim.* 3:1297–315
81. de Haan BJ, Jonas M, Klepper O, Krabec J, Krol MS, Olendrzynski K. 1994. A linked dynamic atmosphere-ocean model for assessing climate policies. *Water Air Soil Pollut.* 76(1–2):283–318
82. Sokolov AP, Stone PH. 1995. *Description and Validation of the MIT Version of the Giss 2-D Model. Rep. No. 2,* Jt. Prog. Sci. Policy Glob. Change, MIT, Cambridge, MA
83. Wigley TML, Holt T, Raper SCB. 1991. *STUGE: An Interactive Greenhouse Model. User's Manual.* Norwich, UK: Clim. Res. Unit
84. Santer BD, Wigley TML, Schlesinger ME, Mitchell JFB. 1990. *Developing Climate Scenarios from Equilibrium GCM Results, Rep. 47.* Max Planck Inst. Meteorol., Hamburg
85. Hulme M, Zhao Z-C, Jiang T. 1994. Recent and future climate changes in East Asia. *Int. J. Clim.* 14:637–58
86. Giorgi F, Mearns LO. 1991. Approaches to the simulation of regional climate change: a review. *Rev. Geophys.* 29(2):191–216
87. Carter TR, Parry ML, Harasawa H, Nishioka S. 1994. *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations. Special Rep. CGER-1015-94.* Work. Group II, IPCC, Geneva
88. Gates WL, Henderson-Sellers A, Boer GJ, Folland CK, Kitoh A, et al. 1996. Climate models—evaluation. See Ref. 192, pp. 229–84
89. Henderson-Sellers A. 1996. Bridging the climate gaps. In *Climate Change: Developing Southern Hemisphere Perspectives,* ed. TW Giambelluca, A Henderson-Sellers. New York: Wiley
90. Stone P, Risbey J. 1990. On the limitations of general circulation climate models. *Geophys. Res. Lett.* 17(12):2173–76
91. Glantz MH, ed. 1988. *Societal Responses to Regional Climatic Change: Forecasting by Analogy.* Boulder, CO: Westview
92. Rosenberg NJ, ed. 1993. *Towards an Integrated Impact Assessment of Climate Change: The MINK Study.* Dordrecht: Kluwer Acad. Publ.
93. Cohen SJ, ed. 1994. McKenzie Basin Impact Study, Interim Rep. 2. *Proc. 6th Biennial AES/DIAND Meet. North. Clim. Mid-Study Workshop McKenzie Basin Impact Study. Environment Can., Yellowknife, NWT, Can.*
94. Melillo JM, Prentice IC, Farquhar GD, Schulze E-D, Sala OE. 1996. Terrestrial biotic responses to environmental change and feedbacks to climate. See Ref. 92, pp. 445–81
95. Denman K, Hofmann E, Marchant H. 1996. Marine biotic responses to environmental change and feedbacks to climate. See Ref. 192, pp. 483–516
96. Xiao X, Kicklighter D, Melillo J, McGuire A, Stone P, Sokolov A. 1995. *Responses of Primary Production and Total Carbon Storage to Changes in Climate and Atmospheric CO_2 Concentration. Rep. No. 3,* Jt. Prog. Sci. Policy Glob. Change, MIT, Cambridge, MA
97. Smith TM, Shugart HH. 1993. The transient-response of terrestrial carbon storage to a perturbed climate. *Nature* 361(6412):523–26
98. Parton WJ, Ojima DS, Schimel DS, Kittel TGF. 1993. Development of simplified ecosystems models for applications in earth system studies: the century experience. In *Modeling the Earth System,* ed. D Ojima, pp. 281–302. Boulder, CO: UCAR/Off. Interdiscip. Earth Stud.
99. Shugart HH, Leemans R, Bonan GB, eds. 1992. *A Systems Analysis of the Global Boreal Forest.* Cambridge: Cambridge Univ. Press
100. Solomon AM, Shugart HH, eds. 1993. *Vegetation Dynamics and Global Change.* New York: Chapman Hall
101. Melillo JM, et al. 1993. Global climate change and terrestrial net primary production. *Nature* 363:234–40
102. Huntley B, Berry PM, Cramer WP, Mcdonald AP. 1995. Modelling present and potential future ranges of some European

higher plants using climate response surfaces. *J. Biogeogr.* 22:967–1001
103. Huntley B, Cramer WP, Morgan AV, Prentice HC, Allen JRM, eds. 1996. *Past and Future Rapid Environmental Changes: The Spatial and Evolutionary Responses of Terrestrial Biota*. Berlin: Springer-Verlag
104. Prentice I, Colin JG, Huntley B, Jolly D, Cheddadi R. 1996. Reconstructing biomes from paleoecological data: a general method and its application to European pollen data at 0 and 6 Ka. *Clim. Dynam.* 12:185–94
105. Nordhaus WD. 1991. To slow or not to slow: the economics of the greenhouse effect. *Econ. J.* 101:920–37
106. Smith JB, Tirpak DA, eds. 1989. *The Potential Effects of Global Climate Change on the United States.* Washington, DC: US Environ. Protection Agency Off. Policy Plan. Eval.
107. Pearce DW, et al. 1996. The social costs of climate change: greenhouse damage and the benefits of control. In *Climate Change 1995: Economic and Social Dimensions of Climate Change.* Contrib. Work. Group III to 2nd Assess. Rep. IPCC, ed. JP Bruce, H Lee, EF Haites, pp. 179–224. Cambridge: Cambridge Univ. Press
108. Peck SC, Teisberg TJ. 1995. International CO_2 emissions control: an analysis using CETA. *Energy Policy* 23(4/5):297–308
109. Fankhauser S, Tol RSJ. 1996. Climate change costs: recent advancements in the economic assessment. *Energy Policy* 24(7):665–73
110. Hammitt JK, Atul KJ, Adams JL, Wuebbles DJ. 1996. A welfare-based index for assessing environmental effects of greenhouse-gas emissions. *Nature* 381:301–3
111. Kandlikar M. 1995. The relative role of trace gas emissions in greenhouse abatement policies. *Energy Policy* 23:879–83
112. Jain AK, Kheshgik HS, Wuebbles DJ. 1994. *Integrated Science Model for Assessment of Climate Change. UCRL-JC 116526.* Livermore, CA: Lawrence Livermore Lab.
113. Parry M. 1990. *Climate Change and World Agriculture.* London: Earthscan
114. Rosenzweig C, Parry M. 1994. Potential impact of climate change on world food supply. *Nature* 367:133–38
115. Titus JG, Narayanan V. 1996. The risk of sea level rise. *Clim. Change* 33(2):151–212
116. Waggoner PE. 1990. *Climate Change and US Water Resources.* New York: Wiley
117. Peters RI, Lovejoy TE. 1992. *Global Warming and Biological Diversity.* New Haven, CT: Yale Univ. Press
118. McMichael AJ, Haines A, Slooff R, Kovats S, eds. 1996. *Climate Change and Human Health. Assess.* Prepared by Task Group on Behalf of World Health Organ., World Meteorol. Organ., and United Nations Environ. Prog. Geneva: WHO
119. McMichael AJ, Martens WJM. 1995. The health impacts of global climate change: grappling with scenarios, predictive models, and multiple uncertainties. *Ecosyst. Health* 1(1):23–33
120. Patwardhan A, Small M. 1992. Bayesian methods for model uncertainty analysis with applications to future sea level rise. *Risk Anal.* 12:513–25
121. Yohe GW. 1992. Embedding dynamic responses with imperfect information into static portraits of the regional impact of climate change. In *Economic Issues in Global Climate Change: Agriculture, Forestry and Natural Resources*, ed. J Reilly, M Anderson, pp. 200–14. Boulder, CO: Westview
122. Mendelsohn R, Nordhaus WD, Shaw D. 1994. The impact of global warming on agriculture: a Ricardian analysis. *Am. Econ. Rev.* 84(4):753–71
123. Deleted in proof
124. Reilly J, Hohmann N. 1993. Climate change and agriculture: the role of international trade. *Am. Econ. Rev.* 83(2):306–12
125. Yohe G, Neumann J, Marshall P, Ameden H. 1996. The economic cost of greenhouse-induced sea-level rise for developed property in the United States. *Clim. Change* 32:387–410
126. Dornbusch R, Poterba J, eds. 1991. *Economic Policy Responses to Global Warming.* Cambridge, MA: MIT Press
127. Edmonds J, Wise M, Barns DW. 1995. Carbon coalitions: the cost and effectiveness of energy agreements to alter trajectories of atmospheric carbon dioxide emisisons. *Energy Policy* 23(4/5):309–35
128. Hammitt JK, Adams JL. 1996. The value of international cooperation for abating climate change. *Resour. Energy Econ.* 18(3):219–42
129. Nordhaus W, Yang Z. 1996. A regional dynamic general-equilibrium model of alternative climate-change strategies. *Am. Econ. Rev.* 86(4):741–65
130. Schelling TC. 1996. The economic diplomacy of geoengineering. *Clim. Change* 33:303–7
131. Keith DW, Dowlatabadi H. 1992. A serious look at geoengineering. *Eos Trans. AGU* 73(27):289–96

132. Schneider SH. 1996. Geoengineering: Could—or should—we do it? *Clim. Change* 33:291–302
133. Leemans R, Agrawala S, Edmonds JA, MacCracken MC, Moss R, Ramakrishnan PS. 1996. Mitigation: cross-sectoral and other issues. In *Climate Change 1995: Impacts, Adaptation, and Mitigation of Climate Change: Scientific-Technical Analysis*, ed. RT Watson, AMC Zonyower, RH Moss, pp. 193–227. Contrib. Work. Group II to 2nd Assess. Rep. IPCC. Cambridge: Cambridge Univ. Press
134. Dowlatabadi H. 1995. Integrated assessment of climate change: an incomplete overview. *Energy Policy* 23(4/5):289(8)
135. Solow RM. 1970. *Growth Theory: An Exposition.* Oxford: Clarendon
136. Peck SC, Teisberg TJ. 1992. CETA: a model for carbon emissions trajectory assessment. *Energy J.* 13(1):55–77
137. Peck SC, Teisberg TJ. 1993. The importance of non-linearities in global warming damage costs. In *Assessing Surprises and Nonlinearities in Greenhouse Warming*, ed. J Darmstadter, M Toman. Washington, DC: Resour. Future
138. Peck SC, Teisberg TJ. 1993. Global warming uncertainties and the value of information: an analysis using CETA. *Resour. Energy Econ.* 15(1):71–97
139. Peck SC, Teisberg TJ. 1995. Optimal CO_2 control policy with stochastic losses from temperature rise. *Clim. Change* 31:19–34
140. Nordhaus WD. 1994. Expert opinion on climate change. *Am. Sci.* 82:45–51
141. Morgan MG, Keith DW. 1995. Subjective judgements by climate experts. *Environ. Sci. Technol.* 29:A468–76
142. Manne AS, Richels RG. 1995. The greenhouse debate—economic efficiency, burden sharing and hedging strategies. *Energy J.* 16:(4):1-37
143. Hourcade J-C, Chapuis T. 1995. No-regret potentials and technical innovation: a viability approach to integrated assessment of climate change. *Energy Policy* 23(4/5):433–46
144. Hammitt JK. 1996. *Evaluation Endpoints and Climate Policy: Atmospheric Stabilization, Benefit-Cost Analysis, and Near-Term Greenhouse-Gas Emissions.* Cambridge, MA: Harvard School Public Health, Cent. Risk Anal. (Mimeo)
145. Krause F, Bach W, Koomey J. 1992. *Energy Policy in the Greenhouse.* New York: Wiley
146. Richels RG, Edmonds J. 1995. The economics of stabilizing atmospheric CO_2 concentrations. *Energy Policy* 23(4/5): 373–78
147. Wigley TML, Richels RG, Edmonds JA. 1996. Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. *Nature* 379:240–43
148. Manne AS, Richels RG. 1997. *On Stabilizing CO_2 Concentrations: Cost-Effective Emission Reduction Strategies.* Palo Alto, CA: Electr. Power Res. Inst. (Mimeo)
149. Alcamo J, Kreileman GJJ. 1996. Emission scenarios and global climate protection. *Glob. Environ. Change* 6:305–34
150. Swart R, Berk N, Kreileman E, Janssen N, Bollen J, et al. 1996. *The safe landing approach: risks and trade-offs in global climate change.* Presented at Spec. Sess. 2nd Conf. Parties Framework Conv. Clim. Change, Geneva
151. Hope C. 1992. *A Fast and Simple Model of Global Warming from Greenhouse Gas Emissions. Research Papers in Management Studies 1992-1993.* Cambridge, UK: Judge Inst. Manage. Stud.
152. Morgan MG, Henrion M. 1990. *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis.* New York: Cambridge Univ. Press
153. Dowlatabadi H, Morgan MG. 1993. Integrated assessment of climate change. *Science* 259:1813
154. Dowlatabadi H, Ball M, Morgan MG, Patwardhan A, Kandlikar M, Shewliakowa E. 1994. *An overview of the integrated climate assessment model version 2 (ICAM-2).* Presented at West. Econ. Assoc., Vancouver, BC
155. Lave LB, Dowlatabadi H. 1993. Climate change: the effect of personal beliefs and scientific uncertainty. *Environ. Sci. Technol.* 27(10):1962–72
156. Tol RSJ. 1995. The damage costs of climate change: toward more comprehensive calculations. *Environ. Resour. Econ.* 5:353–74
157. Tol RSJ. 1996. The damage costs of climate change: towards a dynamic representation. *Ecol. Econ.* 19:67–90
158. Webster M, Tatang MA, McRae GJ. 1996. *Application of the Probabilistic Collocation Method for an Uncertainty Analysis of a Simple Ocean Model. Rep. No. 4,* Jt. Prog. Sci. Policy Glob. Change, MIT, Cambridge, MA
159. Scott MJ, Sands RD, Edmonds JE, Liebetrau AM. 1995. *Uncertainty in MiniCAM: An Investigation of Uncertainty Issues in an Integrated Assessment Framework.* Washington, DC: Battelle Pac. Northwest Lab.

160. Yohe GW, Wallace R. 1996. Near term mitigation policy for global change under uncertainty: minimizing the expected cost of meeting unknown concentration thresholds. *Environ. Model. Assess.* 1(12):47–57
161. Hammitt JK, Lempert RJ, Schlesinger ME. 1992. A sequential-decision strategy for abating climate change. *Nature* 357:315-18
162. Lempert RJ, Schlesinger ME, Hammitt JK. 1994. The impact of potential abrupt climate changes on near-term policy choices. *Clim. Change* 26:351–76
163. Kolstad CD. 1994. George Bush vs. Al Gore: irreversibilities in greenhouse gas accumulation and emission control investment. *Energy Policy* 22(9):771–78
164. Chao H-P. 1995. Managing the risk of global climate catastrophe: an uncertainty analysis. *Risk Anal.* 15(1):69–78
165. Thompson M, Ellis R, Wildvsky A. 1990. *Cultural Theory.* Polit. Cult. Ser. Boulder, CO: Westview
166. van Asselt MBA, Beusen AHW, Hilderink HBM. 1996. Uncertainty in integrated assessment: a social scientific perspective. *Environ. Model. Assess.* 1:71–90
167. Rotmans J, Hulme M, Downing T. 1994. Climate change implications for Europe: an application of the ESCAPE model. *Glob. Environ. Change* 4:97–124
168. Alcamo J, Kreileman GJJ, Krol MS, Zuidema G. 1994. Modeling the global society-biosphere-climate system: Part 1: model description and testing. *Water Air Soil Pollut.* 76:1–35
169. de Vries HJM, Olivier JGJ, Van Den Wijngaart RA, Kreileman GJJ, Toet AMC. 1994. Model for calculating regional energy use, industrial production, and greenhouse gas emissions for evaluating global climate scenarios. *Water Air Soil Pollut.* 76:79–132
170. Leemans R, Van Den Born GJ. 1994. Determining the potential distribution of vegetation, crops, and agricultural productivity. *Water Air Soil Pollut.* 76:133–62
171. Prentice IC, Cramer W, Harrison SP, Leemans R, Monserud RA, Solomon AM. 1992. A global biome model based on plant physiology and dominance, soil properties, and climate. *J. Biogeogr.* 19:117–34
172. Kreileman GJJ, Bouwman AF. 1994. Computing land use emissions of greenhouse gases. *Water Air Soil Pollut.* 76:231-58
173. Alcamo J, Van Den Born GJ, Bouwman AF, de Haan BJ, Goldewijk KK, et al. 1994. Modeling the global society-biosphere-climate system: Part 2: computed scenarios. *Water Air Soil Pollut.* 76:37–78
174. Brown S. 1996. Mitigation potential of carbon dioxide emissions by management of forests in Asia. *Ambio* 25:273–78
175. Burniaux J-M, Nicoletti G, Oliveira-Martins J. 1992. Green: a global model for quantifying the costs of policies to curb CO_2 emissions. *OECD Econ. Stud.* 19:52–90
176. Oliveira-Martins J, Burniaux J-M, Martin JP, Nicoletti G. 1992. The costs of reducing CO_2 emissions: a comparison of carbon tax curves with green. *OECD Econ. Dep. Work. Pap. 118,* pp. 1–54. Paris: OECD
177. Yang Z, Eckaus RS, Ellerman AD, Fitzmaurice J, Jacoby HD. 1996. *The MIT Emissions Prediction and Policy Analysis (EPPA) Model. Rep. No. 6,* Jt. Prog. Sci. Policy Glob. Change, MIT, Cambridge, MA
178. Edmonds JA, Pitcher HM, Rosenberg NJ, Wigley TML. 1993. *Design for the global change assessment model.* Presented at Int. Workshop Integrative Assess. Mitigation, Impacts, Adaptation to Clim. Change, Oct. 13–15, Int. Inst. Appl. Syst. Anal., Laxenburg, Austria
179. Fisher-Vanden K, Edmonds JA, Pitcher HM, Barns P, Baron R, et al. 1993. *The second generation model of energy use, the economy, and greenhouse gas emissions L.* Presented at Annu. Fed. Forecasters' Conf., 6th, Crystal City, VA
180. Matsuoka Y, Kainuma M, Morita T. 1995. Scenario analysis of global warming using the Asia-Pacific integrated model (AIM). *Energy Policy* 23:357–72
181. Matsuoka Y, Takahashi K, Harasawa H, Morita T. 1997. *Climatic impacts on the Asia and Pacific regions.* Presented at IPCC Asia-Pacific Workshop Integrated Assess. Models, Mar. 10–12, United Nations Univ., Tokyo
182. Kandlikar M, Risbey J. 1998. Developing insights from integrated assessment modeling. *Environ. Model. Assess.* In press
183. Peck SC, Teisberg TJ. 1993. CO_2 emissions control: comparing policy instruments. *Energy Policy* 21:222–30
184. Kolstad CD. 1996. Learning and stock effects in environmental regulation: the case of greenhouse gas emissions. *J. Environ. Econ. Manage.* 31:1–18
185. Cline W. 1992. *The Economics of Global Warming.* Washington, DC: Inst. Int. Econ.

186. Manne AS. 1995. The rate of time preference: implications for the greenhouse debate. *Energy Policy* 23:391–94
187. Lind RC. 1995. Intergenerational equity, discounting, and the role of cost-benefit analysis in evaluating global climate policy. *Energy Policy* 23:379–90
188. Morgan MG, Keith D. 1995. Subjective judgments by climate experts. *Environ. Sci. Technol.* 29:A468-76
189. Hammitt JK. 1995. Outcome and value uncertainties in global-change policy. *Clim. Change* 30:125–45
190. Pitcher H, Wise M. 1995. *Minicam Thematic Guide.* CIESIN URL: http://sedac.ciesin.org/mva/minicam/MCHP.html
191. Toth FL. 1994. *Policy exercises: the first ten years.* Presented at 1994 Meet. ISAGA (Int. Simulation Gaming Assoc.), Ann Arbor, MI
192. Houghton JT, Miera Filho LG, Callander BA, Harris N, Katenberg A, Maskell K, eds. 1996. *Climate Change 1995: The Science of Climate Change.* Contrib. Work. Group I to 2nd Assess. Rep. IPCC. Cambridge, UK: Cambridge Univ. Press