Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results

John Weyant
Stanford University

Ocen Davidson
Makerere University

Hadi Dowlatabadi
University of British Columbia

James Edmonds
Pacific Northwest National Laboratory

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Convening Lead Author:
J. WEYANT

Principal Lead Authors:
O. DAVIDSON, H. DOWLATABADI, J. EDMONDS, M. GRUBB, E.A. PARSON, R. RICHELS, J. ROTMANS, P.R. SHUKLA, R.S.J. TOL

Lead Authors:
W. CLINE, S. FANKHAUSER

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SUMMARY

Integrated assessments are convenient frameworks for combining knowledge from a wide range of disciplines. These efforts address three goals:

(1) Coordinated exploration of possible future trajectories of human and natural systems
(2) Development of insights into key questions of policy formation
(3) Prioritization of research needs in order to enhance our ability to identify robust policy options

The integration process helps the analyst coordinate assumptions from different disciplines and introduce feedbacks absent in conclusions available from individual disciplinary fields.

Historically, the most common approach to integrated assessment has been the attempt by individual researchers or research teams to integrate the information available from the relevant disciplines and provide policy advice in books and reports. Although this has typically been accomplished via informed qualitative linkages, Integrated Assessment Models (IAMs) use a computer program to link an array of component models based on mathematical representations of information from the various contributing disciplines. This approach makes it easier to ensure consistency among the assumptions input to the various components of the models, but may tend to constrain the type of information that can be used to what is explicitly represented in the model.

IAMs can be divided into two broad classes: *policy optimization models* and *policy evaluation models*. Policy optimization models optimize key policy control variables such as carbon emission control rates or carbon taxes, given formulated policy goals (e.g., maximizing welfare or minimizing the cost of meeting a carbon emission or concentration target). Policy evaluation models, on the other hand, project the physical, ecological, economic, and social consequences of specific policies.

Policy optimization models can be divided into three principal types:

(1) Cost-benefit models, which attempt to balance the costs and benefits of climate policies
(2) Target-based models, which optimize responses, given targets for emissions or climate change impacts
(3) Unceraınty-based models, which deal with decision making under conditions of uncertainty

Policy evaluation models are of two types:

(1) Deterministic projection models, in which each input and output takes on a single value
(2) Stochastic projection models, in which at least some inputs and outputs are treated stochastically

Each approach has strengths and weaknesses and produces particular insights regarding climate change and potential policy responses to it. Some of the more advanced models can be used for several purposes.

Cost-benefit models

Cost-benefit IAMs balance the marginal costs of controlling greenhouse gas emissions against those of adapting to any climate change. In this approach any constraint on human activities is explicitly represented and costed out. At present, models of this type include highly aggregated representations of climate damages, generally representing economic losses as a function of mean global surface temperature but sometimes disaggregating total damages into market and nonmarket damage components.

Keeping in mind the uncertainties and limitations inherent in these models, they can nevertheless be used to compute optimal control strategies. Specifically, results relating to optimal CO_2 emission control rates (percentage reductions in emissions relative to baseline emissions) and carbon taxes (equivalent to the marginal cost of efficient carbon emission reductions) over the next century vary widely, in part because of debates about the nature and valuation of climate impacts and in part because of debates about how to represent the dynamics of energy systems and technology development processes. However, the models do agree that higher control costs, lower damage estimates, and higher discount rates lead to lower initial optimal control rates, whereas lower control costs, higher damage estimates, and lower discount rates lead to higher initial control rates. For example, if new technology development is highly responsive to the level of control, lower control costs will result over time and a higher initial optimal control rate will be implied. Conversely, breakthroughs in biotechnology that would be expected to reduce the damages resulting from climate change on agriculture would (other things being equal) reduce the optimal initial control rate.

Target-based models

In target-based IAMs, targets for greenhouse gas emissions, atmospheric concentrations of greenhouse gases, climate change, or climate impacts can be set to avoid certain types of risks, perhaps according to the "precautionary principle." As a

result, the guiding principle of the cost-benefit models, economic optimization (i.e., the marginal cost of implementing the mitigation and adoption measures resulting from the individual targets should equal the marginal economic benefits of the impacts avoided), is replaced by an emphasis on precautionary targets, risk aversion, and physical criteria.

Several integrated assessment efforts have attempted to identify the cost-effective emission timepath for reaching a particular CO_2 concentration target, that is, to identify the emission profile that minimizes abatement costs. The initial path depends on assumptions about the current availability of low-cost measures and the inertia of the system, but after taking account of these factors the least-cost path tends to remain close to the reference path initially and to diverge at a rate that depends on the concentration target (among other things). Factors that tend to favour deferral of reductions include

(1) A positive marginal product of capital
(2) The prospect of autonomous reductions in the cost of carbon-free substitutes
(3) More time to achieve an optimal configuration of the capital stock in anticipation of emission constrictions
(4) The carbon cycle (the earlier the release, the more time for removal from the atmosphere)

Conversely, factors that make greater early action optimal include

(1) Lower marginal product of capital
(2) The prospect of inducing further cost reductions through abatement action
(3) The prospect of avoiding being locked in to more carbonintensive patterns of development
(4) The extent to which inertia may amplify the costs of having to make more rapid emission reductions later

It is important to note that these analyses were conducted with top-down models of the global energy-economic system. Although the models incorporate opportunities for "no-regrets" measures, they assume that such options are in insufficient supply to displace fossil fuels altogether. Hence, they show emissions continuing to grow under a wide range of assumptions about population and economic growth. IAMs that include the full range of factors that bear on the optimal timing of emission reductions have not yet been developed.

Uncertainty-based models

As a result of the high level of uncertainty about the future evolution of socioeconomic and natural systems, some researchers have put the analysis of climate change into explicit frameworks of the kind discussed in Chapter 2 for analyzing decision making under uncertainty. Generally, this has been done either by including an uncertainty representation of all key parameters within simplified models of the types discussed above or by adding a limited number of alternative states to full cost-benefit models. In addition, many of these models allow policies to be changed as uncertainties are resolved through time, although the process by which uncertainty is resolved is usually represented quite simplistically, perhaps even unrealistically. The uncertainty-based cost-benefit assessments completed thus far find higher optimal rates of abatement than do the deterministic cost-benefit models. Uncertainty analyses with target-oriented IAMs have also been used to calculate the likelihood of certain key physical thresholds being exceeded in the future.

Policy evaluation models

Policy evaluation IAMs are comprehensive, process-based models that attempt to provide a thorough description of the complex, long-term dynamics of the biosphere-climate system. The dynamic description often includes a description of atmospheric chemistry, climate, and ecological impact processes as well as a number of geophysical and biogeochemical feedbacks within the system. Some of the models even deal with biosphere-climate dynamics at a geograpically explicit level. On the other hand, the socioeconomic system in these models is usually poorly represented. The larger models usually do not serve the purpose of performing cost-benefit or cost-effectiveness analyses, but they can provide insights into the intricate interrelationships between the various components of the human system and the biosphere-climate system. Ideally, such insights can lead to new priority setting in the analysis of the climate change process. Policy evaluation IAMs provide a useful framework for identifying, illuminating, and clarifying current uncertainties. The most important uncertainties can be compared and ranked, and then the model can show how they propagate through the whole human/climate/biosphere system.

Policy Evaluation IAMs have helped identify critical knowledge gaps in several areas. Some of the most important findings from these models relate to the balancing of the carbon cycle, integrated land-use analysis, and sulphur aerosols.

The carbon cycle. IAM assessments of the impact of feedback mechanisms within the global carbon cycle have demonstrated that there are a large number of representations of the cycle that balance the past and present carbon budget, each of which can lead to very different atmospheric concentration levels for a specific projection of future carbon emissions.

Land-use analysis. The integration of geographically explicit representations of agriculture and land cover with climate change calculations has already provided new insights into climate-related shifts in agricultural areas and the influence of changing land cover on climate. Preliminary results suggest that regional demands for land can serve as a surrogate for the regional and local forces that are driving local land cover changes. These results also show the vulnerability of protected areas under shifting vegetation zones, and the consequences for biodiversity and nature conservation.

Sulphur aerosols. The first integrated assessments incorporating both SO_2 and CO_2 emissions show that it is conceivable that reductions in radiative forcing resulting from rapid reductions in coal use in some regions could be more than offset for a decade or two by increased radiative forcing from the associated reductions in SO_2 emissions. However, spatial and temporal differences in sulphur emissions and the local nature of the changes in radiative forcing due to sulphur aerosols mean that the effects cannot be considered to cancel each other out in terms of impacts on regional climate patterns.

Although integrated assessment of climate change is a rapidly evolving field, the following additional preliminary conclusions can be made from the work completed thus far:

(1) Integrated assessments are no stronger than the underlying natural and economic science that supports them. Nevertheless, by bringing many components of the climate change problem into a common framework, they offer potentially useful insights that would be unavailable from a purely disciplinary research programme. In applying these assessments to climate policy design, two critical factors should be noted. First, researchers should provide a measure of the confidence with which such policy assessments can be made; and, second, the models should indicate the distribution across countries and income levels of impacts associated with particular policy goals and implementations.

(2) Recent refinements to Integrated Assessment Models show increased diversity in the distribution of regional costs and benefits. This implies potentially greater difficulty in reaching agreements but also opens up the possibility of greater gains in global welfare from achieving them.

(3) From the integrated assessment perspective, there are important gaps in disciplinary research and inconsistencies between the information produced by the various disciplines whose reconciliation would lead to improved integrated assessments. Much of the underlying fundamental science needed to develop coordinated integrated assessments is not in a form suitable for immediate use. Different disciplinary experts, for example, have held different factors constant. This contributes to the difficulty of developing, calibrating, and validating the models. In addition, some of the underlying fundamental research has not been performed. For example, models of adaptive decision making do not yet explicitly consider how social goals and progress towards them are measured over time or how global change processes are detected. Finally, there are some highly uncertain components in the current set of integrated assessments, including the sensitivity of the climate system to changes in greenhouse gas concentrations, the physical and economic impacts of any climate change that may occur, and the applicability and choice of discount rates. One of the main values of the integrated assessment approach to the study of climate change lies in the identification of gaps and inconsistencies in our knowledge of the underlying phenonema and their implications for future research.

(4) Although it is difficult confidently to choose one policy in preference to others based on current knowledge about the climate system and human interactions with it, it has been demonstrated that the policy objective, discount rate, and timing of compliance can be critical to short-term policy formulation and the overall cost of action.

(5) Given the considerable uncertainties associated with how the climate system will evolve and interact with human activities, policies that enhance the flexibility of nations and individuals to respond to any impacts that do emerge tend to have high value. Because they can be focussed directly on the impacts of climate change, research and development activities related to technologies and institutions that facilitate the process of adaptation to climate change generally have a high payoff. Research and development activities directed towards technologies that lower material use in economic activity are also a good bet.

(6) Most current models do not match the social and economic organization of the developing economies well. For example, none of the existing models can incorporate hierarchical decision structures or represent the operation of the informal economies that are important in many developing countries. This can lead to biases in global assessments when impacts in developing countries are valued as if these countries were no different from developed countries.

(7) Finally, climate change is but one dimension of global change. For example, integrated assessments suggest that ecosystem impacts from projected climate change, agriculture management, and urbanization could well be of similar magnitudes.

10.1 Introduction

The historic Framework Convention on Climate Change (FCCC), signed by 154 countries at the UN Conference on Environment and Development (UNCED) in Brazil in June 1992, had as its central objective the stabilization of atmospheric greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system. It also stated that this goal should be realized soon enough that ecosystems could adapt naturally to climate change, that food production would not be threatened, and that sustainable economic development could proceed (FCCC, Article 2). The text does not specify, though, what the operational meaning of "dangerous anthropogenic interference" is, how its occurrence or the risk of its occurrence could be detected, or what measures, applied at what level of stringency, would be justified in avoiding it. The other central concepts in the objective – natural adaptation of ecosystems, threats to food production, and sustainable economic development – are also not articulated precisely. Nor could they be.

Rendering the Convention's objective into operational specifics will require further deliberations, informed by the best available synthesis of current scientific, technical, economic, and sociopolitical knowledge. Such a synthesis can help define and assess the risks associated with climate change, ecosystem responses, and human adaptive responses as well as the feasibility, effectiveness, cost, and side effects of potential response measures. Synthesizing and communicating such knowledge in support of policy deliberations is the function of assessment.

Integrated assessment is distinguished from disciplinary research by its purpose, which is to inform policy and decision making rather than to advance knowledge for its intrinsic value. Integrated assessment is identified by the breadth of knowledge sources and the variety of disciplines from which it draws. It is to be distinguished from those (infrequent) instances in which a significant policy issue can be well informed by clear presentation of a body of knowledge held within a single discipline.

The broader the set of knowledge domains that must be synthesized to inform a policy or decision, the greater the intellectual and managerial problems that must be overcome to do the assessment well and make it useful to its audience. How integrated any particular assessment must be depends on the issue or decision to be informed. Perhaps more than any other policy issue, global climate change requires integrated assessment. Making rational, informed social decisions on climate change potentially requires knowledge of a large number of interrelated processes, beginning with the human activities that affect greenhouse gas emissions and extending to the atmospheric, oceanic, and biological processes that link emissions to atmospheric concentrations, the climatic and radiative processes that link atmospheric concentrations to global and regional climate, the ecological, economic, and sociopolitical processes that link changed climate to valued impacts, and the processes by which such evaluations are made. Any progress in understanding and responding to an issue of such complexity will require the capacity to interpret, integrate, reconcile, organize, and communicate knowledge across domains – that is, to do integrated assessment. This need has been widely recognized in calls to advance methods of integrated assessment and in the large number of projects now underway. Although there have been past examples of integrated assessments of major environmental issues – for example, the American CIAP Project (Grobecker *et al.*, 1974) and the European acid rain studies integrated in the RAINS model (Alcamo *et al.*, 1990) – the current level of integrated assessment activity on global climate change is unprecedented.

10.1.1 Purposes of integrated assessment

Integrated assessment can in principle serve three purposes. First, integrated assessment can help assess potential responses to climate change, by (1) representing physical, ecological, economic, and social processes to project the consequences of climate change and of particular policy responses to it, (2) using a cost-benefit formulation to compare costs of responses to the severity of the impacts they are intended to prevent, or (3) using a cost-effectiveness formulation to compare the relative effectiveness and cost of different responses to meet a specified target. Whichever of these formulations is employed, integrated assessment performs this function by making consistent, contingent, appropriately qualified projections of the likely cost and effect of specified responses.

Second, by providing a coherent, systematic framework to structure present knowledge, integrated assessment can bring two important benefits: It can promote a broad view of the climate issue that may facilitate more systematic searching for possible responses and avoid prematurely settling on one or a few proposed responses; and it can provide a consistent representation of current uncertainties, permitting identification and prioritization of those that are most important in practical terms – that is, those uncertainties that are most important to reduce in order to understand what should be done. Since the most important uncertainties from the perspective of policy relevance will not necessarily be the most important for advancing basic understanding, this function of integrated assessment can be of the highest importance.

Third, integrated assessment can help to address the most fundamental policy question about global climate change: How important is it relative to other matters of human concern? Gaining insight into this question will require comparing the aggregate social effect of climate change and potential responses to it with the aggregate social effect likely to arise from other changes and risks over the same period of time.

In fulfilling these purposes, integrated assessment supplements disciplinary research but does not replace it. A disciplinary research programme in the natural or social sciences, even one including components representing every relevant discipline that could contribute to informing policy choice, will not normally emphasize a synthesis of knowledge across domains and so cannot typically do the jobs of assessing the consequences of potential responses or prioritizing decision-relevant uncertainties and research needs. Current experience suggests that cross-disciplinary integration to fill these needs does not happen spontaneously and can be both difficult and costly. But this does not mean that integrated assessment can replace disciplinary research, even for providing policy-relevant knowledge. Although integrated assessment is needed to identify and prioritize policy-relevant and scientific gaps in knowledge, the gaps so identified can normally only be filled by disciplinary research, whether in the natural or social sciences.

10.2 Approaches to Integrated Assessment

Integrated assessments can be integrated over different dimensions and to different degrees. In contributing to general policy-relevant understanding, studies using many different dimensions and degrees of integration, from the broadest to the narrowest, may make important contributions. In informing the deliberations or decisions of a particular policy audience, though, the appropriate form and extent of integration are determined by the needs of the audience. When there is a specific audience or decision to inform, a useful assessment will seek to represent the kinds of policies and decisions they are concerned with, at a resolution that corresponds to their responsibilities and concerns, while taking appropriate opportunities to help broaden their understanding of the issue.

An area of active current exploration is the development of global-scale climate assessments with "end-to-end" integration that combines assessment of emissions and abatement measures with impacts and adaptation measures. Such projects often (implicitly or explicitly) pursue a cost-benefit framing of the climate issue to shed light on decisions about optimal global emission abatements and efficient means of achieving them. The implied audience for such assessments consists of those decision makers with the authority to balance the extent and form of abatement measures, adaptive and compensatory measures, and possibly geoengineering measures. Assessments of this kind are likely to help improve the general understanding of appropriate responses to the climate issue. Broad balancing of abatement and adaptation measures will be done, implicitly or explicitly, and it is clearly desirable that whatever knowledge is available to illuminate such broad trade-offs be presented to those involved in such choices.

Such assessments, though, are not the only kind that can be useful, or necessarily the most appropriate for informing many specific policy decisions. Certain international deliberations and negotiations, for example, may need assessments that are integrated even more broadly. At this level, it may not be possible to address the climate issue without making judgments of its significance relative to other environmental and policy issues. To engage choices of this breadth, assessments may be required that facilitate comparing the potential impacts of climate change and other issues. End-to-end assessment of climate change may be a necessary component of such assessments, but it may not by itself be sufficient. For questions of such breadth, the most useful assessments may be those that focus not on a single environmental issue but on basic policy choices and long-term technological trends in areas of human activity that affect a variety of environmental and other issues, such as agriculture or energy.

On the other hand, most policy audiences are likely to need less broadly integrated assessments. This may be so even for assessments to inform international negotiations, if, as often happens, a preexisting political commitment either to a simple heuristic principle like the precautionary principle or to a specific numerical policy target truncates the consideration of responses (Parson and Zeckhauser, 1995; Levy, 1993). In such cases the most useful assessment may be to adopt a cost-effectiveness approach, comparing emission types, sources, gases, and regions, to determine feasible, low-cost ways to meet specified abatement goals (see, e.g., Read, 1994b). However, integrated assessment models can also be used to test the cost-effectiveness or welfare implications of those principles.

Integrated assessment may also be of interest to small countries or regions that may suffer climate impacts but have little or no influence over global emissions. For authorities in such jurisdictions, the crucial dimension of integration will be across dimensions of impact – sector, location, group, and time – under an illustrative set of climate change scenarios. This type of assessment could inform their decisions about long-term climate-dependent investment, emergency response measures, zoning, and insurance and compensation schemes that form the bulk of adaptation response. Recent empirical study suggests that assessments conducted at relatively fine levels of spatial or sectoral aggregation and initiated by decision makers with direct responsibility for making such decisions or responding to such impacts tend to be more immediately useful and more directly used than assessments with national or international scope (Clark and van Eijndhoven, 1996).

10.2.1 Integrated modelling and other methods of integration

A variety of methods to conduct integrated assessment are possible. Current projects on global climate have largely, but not exclusively, pursued integration through a formal integrating model, though the centrality and manner of use of the model vary among projects (Rotmans *et al.*, 1995). Other integration methods that have been tried include special senior commissions or panels whose members span the required range of expertise and integrate knowledge judgmentally through their deliberations; formal models of problem subcomponents, linked through an external, judgmental combination of results rather than through a formal integrating model; collaborative interdisciplinary research teams whose continuing interactions develop collective skills at exchanging and sharing knowledge across their fields; and individual essays by authors with sufficient multidisciplinary competence to encompass the policy problems (see Box 10.1). Other integrating devices are not yet thoroughly developed but may hold substantial promise. These include simulations or policy exercises – devices for joint deliberation by researchers and policymakers in a hypothetical policy setting employing knowledge available from a variety of sources, including existing literatures, formal models, and expert judgment (Brewer, 1986; Parson, 1995b).

BOX 10.1: HISTORY OF INTEGRATED ASSESSMENT

Integrated assessment is neither a new concept nor an activity restricted to climate change. This box provides an illustrative review of landmarks in the history of integrated assessment of global environmental issues.

The first integrated assessment of a global environmental issue was the Climatic Impacts Assessment Program (CIAP), conducted by the U.S. Department of Transportation to assess the environmental impacts of stratospheric flight by supersonic aircraft (Grobecker *et al.*, 1974). Six separate interdisciplinary expert teams examined one link in a causal chain stretching from human activities (scenarios of supersonic flight and jet engine design) through atmospheric chemistry and radiation to biological, economic, and social impacts. The teams exchanged numerical estimates of key quantities, ultimately yielding quantitative estimates of the environmental and economic impacts of specific scenarios of stratospheric flight.

Through the 1970s and early 1980s, several other major integrated assessments were conducted using a similar structure of interdisciplinary expert panels. Early assessments of global climate change that helped lay the groundwork for the present IPCC approach included Clark (1982) and the U.S. National Research Council (1983). This comprehensive, interdisciplinary approach, which does not centrally depend on formal modelling, continues to the present in such bodies as the Assessment Panels of the Montreal Protocol and the IPCC itself. Since CIAP, however, no assessment has attempted such a precise, comprehensive integration of processes, from human activities to valued consequences, without using a formal integrating model.

Formally modelled integrated assessment studies trace their inspiration, if not their precise methods, to the global models of the 1970s, such as Meadows *et al.* (1972) and Mesarovic and Pestel (1974). (This field was reviewed in Meadows *et al.*, 1982.) These highly aggregated dynamic models of world development included generalized representations of pollution and resource depletion but did not address any particular environmental issue.

Formal integrated assessment models of climate change emerged in the late 1970s from earlier economic and technical models of energy policy. Nordhaus (1979) presented the first model that combined energy conversion, emissions, and atmospheric CO_2 concentration. Subsequent efforts in integrated assessment of climate change that stressed formal modelling included the IIASA energy project (Häfele *et al.*, 1981), Nordhaus and Yohe (1983), which added uncertainty to modelled projections of future CO_2 concentrations, and Edmonds and Reilly (1985).

Through the 1980s, climate assessment studies using formal integrated modelling were narrower in scope than those using interdisciplinary expert panels. The modelled assessments normally extended no further than atmospheric CO_2 concentration, excluding both non-CO_2 greenhouse gases and resultant changes in climate and impacts. A separate line of work, beginning with the MINK project (Rosenberg and Crosson, 1991; Rosenberg, 1993) focussed specifically on climate impacts, combining detailed sectoral models of agriculture, forests, energy, and water resources.

The first integrated assessment model to extend fully from emissions to impacts did not address climate change but the more analytically tractable issue of acid rain. The RAINS model of acidification in Europe was developed at IIASA beginning in the early 1980s (Alcamo, Shaw, and Hordijk, 1990). RAINS integrates models of acid emissions, atmospheric transport and deposition, and effects. The RAINS project also pioneered a close relationship between the modelling team and policymakers, arguably leading to a more policy-relevant model and a more useful contribution to negotiations and policy making than has yet been attained on other issues.

The first steps to extend formal integrated modelling of climate change were taken by Mintzer (1987), who added non-CO_2 gases and global temperature change, and subsequently by Lashof and Tirpak (1989) in their Atmospheric Stabilization Framework. The first model to attempt a fully integrated representation of climate from sources to impacts was IMAGE 1.0 (Rotmans, 1990), which subsequently became the basis for the integrated European model ESCAPE (Hulme *et al.*, 1995).

Since 1990, the number of projects in integrated assessment modelling of global climate change has expanded rapidly. The idea that useful models could be developed to span the full range of the climate issue has gained increasing acceptance, as advances in computing power and in the disciplinary understanding and sectoral modelling efforts on which such integrated modelling projects depend have made projects of this kind increasingly feasible. A landmark of the maturation of integrated assessment modelling of climate change was the first conference to assess activity in the field (Nakicenovic *et al.*, 1994). Since then, as discussed in the text of this chapter, the field has continued to expand and develop rapidly.

Doing integrated assessment by building an integrating model has several evident advantages. Constructing a model imposes common standards of coherent, precise communication on project participants. It also imposes common data definitions and standards of consistency and scale on problem components and can facilitate the incorporation of new knowledge in an assessment. Attendant disadvantages are that the modelling may force more precise representation than the underlying knowledge in particular domains allows, may impose inappropriate restrictions, and may direct excessive project effort toward technical problems of model convergence, hence giving aggregate results that say as much about algorithmic artifacts as they do about component understanding. Integration through integrated modelling may be particularly

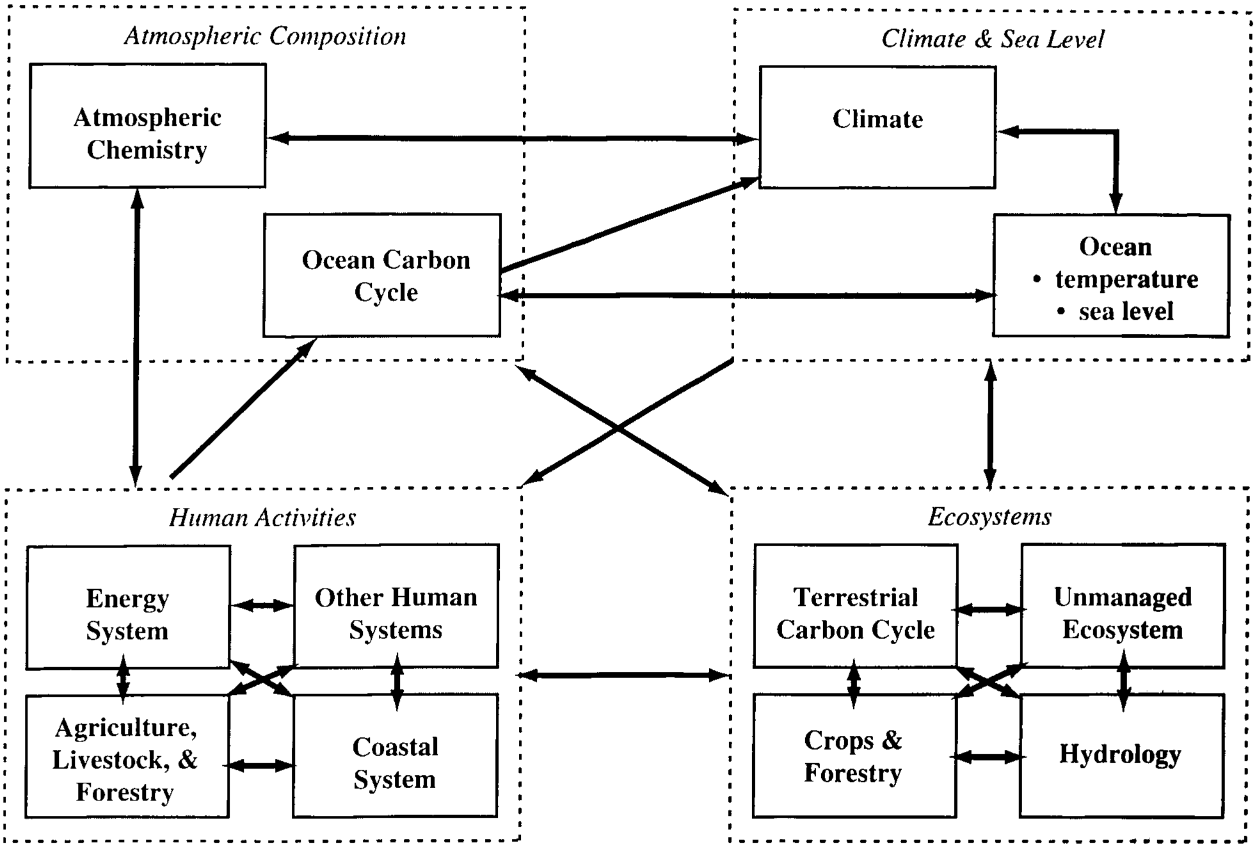


Figure 10.1: Key components of full scale IAMs.

weak in representing policies and decisions realistically and in reflecting knowledge of relevant social, political, institutional, and negotiation processes.

10.2.2 The current state of integrated assessment activity

Most current integrated assessment projects focus principally on building integrated models, although this is only one of various possible approaches to integrated assessment. In addition, most current projects are characterized by a national to global scale, a rather coarse spatial and sectoral resolution, and weak representation of policies and political processes. The balance of this chapter focusses on recent and current work in integrated assessment modelling (IAM), discussing the structure, modelling approaches, and major weaknesses of present projects and reviewing preliminary results.

Despite its importance, the field of integrated assessment is relatively immature and lacks a shared body of professional knowledge and standards of "best practice." Such knowledge will require more experience to develop; in its absence, it would be ill-advised to pursue a single, authoritative vision of integrated assessment. On many intellectual and managerial dimensions, there are many plausible ways of meeting the challenges of integrated assessment, but there is no evident single right way. Consequently, there is much to be gained from the parallel pursuit of diverse approaches, including those both more and less strongly dependent on integrated modelling.

10.3 Elements of an Integrated Assessment Model

A large number of integrated assessment models, with a wide variety of differing goals and objectives motivating their construction, are now being used to examine the issue of climate change. They vary greatly in their level of detail, but all share the defining trait that they incorporate knowledge from more than one field of study. However, they also vary greatly with regard to their scope. It is therefore important to distinguish between models in terms of this dimension as well as their level of detail. Models that attempt to represent the full range of issues raised by climate change are referred to as "full-scale" IAMs.

Full-scale IAMs must grapple with all the complexity of an IPCC assessment. This is an intimidating array of concerns. But although an IAM for climate change must consider a wide variety of issues, the number of issues is bounded. For the purpose of exposition, we group the principal considerations into four general categories, depicted in Figure 10.1:

- human activities
- atmospheric composition
- climate and sea level
- ecosystems

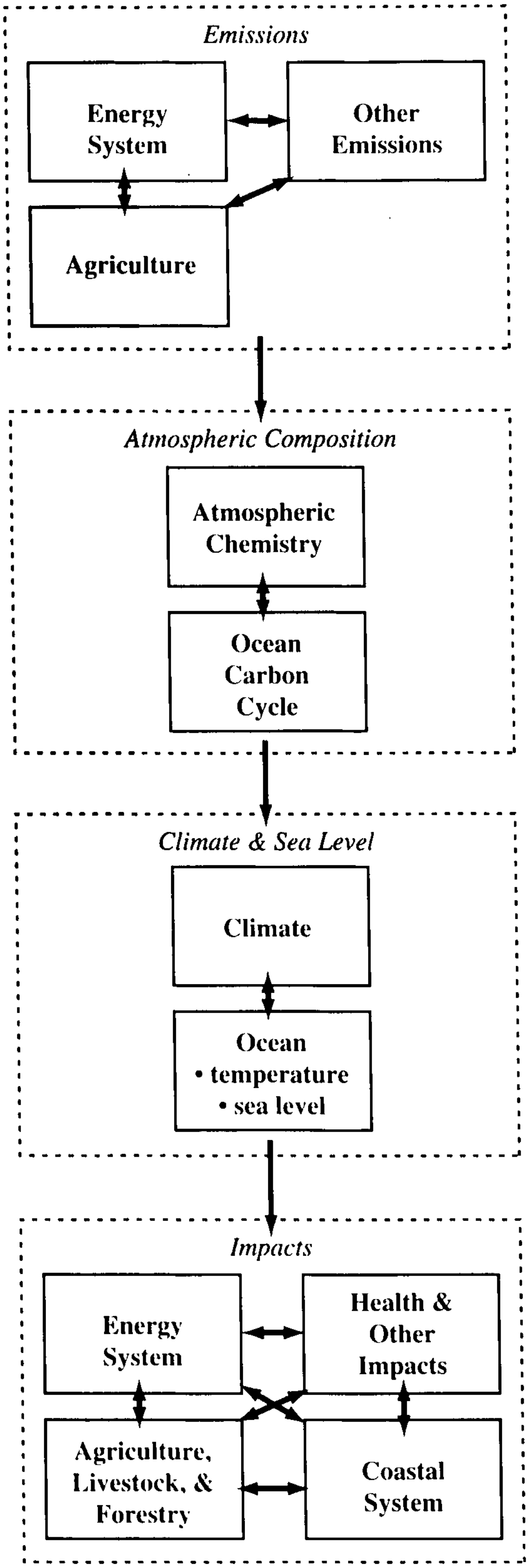


Figure 10.2: End-to-end characterization of IAMs.

Figure 10.1 is not the only possible depiction of the climate change system. An infinite number of aggregations are possible and a great many "wiring diagrams" already exist. This particular diagram has the virtue of including both human and natural system components. One alternative organization is the "end-to-end" characterization depicted in Figure 10.2. In this organizational formulation there are also four categories, this time beginning with emissions and ending with impacts. The principal organizational difference is that human activities and ecosystems are partitioned, with some features of each contained in the emissions and impacts components. This characterization deemphasizes the interactive character of the IAMs, in particular the fact that the same human and natural systems that produce emissions also suffer impacts.

Human systems interact with natural systems in two ways. Human activities are responsible for the emissions of greenhouse-related gases that are the centre of concern in the climate change issue. Human activities are also affected by climate change, either directly, for example, through changes in temperature, which affect demands for space heating and cooling, or indirectly, for example, through changes in sea level, crop productivity, or biodiversity.

Full-scale IAMs must consider the issue of emissions of greenhouse-related gases. The array of gases that matter from the perspective of emissions differs slightly from the array of gases that matter from the perspective of climate. From the perspective of climate change only, the set of gases and particles that have the capacity to change the radiative balance of the planet needs to be considered. At present the set consists principally of the following: water vapour (H_2O), ozone (O_3), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur aerosols, and the chlorofluorocarbons (CFCs) and their substitutes.

The set of gases that must be considered from the perspective of emissions is strongly overlapping, but includes some important differences. Water vapour and O_3 are not emitted in sufficient quantities by human activities to matter. Ozone concentrations are, however, affected by the emissions of other greenhouse-related gases such as carbon monoxide (CO), odd-nitrogen (NO_x), and nonmethane hydrocarbons (NMHC), whereas water vapour concentrations are influenced by the effect of temperature change on the water cycle. Likewise, sulphur aerosols are not emitted but are formed in the atmosphere at a rate that depends on emissions of sulphur oxides and particulate matter as well as other aspects of atmospheric chemistry.

With regard to the emissions of greenhouse-related gases the following human activities figure prominently:

- energy systems
- agriculture, livestock, and forest systems
- industrial systems

The role of energy systems is the single most critical component determining emissions in IAMs. Not only are energy systems associated with the greatest anthropogenic release of carbon to the atmosphere, but they are also associated with the largest anthropogenic release of sulphur compounds as well.

Systems that determine rates of land use change figure importantly, though the relationship between specific human actions and land use change is less well defined than the relationship between energy production and use and the release of greenhouse-related gases. Agriculture, livestock, and forestry represent the most extensive anthropogenic uses of land. In addition, agriculture and livestock are important determinants of CH_4 and N_2O releases.

Finally, full-scale IAMs must consider the array of other greenhouse-related emissions to the atmosphere. Most prominent among these are the chlorofluorocarbons and their substitutes, although there are others.

From the perspective of the consequences of climate change, an overlapping but somewhat different list of issues must also be dealt with by IAMs. The problem of climate change impacts is more difficult to deal with in IAMs because impacts are anticipated to affect a wide array of human activities, with no single activity thought to be substantially more vulnerable than others. IAMs thus frequently confront the impacts issue abstractly, using "damage functions," rather than explicitly. Nevertheless, underlying any treatment of impacts within an IAM are, at a minimum, the following human activities:

- agriculture, livestock, and forest systems
- energy systems
- coastal zones
- water systems
- human health
- the value of local air quality
- the values of unmanaged ecosystems[1]

The second information set that a full-scale IAM must generate is the concentrations of greenhouse gases, which the model must translate from both natural emissions and the emission flows generated by human activities. Greenhouse gas concentrations also depend on natural sources and sinks. In general, greenhouse gases can be segregated into CO_2 and other gases. The non-CO_2 greenhouse-related gases are controlled by atmospheric processes. Their sinks are predominantly in the atmosphere. CO_2, on the other hand, is governed by the processes of the carbon cycle. The concentration of CO_2 in the atmosphere is determined predominantly by interactions between atmospheric concentrations and the oceans and terrestrial systems.

Models deal with CO_2 in a variety of ways, ranging from simple airborne fraction models, which use a proportional approximation method to determine atmospheric concentrations, to interactive process models of the atmosphere and biosphere. The present understanding of both the carbon cycle and atmospheric chemistry have been surveyed in Volume 1 of the present report and in previous IPCC scientific reports (see IPCC, 1990, 1992, 1995).

Full-scale IAMs should ultimately also consider the problem of local air quality, as the removal rates for local air pollutants depend on weather conditions, and greenhouse gas abatement influences local air quality. These factors, in turn, interact with the economic value of changes in health conditions. The inclusion of local air quality is not yet possible, however, because of the totally different spatial and temporal scales and aggregation levels of the climate change and local air pollution problems. At the moment, such analyses can only be done through case studies, such as those being done by RIVM (the Dutch National Institute of Public Health and Environmental Protection) for 25 megacities around the world. Chapter 6 assesses these so-called "secondary benefits" of greenhouse gas abatement.

The third information set that a full-scale IAM must generate is the state of climate and sea level. Climate cannot be derived without dealing in one way or another with oceans. Oceans are an important determinant of the timing of climate change, as they represent an enormous heat sink. Thus, ocean-atmosphere feedbacks also influence the rate of sea level rise. In addition, interactions between the atmosphere and cryosphere affect climate change and sea level. Sea level calculations, for example, must include changes in the volume of meltwater from the major land-based ice sheets. Furthermore, the ocean that interacts with atmospheric processes in determining climate and sea level change also absorbs carbon that has been accounted for in the atmospheric composition model.

In Figure 10.1, the fourth category of IAM information is ecosystems. This category includes information associated with natural emissions of greenhouse-related gases, the terrestrial carbon cycle, and the effect of climate change, sea level rise, and CO_2 on crops, pastures, grazing lands, forests, hydrology, and unmanaged ecosystems.

These systems are strongly interactive. Some models handle them in a holistic manner, explicitly considering the interactions of natural system emissions, the status of unmanaged ecosystems, hydrology, ground cover, crop, and forest productivity. Other models treat them as if they were independent. The managed biosphere interacts strongly with human systems, which determine the selection of crop and managed forest species and the allocation of water resources among competing ends. Interactions between ecosystems and the climate and sea level functions are presently thought to be of second-order importance and are not dealt with in a majority of IAMs.

In addition to the degree of complexity (including disaggregation) considered within and between modules, another major design consideration in an integrated assessment model is the treatment of the considerable uncertainties about virtually every major relationship in the climate change assessment system. Future population and economic growth are uncertain; future greenhouse gas emissions, given population and economic activity, are uncertain; future greenhouse gas concentrations, given emissions, are uncertain; future climate, given atmospheric concentrations of greenhouse gases, is uncertain; future physical impacts of climate change are uncertain; and the future valuation of the physical impacts attributable to climate change is uncertain.

Uncertainty can be handled in a number of ways in integrated assessment modelling. Extensive sensitivity analyses can be performed on key model inputs and parameters, or explicit subjective probabilities can be assessed for these inputs and parameters and fed into a formal risk or decision analysis framework. If a formal risk or decision analysis approach is pursued, it is generally possible to calculate the value of information with respect to wholly or partially resolving the uncertainty associated with each key input or parameter. Such calculations can provide a useful screening of uncertainties to determine where research expenditures may or may not have large net expected benefits. Combined with estimates of research costs and success probabilities, they can help in setting research priorities in a rational way. Of course, these priorities can be expected to change over time as research itself changes perceptions of research costs and benefits.

10.4 Overview of Existing Integrated Assessment Models

Prior to 1992, only two integrated assessment models of climate change had appeared in the literature (Nordhaus, 1989, 1991; Rotmans, 1990). Since 1992 a host of new models has emerged. Table 10.1 lists twenty-two integrated assessment models that are in active use or under active development; in addition, a number of other modelling efforts are underway, so the number of existing integrated assessment models might be expected to at least double in the next few years. Even within the group of models listed in Table 10.1, though, there is a wide variation in level of model maturity. Some models are fully operational and documented. Others are up and running but not yet fully operational or documented. Still others are in module development and testing phases, with some modules not yet fully specified. It is anticipated that all the models shown here will be fully operational, albeit in preliminary versions in some cases, by the end of 1995. The modelling in this area is so active that even models that are fully operational are continually being refined and updated substantially every three to six months. Table 10.2 summarizes the current development status and most recent documentation available for the twenty-two models listed in Table 10.1.

The models included in Table 10.1 can be compared structurally according to the amount of emphasis they place on each of the blocks shown in Figure 10.1. The results of this process are shown in Table 10.3 (adapted from Rotmans *et al.*, 1995). Note that some of the models do not explicitly consider the relationships included in each of the blocks. In particular, several of the key models omit direct modelling of economic activity and rely on exogenous greenhouse gas emission trajectories. In addition, more than half the existing models consider both the physical impacts and their valuation only through aggregate damage functions that relate global mean temperature change directly to economic damage.

10.4.1 State of the art in integrated assessment modelling

It is difficult to characterize simply the state of the art in integrated assessment modelling of climate change – a great deal of model development is underway at present, involving a large number of research teams, with members drawn from a myriad of relevant disciplines, focussing on different dimensions of the problem, and using different types of methodologies. Nonetheless, a focus on the trade-offs between the complexity of natural systems models, the complexity of economic models, and the effort devoted to the explicit incorporation of uncertainty can help us understand the model development completed so far, as well as that occurring today or planned or anticipated for the future.

There are two broad classes of integrated assessment models: *policy evaluation models* that project the physical, ecological, economic, and social consequences of policies and *policy optimization models* that optimize key policy control variables (e.g., carbon emission control rates or carbon taxes) given formulated policy goals such as maximizing welfare or minimizing the cost of meeting a carbon emission or concentration target. There are two general types of policy evaluation models: deterministic projection models, in which each input and output takes on a single value, and stochastic projection models, in which at least some inputs and outputs are treated stochastically. Policy optimization models can be divided into three general types: models that optimize responses, given targets for emissions or climate change impacts; models that seek to balance the costs and benefits of climate policies; and models of sequential climate decision making under uncertainty. Each approach has strengths and weaknesses, and each produces particular insights regarding climate change and potential policy responses to it. Some of the more advanced models can be used for several of the above purposes.

Policy optimization IAMs focus on balancing the marginal costs of controlling greenhouse gas emissions and adapting to any climate change impacts that may occur with the damages that result after implementation of the mitigation and adaptation policies. These models reflect the strict cost-benefit paradigm discussed in Chapter 5. In this approach any constraint on human activities is explicitly represented and costed out. At present, models of this type include highly aggregated representations of climate damages, generally representing economic losses as a function of mean global surface temperatures but sometimes disaggregating these losses into market and nonmarket damage components.[2] However, as additional research on climate change impacts proceeds, it may be determined that these measurements are inaccurate. Moreover, it may be difficult to get policymakers to implement policies based on aggregate damages, as they are more likely to be able to relate to impacts on particular countries, regions, or sectors (e.g., agriculture or biodiversity in tropical rain forests) which are not explicitly represented in the current cost-benefit type of integrated assessment models. Early models of this type were also so complicated that it was difficult to incorporate explicit representation of uncertainty (and risk aversion) within the model structures. As discussed below, this situation has improved somewhat over the last couple of years.

The policy evaluation IAMs add detail on the physical impacts of climate change on various market and nonmarket sectors in different countries or regions, based in part on the impacts and mitigation areas addressed in Volume 2 of this report. Economic values have generally not yet been put on these impacts, an omission that reflects both the paucity of valuation studies in some sectors and the modellers' percep-

Table 10.1. *Integrated assessment models*

Model	Modellers
AS/ExM (Adaptive Strategies/Exploratory Model)	R. Lempert, S. Popper (Rand); M. Schlesinger (U. of Illinois)
AIM (Asian-Pacific Integrated Model)	T. Morita, M.Kainuma (National Inst. for Environmental Studies, Japan); Y. Matsuoka (Kyoto U.)
CETA (Carbon Emissions Trajectory Assessment)	S. Peck (Electric Power Research Institute) T. Teisberg (Teisberg Assoc.)
Connecticut (also known as the Yohe model)	G. Yohe (Wesleyan University)
CRAPS (Climate Research And Policy Synthesis model)	J. Hammitt (Harvard U.); A. Jain, D. Wuebbles (U. of Illinois)
CSERGE (Centre for Social and Economic Research on the Global Environment)	D. Maddison (University College of London)
DICE (Dynamic Integrated Climate and Economy model)	W. Nordhaus (Yale U.)
FUND (The Climate Framework for Uncertainty, Negotiation, and Distribution)	R.S.J. Tol (Vrije Universiteit Amsterdam)
DIAM (Dynamics of Inertia and Adaptability Model)	M. Grubb (Royal Institute of International Affairs), M.H. Dong, T. Chapuis (Centre Internationale de recherche sur l'environnement et développement)
ICAM-2 (Integrated Climate Assessment Model)	H. Dowlatabadi, G. Morgan (Carnegie-Mellon U.)
IIASA (International Institute for Applied Systems Analysis)	L. Schrattenholzer, Arnulf Grubler (IIASA)
IMAGE 2.0 (Integrated Model to Assess the Greenhouse Effect)	J. Alcamo, M. Krol (Rijksinstitut voor Volksgezondheid Milieuhygiene, Netherlands)
MARIA (Multiregional Approach for Resource and Industry Allocation)	S. Mori (Sci. U. of Tokyo)
MERGE 2.0 (Model for Evaluating Regional and Global Effects of GHG Reductions Policies)	Alan Manne (Stanford U.), Robert Mendelsohn (Yale U.), R. Richels (Electric Power Research Institute)
MiniCAM (Mini Global Change Assessment Model)	J. Edmonds (Pacific Northwest Lab), R. Richels (Electric Power Research Institute), T. Wigley (University Consortium for Atmospheric Research (UCAR))
MIT (Massachusetts Institute of Technology)	H. Jacoby, R. Prinn, Z. Yang (Massachusetts Institute of Technology)
PAGE (Policy Analysis of the Greenhouse Effect)	C. Hope (Cambridge U.); J. Anderson, P. Wenman (Environmental Resources Management)
PEF (Policy Evaluation Framework)	J. Scheraga, S. Herrod (EPA); R. Stafford, N. Chan (Decision Focus Inc.)
ProCAM (Process Oriented Global Change Assessment Model)	J. Edmonds, H. Pitcher, N. Rosenberg (Pacific Northwest Lab); T. Wigley (UCAR)
RICE (Regional DICE)	W. Nordhaus (Yale U.); Z. Yang (MIT)
SLICE (Stochastic Learning Integrated Climate Economy Model)	C. Kolstad (U. of California, Santa Barbara)
TARGETS (Tool to Assess Regional and Global Environmental and Health Targets for Sustainability)	J. Rotmans, M.B.A. van Asselt, A. Beusen, M.G.J. den Elzen, M. Janssen, H.B.M. Hilderink, A.Y. Hoekstra, H.W. Koster, W.J.M. Martens, L.W. Niessen, B. Strengers, H.J.M. de Vries (Rijksinstitut voor Volksgezondheid en Milieuhygiene, Netherlands)

Table 10.2. *Development Status of Integrated Assessment Models (June 1995)*

Model	Status	Reference
AS/ExM	Preliminary version operational	Lempert *et al.* (1994, 1995)
AIM	Operational	Morita *et al.* (1994); Matsuoka *et al.* (1995)
CETA	Operational, with regional and uncertainty variants	Peck and Teisberg (1992, 1993, 1994, 1995)
Connecticut	Operational	Yohe (1995a,b); Yohe and Wallace (1995)
CRAPS	Preliminary version operational	Hammitt (1995a,b); Jain *et al.* (1994)
CSERGE	Preliminary version operational	Maddison (1995)
DICE	Operational, with regional and uncertainty variants under development	Nordhaus (1994)
FUND	Operational	Tol *et al.* (1995)
DIAM	Analytic version operational	Grubb *et al.* (1993, 1995)
	Numeric version operational	Chapuis *et al.* (1995)
ICAM-2	ICAM-1 operational; ICAM-2 operational	Dowlatabadi and Morgan (1993); Dowlatabadi (1995)
IIASA	Energy, economy, and agriculture modules operational	WEC/IIASA (1995)
IMAGE 2.0	Operational	Alcamo (1994)
MARIA	Operational	Mori (1995a,b)
MERGE 2.0	Operational, with uncertainty variant under development	Manne *et al.* (1993)
MiniCAM	Operational	Edmonds *et al.* (1994a,b); Wigley *et al.* (1993)
MIT	Various stages of module testing	MIT (1994)
PAGE	Operational	Commission of the European Communities (1992)
PEF	Prototype operational, enhanced version under development	Cohan *et al.* (1994)
ProCAM	Most modules in testing phase	Edmonds *et al.* (1994a,b)
RICE	Operational	Nordhaus and Yang (1995)
SLICE	Operational	Kolstad (1993, 1994a,b,c)
TARGETS	Targets 1.0 operational	Rotmans *et al.* (1995)

tion that policymakers feel more comfortable trading off natural and physical impacts than dollars. In addition, the targets can be set to avoid certain types of risks, perhaps according to the precautionary principle. On the other hand, there is no guarantee that the marginal cost of implementing the mitigation and adaptation measures resulting from the individual targets will equal the marginal benefit (if that can be assessed) of the impacts avoided. Furthermore, because of the large size of these models, only limited amounts of sensitivity analysis can be performed, and more explicit representations of uncertainty (and risk aversion) have generally not been possible, except for the ICAM-2 model (Dowlatabadi, 1995) and the TARGETS model (Van Asselt and Rotmans, 1995).

Reflecting the high level of uncertainty about the future evolution of socioeconomic and natural systems, some analysts have put the analysis of climate change into explicit frameworks, of the kind discussed in Chapter 2, for decision making under conditions of uncertainty. These models have generally been either the result of a relatively complete uncertainty representation of all key parameters within simplified models or the result of adding a limited number of alternative states to more complex policy evaluation and policy optimization models. In addition, many of these models allow policies to be changed as uncertainties are resolved through time, although the process by which uncertainties will be resolved is usually represented quite simplistically. Stochastic models can generate multiple scenarios that in some cases have probabilities associated with them. Then, the (usually more complex) deterministic models can be run to investigate specific scenarios further. Table 10.4 places the models listed in Table 10.3 into the two primary categories and relevant subcategories discussed above.

10.5 First Results from Integrated Assessment Models

Most integrated assessment models of climate change have been constructed since 1992. By the end of 1994, however, results from a number of these models had already been published. This section gives an overview of these results, highlighting the insights that seem most relevant to the current debate on appropriate global change policies. The variety of different approaches employed to study the climate change issue makes comparison and reconciliation difficult.

In what follows, we group the available model results into two main categories: (1) results from policy evaluation models that include many linkages and interactions between the several key elements of the climate/biosphere system and (2) results from policy optimization models that directly consider the costs and benefits of potential climate change policy responses or minimize costs subject to constraints on emissions, concentrations, climate change, or climate impacts.

There are also large differences in the outputs that individual modellers report from their integrated analyses and the time periods for which those outputs are reported. Some of the more common outputs from the policy optimization models are projections of the cost of controlling greenhouse gas emis-

Table 10.3. *Summary characterization of integrated assessment models*

Model	Forcings 0. CO_2 1. other GHG 2. aerosols 3. land use 4. other	Geographic Specificity 0. global 1. continental 2. countries 3. grids/basins	Socioeconomic Dynamics 0. exogenous 1. economics 2. technology choice 3. land use 4. demographic	Geophysical Simulation[a] 0. Global ΔT 1. 1-D ΔT, ΔP 2. 2-D ΔT, ΔP 3. 2-D Climate	Impact Assessment[b] 0. ΔT 1. Δ sea level 2. agriculture 3. ecosystems 4. health 5. water	Treatment of Uncertainty 0. None 1. Uncertainty 2. Variability 3. Stochasticity 4. Cultural Perspectives	Treatment of Decision Making 0. optimization 1. simulation 2. simulation with adaptive decisions
AS/ExM	0	0	0	0	0	1	2
AIM	0,1,2,3	2,3	1,2,3,4	1,2	0,1,2,3,5	0	1
CETA	0,1	0	1,2	0	0	0 or 1	0
Connecticut	0	0	1	0	0	1	0
CRAPS	0	0	1	0	0	1	2
CSERGE	0	0	1	0	0	1	0
DICE	0	0	1	0	0	0 or 1	0
FUND	0,1	1	1,4	0	0,1,2,3,4	0 or 1	0
DIAM	0	0	1,2	0	0	0 or 1	0
ICAM-2	0,1,2,3	1,2	1,3,4	1,2	0,1,3	1,2,3	1,2
IIASA	0	0	1	1	2	0	0
IMAGE 2.0	0,1,2,3	3	0,2,3	2	1,2,3	1	1
MARIA	0	0,1	1	0	0	0	0
MERGE 2.0	0,1	1	1,2	0	0	0 or 1	0
MiniCAM	0,1,2,3	2,3	1,2,3	2	0	0	1
MIT	0,1,2,3	2,3	1	2,3	0,2,3	1	0,1
PAGE	0,1	1,2	1	0	0,1,2,3,4	2	1
PEF	0,1	1,2	1	0	0	2	1
ProCAM	0,1,2,3	2,3	1,2,3,4	2	0,2,3,5	1	1
RICE	0	1	1	0	0	0	0
SLICE	0	1	1	0	0	1	2
TARGETS	0,1,2,3,4	0	1,2,3,4	2	1,2,3,4	4	1,2

[a]TARGETS includes ozone depletion, soil erosion, acid rain, and toxic and hazardous pollutant releases.
[b]In AIM, FUND, IMAGE, PAGE, and ProCAM, the impacts are calculated separately for each sector.
Source: Adapted from Rotmans et al. (1995).

sions, the damages resulting from climate change, the "control rate," stated in terms of the percentage reduction in greenhouse gas emissions in each year relative to level of emissions projected to occur in the absence of new policy initiatives, and the carbon tax required in each year to limit greenhouse emissions to the levels specified in the scenario under consideration. Policy evaluation models, on the other hand, tend to report physical changes in emissions, concentrations, temperature, and sea level, as well as changes in land use by activity (e.g., agriculture, forestry, etc.), and/or physical impacts like ecosystems at risk, coastal land area lost, fresh water requirements, and mortality rates.

10.5.1 Results from policy evaluation models – contributions to the scientific debate

Policy evaluation models are rich in physical detail and have produced useful insights, for example, into the potential for deforestation as a consequence of interactions between demographics, agricultural productivity, and economic growth and into the relationship between climate change and the extent of potentially malarial regions (see Volume 2, Chapter 25).

10.5.1.1 Balancing the carbon budget

To assess the impact of a number of feedback mechanisms within the global carbon cycle, an integrated assessment model has been used to balance the past and present carbon budget. They show that both a historical and a present carbon balance can be obtained in many different ways, resulting in different biospheric fluxes and, thus, in considerably different atmospheric projections. The CO_2-fertilization feedback appears to determine the balance and to dominate the temperature-related feedbacks, whereas the feedback from net biological primary production seems to counterbalance the soil and respiration feedback effect. Future projections based on the IPCC's 1990 "business-as-usual" scenario show that the CO_2 concentrations calculated with the integrated assessment models are lower than the IPCC values, reaching a difference

Table 10.4. *Integrated assessment models by type*

Policy Evaluation Models
Deterministic Projection Models
AIM
IIASA
IMAGE 2.0
MIT
ProCAM
TARGETS
Stochastic Projection Models
PAGE
ICAM-2
TARGETS
Policy Optimization Models
Cost-Benefit and Target-Based Models
CETA
Connecticut
CSERGE
DICE
FUND
DIAM
MARIA
MERGE 2.0
MiniCAM
RICE
Uncertainty-Based Models
AS/ExM
CETA
CRAPS
CSERGE
DICE
FUND
ICAM-2
MERGE 2.0
PEF
SLICE

of about 15% (Rotmans and Den Elzen, 1993; Wigley, 1993). This difference can be explained by the fact that most global carbon cycle models used by the IPCC were unbalanced; the balanced models do not produce terrestrial fluxes that correspond to observations.

10.5.1.2 Integrated land-use analysis

A first attempt to integrate the various aspects of the global land use problem on a geographically explicit base has been made using the IMAGE 2.0 model. The model represents the transformation of land cover as it is affected by climatic, demographic, and economic factors and links these explicitly with the flux of CO_2 and other greenhouse gases between the biosphere and atmosphere. Conversely, it also takes into account the effect of productivity changes in the terrestrial and oceanic biospheres. The integration of agricultural and land cover calculations can provide new insights about shifts in agricultural areas related to climate and the influence that changing land cover has on climate. The first, preliminary, results show that there may be some validity to the hypothesis that regional demands for land can serve as a surrogate for measuring local land cover changes, and that land use rules can be used to represent the forces driving land conversions. Other results relate to the vulnerability of protected areas under shifting vegetation zones, the consequences for biodiversity and nature conservation, and the determination of risks associated with current productivity levels of specific crops with shifting agricultural patterns. These analyses could in due time assist regional policymakers in assessing the seriousness of climate change impacts (Alcamo, 1994).

10.5.1.3 Global warming potentials

A slightly improved version of the IMAGE 1.0 model has been used to investigate the input and parameter uncertainties as well as methodological uncertainties associated with Global Warming Potentials (GWPs) for greenhouse gases (Den Elzen, 1993; Rotmans and Den Elzen, 1992). In particular, the role of the emission scenario used and the difference between transient and equilibrium GWPs have been discussed. Although integrated assessment models have structural limitations, they can produce estimates for at least the direct impact of greenhouse gases as well as some of the indirect effects.

The advantages of using integrated assessment models of climate change in estimating GWPs are twofold: (a) they can calculate GWPs for each conceivable scenario, so the influence of the emission scenario selected can be stated explicitly; and (b) they also deal with the rates of change of all kinds of targeting processes, so the cumulative effect can be combined with the rate at any time. The results show that the GWPs calculated with integrated assessment models differ from the ones previously published by the IPCC. Considering a time horizon of 100 years, the difference might be as much as 5-10%. This difference demonstrates the crucial role of the chosen scenario in calculating GWPs and cannot be addressed by analytical methods.

10.5.1.4 The sulphate aerosols debate

As discussed at length in Volume 1 of this report, the presence of sulphate aerosols in the atmosphere is now thought to have a strong local cooling effect. This effect is manifested through three pathways: scattering and absorption of shortwave (solar) radiation, cloud reflectivity, and cloud persistence. By incorporating a simplified mathematical expression of the relationship between sulphate aerosols and radiative forcing into integrated assessment models, some of the sulphate aerosol effect can be taken into account. In this way, the sensitivity of the climate system to simultaneous changes in SO_2 and CO_2 emissions can be examined. The first calculations show that over the next decade, it is conceivable that the increased radiative forcing due to SO_2 concentration changes could more than offset reductions in radiative forcing due to reduced CO_2 emissions (Edmonds *et al.*, 1994b), depending on the rate of reduction and a number of other assumptions. Therefore, policies that reduce fossil fuel use may not be so effective in reducing near-term average radiative forcing as a simple calculation based on greenhouse gas emissions alone might imply. The proper treatment of SO_2 is, therefore, an important consideration in the integrated analysis of the consequences of technology development and deployment for climate change.

***10.5.1.5** IPCC scenarios*

In 1989, a U.S.-Netherlands expert group of the IPCC was asked to develop four different pathways for future global emissions of CO_2, CH_4, N_2O, halocarbons, and the ozone precursors NO_x and CO. The expert group used two alternative integrated assessment models to construct these scenarios: the ASF model from the U.S. Environmental Protection Agency and the IMAGE 1.0 model from the RIVM, the Dutch National Institute of Public Health and Environmental Protection (Rotmans, 1990). Three scenarios were designed in such a way that they would lead to a doubling of the CO_2-equivalent concentration in the atmosphere in the years 2030, 2060, and 2090. These were referred to as the "Business-as-Usual," "2060 Low Emissions," and "Control Policies" scenarios, respectively. The fourth scenario, the "Accelerated Policies" scenario, leads to stabilization of the CO_2-equivalent concentration in the atmosphere at well below doubling of preindustrial concentrations. Each scenario is based on a set of assumptions for key factors, including population growth, economic growth, the costs of technology used to convert energy from one form to another, energy end-use efficiency levels, deforestation rates, CFC emissions, and agricultural emissions.

***10.5.1.6** Delayed response analysis*

The IMAGE 1.0 model (Rotmans, 1990) was used by the IPCC to analyze delayed policy response options in which the start of the international policy response was delayed to 2000, 2010, 2020, and 2030 respectively. It was calculated that delaying implementation of the "Control Policies" scenarios by 10 years would result in only a minor increase in global mean temperatures, but that it would require a reduction of global CO_2 emissions of 20% with respect to year 2000 levels, whereas starting immediately would require only a 5% reduction with respect to 1990 levels over the same period. This integrated analysis shows that the timing of the climate response policies is crucial for the control of climate change, and that the feasibility of the required transition decreases over time.

***10.5.1.7** Risk assessment*

The Advisory Group on Greenhouse Gases (AGGG) recommended a maximum rate of global mean temperature increase of 0.1°C per decade, together with a maximum temperature increase of 2°C above the preindustrial global mean temperature level. These temperature targets might be considered as limits beyond which damages to sensitive ecosystems and coral areas might be expected to increase rapidly. One difficulty with these targets is that they are global, whereas large regional variations in temperature change and impacts are likely. Moreover, the targets need to be reviewed periodically in light of potential feedbacks and nonlinearities that may produce surprises and unexpected changes. The "Risk Assessment" calculations showed that (1) all IPCC 1990 and 1992 scenarios except the 1990 "Control Policies" scenario lead to temperature increases and rates of temperature change greater than the target values, and (2) even the IPCC 1990 "Control Policies" scenario leads to mean global temperature changes that are close to the targets (Den Elzen, 1993).

Table 10.5. *Key results from deterministic cost-benefit analyses*

Model	Control Rate (percentage reduction relative to baseline emissions)	Carbon Tax (1990 U.S. dollars/tonne)
	1990–2000	1990–2000
CETA		
Linear damages	0–1	7–8
Cubic damages	0–2	8–12
DICE	9	5

10.5.2 Results from cost-benefit policy optimization models

In this section we consider results from cost-benefit integrated assessment models run with all inputs and parameters set at their median or best-guess values. Notwithstanding the immense uncertainties inherent in the climate change issue, a number of analysts have suggested that the results from these deterministic analyses provide a useful benchmark for near-term decision making, if not an adequate approximation of the results obtained from more complex approaches that explicitly include consideration of the key uncertainties.

Table 10.5 shows some key results from two models that balance the costs and benefits of greenhouse gas emission reductions. For example, the "optimal run" results from the DICE model (Nordhaus, 1994) show a 1995 control rate (i.e., percentage reduction in emissions relative to baseline greenhouse gas emissions) of about 8.8% with an associated carbon tax[3] of $5.29 per tonne of carbon. This programme leads to an increase in the discounted present value of consumption of 271 billion 1989 dollars or about .04% of discounted baseline consumption. Similar results are obtained from the CETA, MERGE, and SLICE models when run under similar assumptions.

In *The economics of global warming*, Cline (1992) analyzes the time profile of abatement and damage costs under a policy of limiting global carbon emissions to 4 Gt annually and similarly reducing other greenhouse gas emissions. The abatement cost curve is low at first, then peaks at about 3.5% of gross world product, and thereafter declines to a plateau of about 2.5% as a consequence of widening technological alternatives.

The cost-benefit decision for greenhouse policy involves a trade-off between substantial abatement costs early in the horizon and avoidance of potentially large damages later in the horizon. The discounting of future costs and benefits relative to current ones is critical in such a trade-off. On the grounds that policymakers would be risk averse, Cline also weights a high-damage case three times as heavily as a low-damage case. Discounting at a zero rate of time preference, he

Table 10.6. *Key sensitivities from deterministic cost-benefit analyses*

Sensitivity Model and Cases		Control Rate (percentage) 1990–2000	Carbon Tax (1990 U.S. dollars/tonne) 1990–2000
CETA			
Warming per $2XCO_2$			
Low	1°	0	2
Baseline	3°	0–2	9–12
High	5°	0–7	22–29
Damage Function Power			
Low	1	0–1	8–9
Baseline	2	0–2	9–12
High	3	0–2	10–13
Utility Discount Rate			
Low	2%	8	19–24
Baseline	3%	5	9–12
High	4%	1	5–7
DICE			
Warming per $2XCO_2$			
Baseline	3°	9	5
High	4.5°	11	8
Damage Function Power			
Baseline	2	9	5
High	4	9	5
Utility Discount Rate			
Low	1%	19	24
Baseline	3%	9	5

finds that the overall benefit-to-cost ratio for aggressive action limiting carbon emissions to 4 Gt is a favourable 1.3. Thus, Cline endorses a much more aggressive control policy than calculated in most of the other pure cost-benefit studies. Much of the difference in results stems from Cline's assumption of risk aversion on the part of national and international policymakers and his use of a zero rate of pure time preference, whereas the other studies generally employ a pure rate of time preference of about 3% and no risk aversion by policymakers. In fact, Cline has shown that the optimal control rate in 2100 in the DICE model would be 50% if a zero rate of pure time preference is employed as opposed to the 15% reported for the 3% rate of time preference in the DICE baseline. Moreover, as discussed below, Nordhaus (1994) reports that the pure rate of time preference is the input to which DICE results are most sensitive. The subject of the appropriate rate of pure time preference is a major focus of Chapter 4 of this report.

Although optimal control rates and carbon taxes vary widely for the year 2100, results from the two models, as shown in Table 10.6, are not all that disparate in the 1990s, though the sensitivity analysis shows a variation in the tax. This reflects the time dynamics of climate change. The costs of control are related to decreases in the rate of emissions as soon as the controls are applied. The benefits of control, on the other hand, are related to temperature change, which responds to changes in atmospheric concentrations of greenhouse gases with a long lag, whereas atmospheric concentrations respond only slowly to changes in emission rates because of the large stock and long lifetimes of greenhouse gases already in the atmosphere. Thus, the marginal costs of controlling greenhouse gases tend to be highly nonlinear with respect to the control rate, whereas most of the marginal benefits tend to be delayed by several decades.

10.5.3 Cost-effective strategies for stabilizing atmospheric CO_2 concentrations

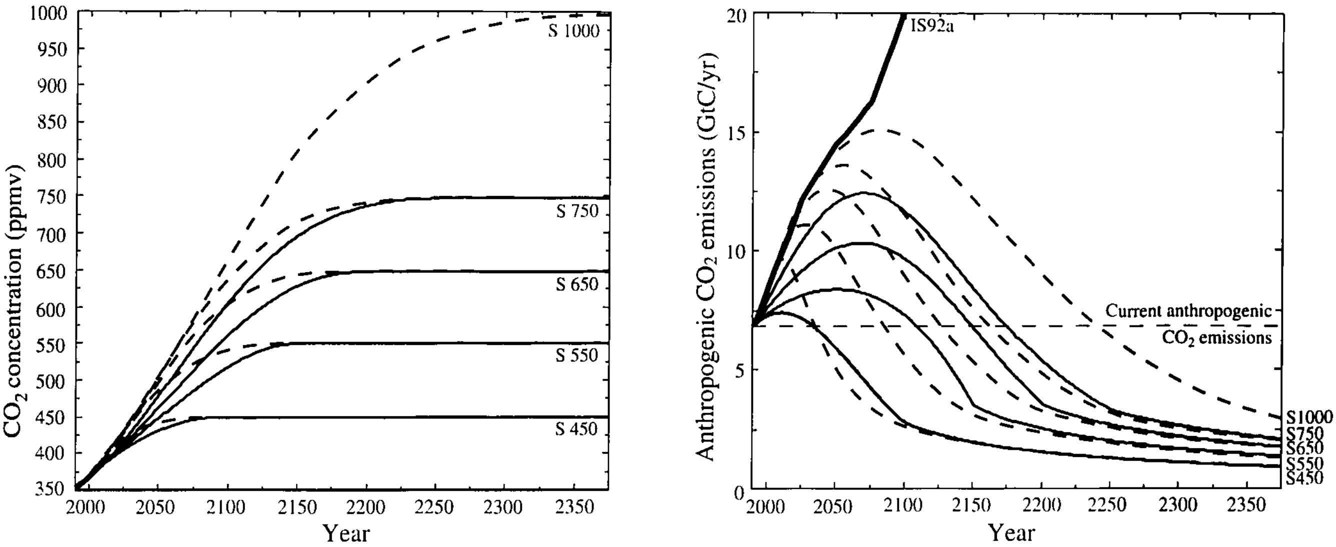
There have been several interesting applications of integrated assessment modelling to the issue of concentration targets. The ultimate goal of the UN Framework Convention on Climate Change is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." Under the terms of the Convention, mitigation costs are to play a limited role in establishing the concentration target. The permissible concentration level will depend on our understanding of the greenhouse effect and its potential consequences.

Mitigation costs are a more important consideration in determining how the target is to be achieved. The Convention states that "policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost." A particular concentration target can be met in a variety of ways. For example, Figure 10.3(a), drawn from the IPCC Synthesis Report, shows trajectories for stabilizing CO_2 concentrations at 450, 550, 650, 750, and 1,000 ppmv. Figure 10.3(b) shows two alternative emission paths for reaching each of the four lowest CO_2 concentrations. Some ways of meeting concentration targets will be more costly than others. Integrated assessment modelling can help identify emission paths that minimize the costs of meeting a prespecified concentration level (see Chapter 9).

Richels and Edmonds (1995) have examined the question of cost-effectiveness in achieving a particular concentration target. They found that the emission timepath can be as important as the concentration level itself in determining the ultimate price tag. Specifically, they examined alternative emission profiles for limiting CO_2 concentrations to 500 ppmv in the year 2100. Employing two widely used energy-economy models (the Edmonds-Reilly model and Global 2100), they found that emission timepaths involving modest reductions in the early years followed by sharper reductions later were less expensive than those involving substantial reductions in the short term. A similar conclusion can be found in Kosobud *et al.* (1994).

There are several reasons why shifting emission reductions into the outer years can reduce mitigation costs. As noted in Wigley *et al.* (1996)

> to a first approximation, a concentration limit defines a "carbon budget" (e.g., an allowable amount of carbon that can be released into the atmosphere between now



(a) CO_2 concentration profiles leading to stabilization at 450, 550, 650 and 750 ppmv following the pathways defined in IPCC (1995) (solid curves) and for pathways that allow emissions to follow the IS92a scenario (IPCC, 1992) until at least the year 2000 (dashed curves). A single profile that stabilizes CO_2 concentration at 1,000 ppmv and follows IS92a emissions at least until 2000 is also shown.

(b) CO_2 emissions leading to stabilization at concentrations of 450, 550, 650, 750 and 1,000 ppmv following the profiles shown in (a) from a mid-range carbon cycle model. Results from other models could differ from those shown by up to approximately ±15%. For comparison, the CO_2 emissions for IS92a and current emissions (dotted line) are also shown.

Figure 10.3: Emission profiles consistent with stabilization of CO_2 concentrations at levels from 450 to 1,000 ppmv.

and the date at which the target is to be achieved). The issue is how the carbon budget is to be allocated over time. Several factors argue for drawing more heavily on the budget in the early years. With the economy yielding a positive return on investment, emission reductions in the future will be cheaper than emission reductions today. That is, a smaller amount of today's resources needs to be set aside to finance them. As a result, the same level of cumulative emission reductions can be achieved at a lower total cost to society. In addition, slowing the transition away from fossil fuels provides valuable time to develop low-cost, carbon-free alternatives, to allow the capital stock to adapt, and to remove carbon from the atmosphere via the carbon cycle. Cumulative emissions for a 550 ppmv ceiling can differ by more than 60 PgC, with higher cumulative emissions associated with higher near term emissions. (See Volume 1)

Building on the earlier work of Nordhaus (1979), Manne and Richels (1992, 1993) have explored least-cost mitigation paths for achieving concentration targets of 450-750 ppmv. Figure 10.4 shows results from their MERGE model. In each instance, the least-cost path allows for some growth in global emissions in the early years, but this is followed by sharp reductions later on.

These studies should not, however, be seen as supporting a "do nothing" or "wait and see" strategy. First, each concentration path still requires that future capital equipment be less carbon-intensive than under a scenario with no carbon limits. Given the long-lived nature of energy-producing and -using equipment, this has implications for current investment decisions. Second, new supply options typically take many years to enter the marketplace. To have sufficient quantities of low-cost, low-carbon substitutes in the future would require a sustained commitment to research, development, and demonstration today. Third, any available no-regrets measures for reducing emissions are assumed to be adopted immediately. Finally, it is clear that emissions must ultimately be reduced. One cannot go on deferring emission reductions indefinitely. The lower the concentration target, the more substantial the required emission reductions.

Other authors cite reasons for more mitigation sooner. These include the prospect of inducing further cost reductions through abatement action, the prospect of avoiding being locked in to more carbon-intensive patterns of development, and the extent to which inertia may amplify the costs of having to make more rapid emission reductions later.

Models that emphasize inertia and induced innovation (e.g., Hourcade and Chapuis, 1995) place greatest emphasis on the need to avoid investments that tend to "lock in" a higher carbon future and on the fact that evasive action now reduces both the climate risks and the possibility of having to take more rapid action later. His results show that for an atmospheric limit of 500 ppmv, delaying the response by 20 years could double the subsequent required rate of abatement. A parallel study of CFCs showed that if the phase-out had begun

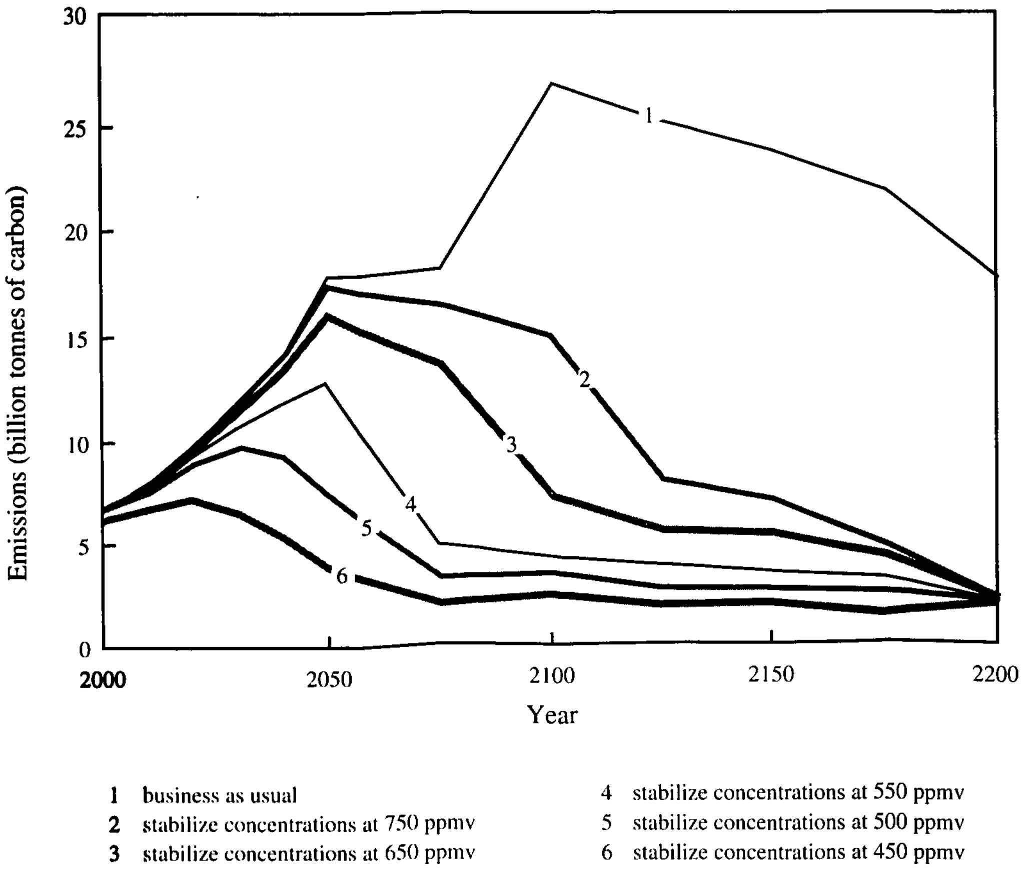


Figure 10.4: Least-cost emission paths for achieving alternative atmospheric concentration targets.

ten years earlier, it would have allowed much slower reductions of CFC use. The level of protection of the ozone layer resulting from the London Amendments to the Montreal Protocol could have been achieved while CFC use continued during the 1990s and with far less need to scrap capital stock.

Another line of analysis is developed by Grubb *et al.* (1994, 1995), drawing on studies of energy systems and the observation that much innovation comes from "learning by doing." Such innovation represents an external benefit that is not captured in market signals. Their model focusses on inertia and induced innovation and they conclude that induced innovation amplifies the benefits of acting sooner rather than later. If induced innovation is sufficient for systems to adapt to emission constraints over a period of a few decades, then the optimal near-term control rate is likely to be considerably larger than projected with models that do not include induced innovation. However, this is a result derived from a cost-benefit analysis in which many of the benefits from stronger early action arise from reduced impacts. The model has not been run to a fixed limit on the concentration of CO_2 in the atmosphere.

Note also that the focus of these analyses is on mitigation costs. Consequently, they provide only partial guidance for policy making. Different emission profiles yield different concentration levels and rates of change in the years leading up to a particular concentration target. The implications for damages need to be considered. Unfortunately, the knowledge base is not yet available for preparing an optimal strategy considering the full array of costs and benefits. Integrated assessment models that include the full range of factors that bear on the optimal timing of emission reductions have not yet been developed, and the relative importance of the various economic issues that bear on the question is still a matter of debate.

10.5.3.1 *International cooperation*

Integrated assessment models show there is a strong need for international cooperation because developed nations cannot independently reduce atmospheric CO_2 concentrations on their own (OTA, 1994; Bradley *et al.*, 1994; Edmonds *et al.*, 1995; Manne and Richels, 1992; Manne *et al.*, 1993; Nordhaus and Yang, 1995; and Tol *et al.*, 1995; see also Chapter 9).

Regarding the resolution of political conflicts over climate change policy between developed and developing countries, Read (1994b) points to the potential for biofuel production in developing countries. Financed by the developed economies, a biofuel initiative could generate beneficial multiplier effects in underemployed and cash-constrained developing rural economies.

10.5.4 *Results from uncertainty-oriented policy optimization models*

Policy optimization modellers have pursued a number of alternative approaches to incorporating the large uncertainties inherent in the various elements of the climate system into their analyses. The discussion here deals with results obtained from these approaches in the following order:

(1) Sensitivity analyses of key model inputs and parameters
(2) Analyses in which all model inputs and parameters are treated stochastically
(3) Uncertainty analyses that focus on the implications of a small number of uncertainties that seem particularly relevant to the policy issues being addressed

These results also suggest a number of modelling challenges that have been identified as high priority areas for future improvements in integrated assessment modelling.

10.5.4.1 Sensitivity analyses

Given the sizable uncertainties inherent in virtually every major input and model parameter employed in any analysis of global climate change, it is important to assess the implications of the key uncertainties on model results. A common first step in this effort is sensitivity analysis, which involves looking at how key model outputs respond to changes in input or parameter values over plausible ranges.

Table 10.6 shows control rate and carbon tax sensitivities for two models. For example, for the CETA model the initial control rate for the years 1990-2000 moves from 0% below baseline emissions in the base case to 7% when the sensitivity of global mean surface temperature to a CO_2 doubling is increased from 1°C to 5°C. In addition, the initial carbon tax rate for 1990-2000 changes from $2 per tonne to $29/tonne over the same range of global mean surface temperature sensitivities. Similarly, in the DICE model the initial control rate for 1995 changes from 9% below baseline emissions in the base case to 19% when the pure rate of time preference is changed from its base value of 3% to 1%.

Another type of sensitivity analysis involves focussing on a small number of more carefully designed scenarios that are expected to lead to fundamental changes in key model outputs. A recent analysis of carbon-free advanced energy technologies was performed by Edmonds *et al.* (1994b). In this study the implications of advanced energy technologies (including very low-cost biomass fuels) for greenhouse gas emissions and temperature change were investigated. Obviously, the introduction of very low cost noncarbon fuels leads to lower carbon emissions and less temperature rise in the long run (post-2050). A somewhat surprising result of this analysis, though, is an increase in temperature prior to 2050 as the replacement of carbon-based fuels with carbon-free fuels leads to a reduction in sulphur emissions and, therefore, fewer climate-cooling sulphur aerosols in the atmosphere. Lower sulphur emissions, however, would produce benefits in the form of reduced acidic deposition.

10.5.4.2 Baseline projections and uncertainty

Manne and Richels (1993) have argued that any deterministic projection of baseline carbon emissions may be upwardly biased because individual energy consumers should already be reducing their consumption of carbon-based fuels because of the possibility of constraints on carbon emissions in the future. They compute the implicit carbon tax in the year 2000 as a function of the probability that U.S. carbon emissions will be limited to 1990 levels. For example, if consumers feel there is a 50-50 chance that carbon emissions will be constrained in 2010, they will reduce carbon emissions in 2000 as if a carbon tax of $17.50 per tonne of carbon were already in place.

10.5.4.3 Results from stochastic simulation models

Stochastic simulation models generalize the sensitivity analysis idea by including probability distributions for all major inputs and model parameters. Each input distribution is sampled, the value chosen is used in the subsequent calculations of the model, and the process is continued until probability distributions are derived for each output variable of the model. The PAGE (Hope *et al.*, 1993) and ICAM-2 models (Dowlatabadi, 1995) are prominent examples of integrated assessment models that take this approach.

An analysis with PAGE of no control and stringent control options results in a recommendation for adaptation rather than mitigation as a first-best policy initiative. Conditions under which both adaptation and aggressive mitigation options ought to be pursued are also identified.

It is also possible to do a more comprehensive type of sensitivity analysis with the stochastic simulation approach by computing the partial rank correlation coefficient of output measures of interest with respect to variations in each input. For example, Hope *et al.* (1993) report that "cheaper preventative costs of CO_2" and "no action CO_2 emissions (i.e., baseline emissions) of CO_2" have the greatest effect on total cost uncertainty, and "global temperature sensitivity to doubling of CO_2" and "half life of global warming response to change in forcing" have the greatest effect on total impact uncertainty.

The methods described above are unable to make the uncertainties associated with disagreement and subjectivity explicit. Relating the concept of uncertainty to differences in individual perspectives, Van Asselt and Rotmans (1995) arrived at the concept of perspective-based alternative model routes as a methodology to make uncertainties within IAMs visible and tangible. Alternative model routes can be considered as model interpretations in which not only parameters but also relationships are varied according to the bias and preferences of a particular perspective, resulting in alternative model structures.

10.5.4.4 Uncertainty, decision analysis, and the value of information

Climate change may have severe impacts on individuals and societies. On the other hand, the impacts may not be very severe at all. Individuals and societies often attempt to reduce the impact of low probability/high consequence events through various means. As shown in Table 10.7, Nordhaus (1994) groups activities designed to mitigate the effects of uncertainty on economic welfare into three categories: (1) traditional insurance, (2) consumption smoothing, and (3) precautionary investments.

Table 10.7. *Alternative policies to mitigate uncertainty*

Category	Source of Uncertainty	Policy
1. Traditional Insurance	1. Diversifiable (individual) risk	1. (a) Private insurance (b) Social insurance (against terms-of-trade or income losses)
2. Consumption smoothing over time	2. Risk of large or catastrophic loss	2. Investment (for a rainy day)
3. Precautionary investments	3. Uncertain scope of damage or abatement costs	3. (a) Precautionary abatement (e.g., higher carbon tax) (b) Precautionary adaptation (e.g., retreat from coastline) (c) Investment in knowledge (e.g., geophysical and social science research)

Source: Nordhaus (1994).

Traditional insurance involves pooling together large groups of people, each of whom is subject to a small probability of a large loss (such as having a house burn down). Thus, each individual pays the *a priori* expected value of a loss plus a small transaction fee to get compensated for the catastrophe should it occur. The pooling necessary to implement this approach requires that the occurrence of the catastrophe among the members of the population be more or less independent. This is not the case with climate change, however, for which the impacts are likely to be pervasive throughout the globe. On the other hand, since some individuals (e.g., people who live on coastlines) will be affected more severely than others, traditional insurance may help allocate the costs of the total damages resulting from climate change in a way that improves welfare. Even this capability to reallocate the costs of climate change through traditional insurance may also be somewhat limited, though, because those who are most vulnerable may be known in advance or can be easily identified when the impacts of climate change start to be felt.

Consumption smoothing over time amounts to the social equivalent of "saving up for a rainy day." If there are significant thresholds in the impacts of climate change, it is possible that societies will incur large adjustment or mitigation costs. Thus, welfare may be improved by saving capital now to consume when the threshold impacts occur.

Precautionary investments in mitigation, adaptation, or information represent the third type of policy that can be used to mitigate the uncertainty associated with climate change. Such actions enable societies to hedge against the possibility of bad climate outcomes before the major uncertainties determining the severity of the climate change problem have been resolved.

It appears that all three types of policies for coping with climate change uncertainty are valuable. In terms of overall payoff, however, the traditional insurance approach is the most tactical, in that it simply redistributes the costs of any climate change impacts that might occur, and the precautionary societal investment is the most strategic, in that it involves national or international investments now that can significantly reduce the total worldwide costs of climate change impacts in the future. Thus, a number of precautionary investment analyses have started to appear in the literature. One innovative example is the analysis, based on a stochastic optimization model, that is included in Chapter 4 of *Buying greenhouse insurance: The economic costs of CO_2 emission limits* (Manne and Richels, 1992). This analysis deals explicitly only with the cost of CO_2 emission reductions, but it is assumed that U.S. decision makers must act initially without knowing what ultimate limit on carbon emissions will emerge from further scientific research and international negotiation. However, it is assumed that by 2010 it will be revealed whether (1) no limits will be necessary, (2) a 20% emission reduction will be required, or (3) a 50% reduction will be required. Each of these future policy outcomes is assigned a probability of occurrence. This formulation makes the idea of hedging against a range of future outcomes explicit, with the initial control rate and carbon tax for the optimal hedging strategy (the one that maximizes the expected future utility of consumption) lying between the maximum control and no-control strategies, and with the exact level depending on the probabilities assigned to the different control outcomes. Put differently, there is a risk premium associated with emitting carbon, owing to the fact that carbon emissions may be constrained (and possibly severely constrained) in the future.

A study by Hammitt, Lempert, and Schlesinger (1992) traces alternative control strategies for attaining certain temperature constraints. Although not determining an optimal path, this study shows that a "moderate control strategy" is less costly than an "aggressive" approach if either the temperature sensitivity to a doubling of CO_2 is low or the allowable temperature change is above 3° C.

In *Managing the global commons: The economics of climate change*, Nordhaus (1994) performs a decision analysis with his dynamic global cost-benefit model (DICE) using a representation (derived from an extensive stochastic simulation analysis with the model) of the relevant uncertainties associated with climate change. He concludes that "roughly speaking, the optimal carbon tax doubles when uncertainty is taken into account, and the optimal control rate increases by slightly less than half. The increased stringency of controls results from the interaction of different uncertain variables, whereby extreme events may cause significant economic costs."

10.6 Strengths and Limitations of Current Integrated Assessments

The five biggest challenges facing integrated assessment modellers are

(1) Developing a credible way to represent and value the impacts of climate change
(2) Developing a credible way to handle low probability but potentially catastrophic events
(3) Developing realistic representations of the dominant processes and policies in the developing countries
(4) Integrating and managing a large and diverse array of data and models from many researchers and many disciplines
(5) Improving the relevance of the models to policy needs and the presentation of their results to policymakers and the public

10.6.1 Representation and valuation of impacts of climate change

A major problem in attempting to analyze and value climate change impacts is that the projections from most general circulation models, until recently at least, have been based on a hypothetical steady-state situation (a doubled-CO_2 climate). In reality, however, greenhouse gas concentrations are not steady and will not necessarily stabilize at a level equivalent to a doubling of preindustrial CO_2 concentrations. Moreover, there are uncertainties about many elements of these projections, especially at a regional level. The process of projecting transient regionalized changes in the key climate variables – such as temperature and precipitation – that lead to impacts on economies and ecosystems is in its infancy and is thus a source of additional uncertainties. Furthermore, the climate information required to most effectively project the impacts has in many cases not yet been determined, nor have the most appropriate measures of climate impacts, and ecosystems may not currently be in equilibrium. Finally, it may be necessary for this information to be analyzed using valuation methods that are still under development and not tightly linked to the impacts on natural systems in order to provide policymakers with the information they need to decide what to do.

10.6.2 Consideration of low probability/high consequence events

The first results from integrated assessment models, which considered only the expected costs and benefits of controlling greenhouse gases, have generally concluded that only a modest current level of control is warranted. However, it may not be expected conditions that should be our main concern but, rather, relatively low probability catastrophic events that are irreversible or from which it would be very difficult to recover. Unfortunately, lack of data, lack of understanding of the relevant processes, and analytical intractability have prevented such events from receiving adequate attention in the integrated assessments that have been performed to date (see Chapter 6). The implications of these low probability/high consequence events for current decisions have just started to be investigated through the use of integrated assessment models (see Nordhaus, 1994; Peck and Teisberg, 1994; Lempert *et al.*, 1994, 1995).

10.6.3 Critical issues in developing countries

In general, the processes and policy options relevant to climate change are easier to assess in the twenty-four countries of the OECD. This stems from the facts that these countries have been studied more intensively and that their populations and economies are growing relatively slowly. The data and understanding of critical processes and issues in the 140-odd non-OECD countries are more limited. Many of these countries are in a state of rapid development or dynamic change, making projections of key economic drivers and social organizations over even short periods of time extremely difficult. Moreover, the contribution of these countries to climate change and their responses to it are likely to be influenced by other more immediately pressing concerns. Three of the most critical such issues in the developing countries are land use, land tenure, and population.

The way land is used is a key determinant of the net emissions and accumulation of greenhouse gases in the atmosphere and of the impacts of climate change. However, land use and land tenure decisions in the developing countries will be driven by development goals and local pollution concerns rather than climate change concerns over at least the next several decades. Therefore, it is important to track trends in land use and land tenure in order to project the contribution of the developing countries to global climate change and how they will be affected by any changes that might occur. Only a few of the operational integrated assessment models (e.g., Alcamo, 1994; Morita *et al.*, 1993) track land use at all, and even those models are limited by lack of good data regarding current land use patterns in the developing countries, as well as a lack of understanding about who controls land use decisions at present, who is likely to control them in the future, and what criteria will be used in allocating land to alternative uses.

Another fundamental uncertainty that complicates assessments of the magnitude of the global climate change problem and the effectiveness of policy responses to it is future population growth, especially in the developing countries. In general, more population means more economic activity and more greenhouse gas emissions. Again, though, trends and policies regarding future population growth will depend more on other phenomena (the spread of diseases, the level of income, the cultural norms) and policies (e.g., regarding education, health care, and birth control) than on explicit consideration of the implications of population for climate change in the future. Virtually all the existing integrated assessment models take future population growth as given, although the

TARGETS model of Rotmans *et al.* (1994) has recently become the first exception (Van Vienen *et al.*, 1994). Moreover, the projections used generally all come from one or two international agencies.

The extent to which a better understanding and modelling of land use, land tenure, and population growth in the developing countries will alter the insights regarding the climate change problem and potential policy responses to it produced by the current set of aggregate integrated assessment models is an open question. There is no doubt though that there is an urgent need to add detail in these areas that would better reflect the reality of developing countries and thus improve the credibility of the models.

10.6.4 Model integration and management

The complexity and multidisciplinary nature of the climate change issues create another challenge for integrated assessment modellers – that of linking a vast amount of data, analysis, and computer code developed by different researchers from different disciplines into a unified whole. It is particularly important to maintain consistency between the assumptions made in different parts of the analysis and to preserve the integrity of the information passed from one module to another. For example, some of the early integrated assessments made very optimistic assumptions about technical change in some parts of the analysis but not in others.

Another important issue in integrated modelling is the compatibility of the many modules included in the model, each reflecting the modelling approaches and abilities of a distinct set of disciplines. A comparative static model, describing the difference between two equilibrium states (characteristic of many climate and climate impact models run to date), cannot readily be tied to a dynamic model like those used to project economic activity and carbon emissions. But even two dynamic models can work on two entirely different timescales; for instance, larger economic models are at best seasonal whereas general circulation models operate in time steps of tens of minutes. Spatial scales can also differ, not only in resolution, but also conceptually. Economists, for instance, tend to think in terms of nations and geopolitical regions, whereas ecologists think in terms of habitats and life zones. A third difference is the degree to which models approximate the real world. Normative models, which describe how systems should operate (a paradigm reflected in some economic models) cannot be easily integrated with descriptive models of how the world actually operates (common in climate and ecological modelling). The compatibility issue is at present being dealt with through trial and error. Continued feedback with the mother disciplines is required to ensure that modules are not used or changed in an inappropriate manner.

In addition to the specific problems of integrating information across disciplines, modellers have to deal with a number of challenges that need to be addressed in any large-scale modelling enterprise (Karplus, 1992). One issue is separability, or which links to include? This issue was already touched on in the discussion of Figures 10.1 and 10.2. A number of models, for example, neglect the cooling effect of sulphate aerosols (see Section 10.5.1.4), which can have important implications for the temperature profile. In addition, the influence of another link between climate and fossil fuel combustion, hot spells and ozone formation, has only been included parametrically (see Chapter 6), if at all, without having been studied with a full-fledged model. These are just two examples of known links, one with a known effect, one with an unknown effect, that could profitably receive more attention.

Related to the issue of separability is the question of selectivity. Is it appropriate to study the enhanced greenhouse effect in isolation, or should it be studied simultaneously with other major environment and development problems? The TARGETS model (Rotmans *et al.*, 1994) is the first to make such an attempt at integrating these issues. This model tries to address the concept of sustainable development from a world perspective, covering the global issues of human health and demographic dynamics, energy resources, global element cycles, and land- and water-related problems. In addition, the discussion of the secondary benefits of emission control in Chapter 6 and the first results of the FUND model (Tol *et al.*, 1995) indicate that it is worthwhile to tie the analysis of global warming to conventional air pollution issues.

Counteracting the call for more causal links and further integration is the curse of dimensionality. The larger a model, the less transparent it is, and the harder it is for analysts and policymakers to interpret its results. The sheer size of the model renders full sensitivity analyses impossible, and it becomes more difficult for the modellers themselves to oversee what is happening.

A further general problem of modelling, but one that is particularly relevant in the analysis of global change issues, involves the need to consider the consequences of discontinuous climatic or ecological responses. Inputs to IAMs reflect the world as we know it or as we might expect it to evolve, but climate change may bring surprises. Large uncertainties in our knowledge add to the need to consider discontinuous system responses. Atmospheric physics and chemistry seem to react relatively smoothly to external changes. However, ecological and, to some extent, economic responses could potentially be quite discontinuous. In a full uncertainty analysis, low probability events, such as the drying up of the U.S. corn belt, should be considered. The difficulty with such events, however, is that they are unprecedented and therefore hard to model.

The final problem is how to deal with chaotic behaviour of the model itself. A model is chaotic if small changes in its inputs cause large, nonsystematic changes in its output. Because chaos is associated with nonlinear dynamics, integrated assessment models run the risk of being chaotic, yielding advice that arbitrarily depends on how they are calibrated.

10.6.5 Relevance and presentation

The fifth big challenge of integrated assessment modelling is how to improve the capability of modellers to answer the questions that are of greatest concern to politicians and the general public and to present the results in such a manner that they understand the outcome and its limitations. Although this is the eventual aim of integrated assessment, it is not a trivial matter. The majority of the problems obviously arise from the immature state of the current generation of models. Most current models, for example, do not give insight into income distribution or employment issues. Nonmarket impacts can be included only after having been econometrically valued, thus implying substitutability. Economic models of the costs of emission controls often consider only market-based instruments and assess only efficiency. As others have argued in this report, policymakers tend to have a broader outlook that embraces more than economics. On the other hand, integrated assessment models that are more biased towards the natural sciences provide a weaker representation of the societal forces driving emissions and impacts. Evaluation and optimization are often not represented. In addition, some models calculate changes on the basis of potential rather than actual outcomes without considering transitional problems.

With respect to improving the presentation of results, policymakers generally do not welcome voluminous compilations of model results, nor can they usually interpret a set of detailed maps or technical diagrams, nor do they like to have measures prescribed for them, and yet these are broadly the three approaches taken so far. What is needed is an interface where model outcomes can be concisely and understandably represented and perhaps further evaluated and optimized. This implies a further step in integration and the use of information from another discipline: decision support systems.

10.6.6 The state of the art in integrated assessment modelling

A number of approaches to integrated assessment of climate change are being pursued. Each of these has strengths and weaknesses relative to the others. Moreover, individual modelling teams have chosen to focus on different aspects of the climate change issue. At this time, the significant complexities and uncertainties associated with the operation of the climate system, and how it impacts – and is impacted by – human activities, make it impossible to know exactly what to focus on and what methodology to employ. Thus, there is an advantage to the use of multiple research teams pursuing a plethora of alternative approaches. The approaches may provide complementary insights into the causes and effects of climate change or provide identical reenforcing results that increase our confidence in the results from any one approach.

There is also a natural complementarity between the different types of analyses, in that the more aggregate models (particularly if embedded in a probabilistic framework) can be used to focus the development of the more complex models. The more complex models can, in turn, be used as one source of parameter values for the more aggregated models and as a means of testing the effects of the aggregation employed on specific results. Moreover, the simple models can be used to cross-check results from the more complex models for consistency (i.e., they can be used as benchmarks) and to help communicate results from them to the policy development community and to the public. Finally, as each research team continually modifies its work plan and builds on the work of the others, all the approaches may tend to converge. Even if this were to be the case at some point in the future, it is not clear which of the approaches being pursued today would lead most efficiently to that ultimate model. This once again suggests the efficacy of pursuing a multitude of alternative analytic approaches to the study of climate change and the potential responses to it.

Endnotes

1. The following types of values of unmanaged ecosystems are identified in Chapter 6 of this report: (1) direct and indirect use values (e.g., plant inputs into medicine and the role of mangrove forests in coastal protection), (2) option value (preserving a species to retain the possibility that it may be of economic use in the future), and (3) existence value (e.g., the value of knowing that there are still blue whales).

2. An exception is the FUND model (Tol *et al.*, 1995), which has separate damage functions for each of the damage categories discussed in Chapter 6.

3. These "carbon taxes" are actually the marginal costs of efficiently reducing carbon emissions by the optimal amounts. Efficiency in this context means simply that lower cost emission reduction measures are always implemented before higher cost ones.

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