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Overview of Recent Research Results of IAMs

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INSIGHTS FROM INTEGRATED ASSESSMENT

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ELEMENTS OF AN INTEGRATED ASSESSMENT MODEL

Integrated assessment can be defined as any attempt to integrate information from and across disciplines to help in the process of developing policy responses (Parson, 1994). Assessment is distinguished from disciplinary research by its purpose: to inform policy and decision, rather than to advance knowledge for its intrinsic value. Integrated assessment is identified by the breadth of knowledge sources on 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. Distinguishing integrated assessment from other assessment is important because integrated assessment poses distinct and more difficult challenges.

There are a large number of Integrated Assessment Models (IAM) used to examine the issue of climate change with a wide variety of differing goals and objectives motivating their construction. They vary greatly in their scope and detail, but all share the defining trait that they incorporate knowledge from more than one field of study. Thus, a great deal of work in the area of climate change falls within the bounds of this definition. This also means that integrated assessment models will vary greatly with regard to their scope. It is therefore important to distinguish models in this dimension as well as their level of detail. Models which attempt to grapple with the full range of issues raised by the climate issue are referred to as "full scale" IAMs (see chapter 10 in Bruce, et al., 1996).

"Full scale" IAMs must grapple with all of the complexity of an IPCC assessment. This is of course, an intimidating array of concerns. But while an IAM for climate change must consider a wide variety of issues, the venue is bounded. For the purpose of exposition, we group considerations into four general categories, depicted in Figure 1:

- I. Human Activities,
- II. Atmospheric Composition,
- III. Climate and Sea Level, and
- IV. Ecosystems.

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

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 are uncertain; future physical impacts of climate change are uncertain; and the future valuation of the physical impacts attributable to climate change are uncertain.

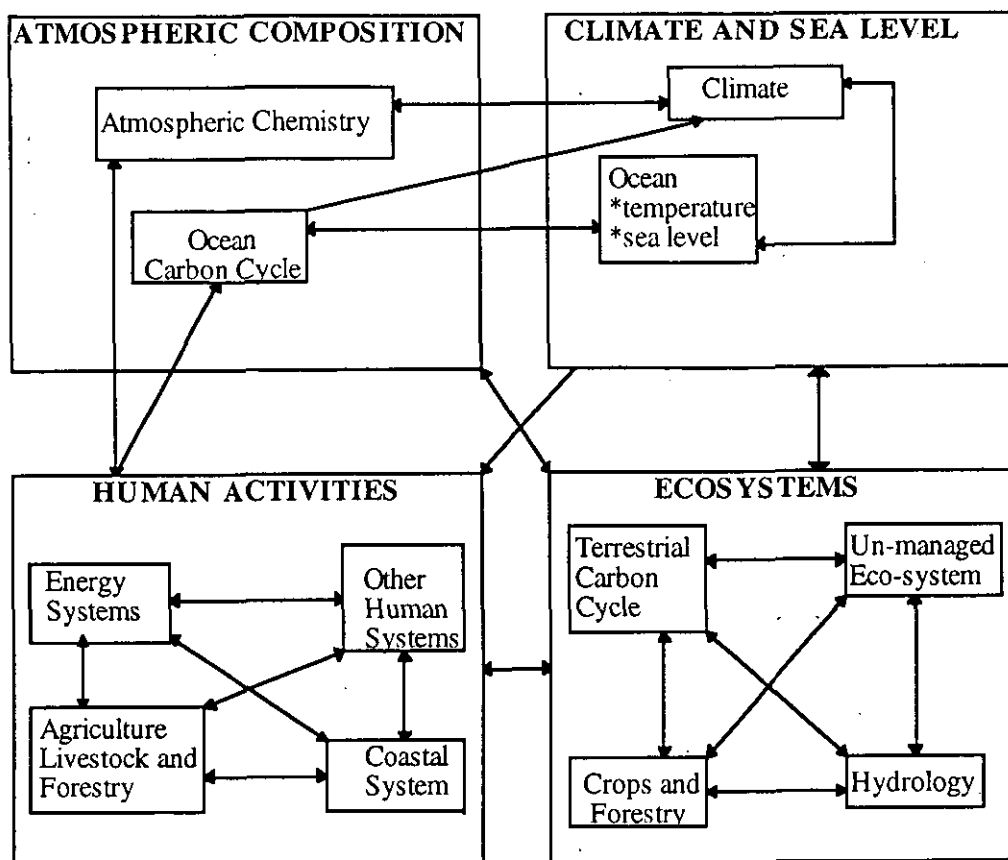


Figure 1: Key Components of Integrated Assessment Models

Uncertainty can be handled in a number of ways in integrated assessment modeling. Extensive sensitivity analysis can be performed on key model inputs and parameters, or explicit subjective probabilities can be assessed for these inputs and parameters and input 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 set research probabilities 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.

TYPES OF INTEGRATED ASSESSMENT MODELS

It is difficult to characterize the state of the art in integrated assessment modeling of climate change simply - 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, focusing on different dimensions of the problem, using different types of methodologies. Nonetheless, a focus on the tradeoffs between natural systems model complexity, economic model complexity, and effort devoted to the explicit incorporation of uncertainty can help us understand the model development that has been completed, that is occurring today, and that is planned or anticipated for the future.

There are three broad classes of integrated assessment models: (1) models that project the physical, ecological, economic and social consequences of policies - these are referred to as policy evaluation models here; (2) models that optimize over key policy control variables (e.g., carbon emission control rates, carbon taxes) given formulated policy goals (e.g., maximize welfare, minimize the cost of meeting a carbon emission or concentration target) - these are referred to as policy optimization models here; and (3) models for decision making under uncertainty, which either consider uncertainty about most major inputs, parameters and structural features, or represent a limited number of parameters and/or inputs from the policy optimization or policy evaluation models in a probabilistic way. Thus, 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. There are three general type of optimizing integrated assessment models: 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 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. Each approach has strengths and weaknesses, and produces particular types of insights regarding climate change and potential policy responses to it.

The policy optimization integrated assessment models focus on equilibrating the marginal costs of controlling greenhouse gas emissions and adapting to any climate change impacts that may occur with the damages that results after implementation of the mitigation and adaptation policies. In this approach any constraint on human activities is explicitly represented and costed out. At present, models of this type include very aggregate representation of climate damages, generally representing economic losses as a function of mean aggregate surface temperatures, but sometimes disaggregated into market and non-market damage components. Thus, as additional research on climate change impacts proceeds, it may be determined that these measurements are inaccurate. Moreover, it may be difficult to get policy makers to implement policies based on aggregate damages, as they are more likely to be able to relate to impacts on particular regions/countries and sectors (e.g., agriculture, biodiversity in tropical rain forests) which are not explicitly represented in the current set of cost/benefit type integrated assessment models. Early models of this type were also complicated enough 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 countries/regions in various market and non-market sectors, based in part on the impacts and mitigation areas being addressed in IPCC Working Group II. Economic values have not generally yet been put on these impacts, reflecting both the paucity of valuation studies in

some sectors, and the modelers perception that policy makers 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," discussed at some length in chapter 2 of the IPCC Working Group III report (Bruce, et al., 1996). On the other hand, there is no guarantee that the marginal cost of implementing the mitigation and adoption measures resulting from the individual targets will equal the marginal benefit (if they can be assessed) of the impacts avoided. In addition, like the early cost/benefit models these models have also been large enough that limited amounts of sensitivity analysis can be performed, but more explicit representations of uncertainty (and risk aversion) have not been included (although preliminary uncertainty analyses have been performed with the TARGETS model, van Asselt, et al., 1995).

Reflecting the high level of uncertainty about the future evolution of socio-economic and natural systems, some analysts have put the analysis of climate change into explicit decision making under uncertainty frameworks. These models have generally either been the results of a relatively complete uncertainty representation of all key parameters within simplified models of the types discussed above, or the result of adding a limited number of alternative states to the policy evaluation and policy optimization models discussed above. 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. Figure 2 places the models listed in Table 1 into the three primary categories, and relevant sub-categories, discussed above.

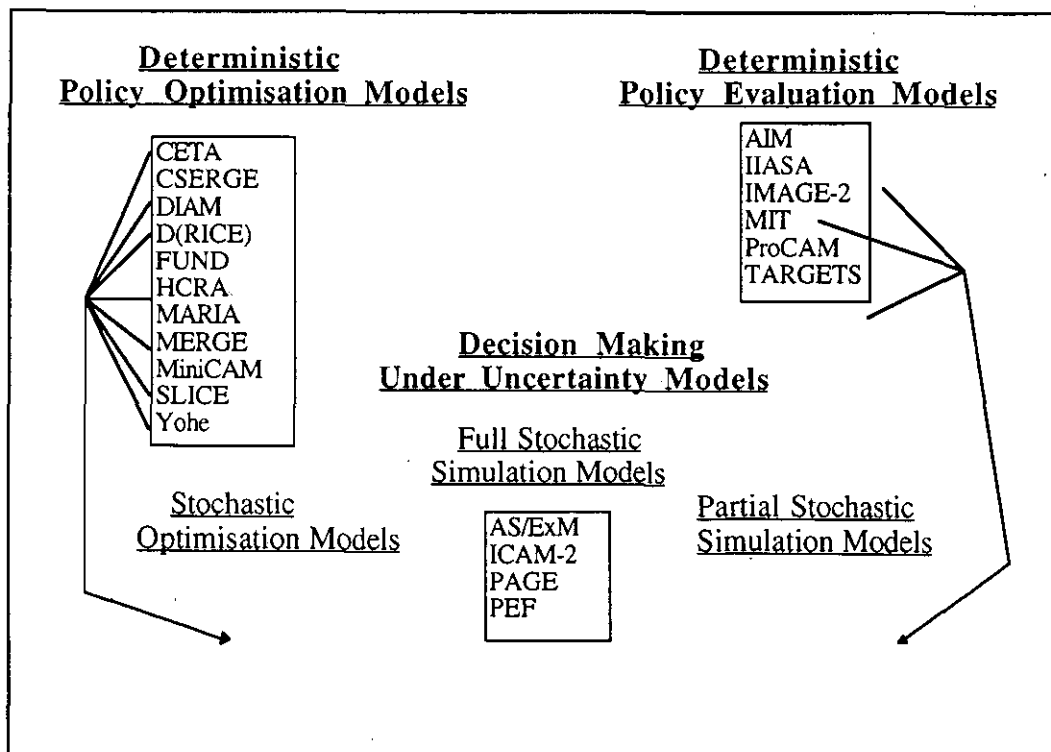


Figure 2: Types of Integrated Assessment Models

Table 1: Integrated Assessment Models

Model Acronym (full model name)	Principal Developers	Reference
As/ExM (Adaptive Strategies / Exploratory Model)	Rob Lempert/Steve Popper (Rand) Michael Schlesinger (Univ. of Illinois)	Lempert et al (1995)
AIM (Asia-Pacific Integrated Model)	T. Morita, M. Kainuma (NIES, Japan)	Morita et al (1994)
CETA (Carbon Emissions Trajectory Assessment)	Stephen Peck (EPRI) Thomas Teisberg (Teisberg Assoc.)	Peck and Teisberg (1992)
Connecticut (the Yohe model)	Gary Yohe (Wesleyan University)	Yohe (1995)
CSERGE (Centre for Social and Economic Research into the Global Environment)	David Maddison (University College of London)	Maddison (1994)
DIAM (Dynamic Integrated Assessment Model)	Michael Grubb, M.H. Dong, T. Chapius (Royal Institute of International Affairs)	Grubb, et al. (1995)
DICE (Dynamic Integrated Climate and Economy Model)	William Nordhaus (Yale University)	Nordhaus (1994)
FUND (Climate Framework for Uncertainty, Negotiation and Distribution)	Richard Tol (Vrije Universiteit Amsterdam)	Tol (1995)
HCRA (Harvard Climate Risk Assessment Model)	Jim Hammit (Harvard) Atul Jain/Don Wuebbles (Univ. of Ill.)	Hammit, et al (1995)
ICAM-2 (Integrated Climate Assessment Model)	Hadi Dowlatabadi (Carnegie Mellon) Granger Morgan (Carnegie Mellon)	Dowlatabadi and Morgan (1993)
IIASA (International Institute for Applied Systems Analysis)	Leo Schrattenholzer (IIASA) Arnulf Grubler (IIASA)	Schrattenholzer (1995)
IMAGE 2.0 (Integrated Model to Assess the Greenhouse Effect)	Joe Alcamo, M. Janssen, M. Krol (RIVM, Netherlands)	Alcamo (1995)
MARIA	Shunsuke Mori (Sci. Univ. of Tokyo)	Mori (1995)
MERGE 2.0 (Model for Evaluating Regional and Global Effects on GHG Reductions Policies)	Alan Manne (Stanford) Robert Mendelsohn (Yale) Richard Richels (EPRI)	Manne, et al. (1993)
MiniCAM (Mini Global Change Assessment Model)	Jae Edmonds (Pacific Northwest Lab) Richard Richels (Electric Power Research Institute) Tom Wigley (UCAR)	Edmonds, et al (1995)
MIT	Henry Jacoby/Ron Prinn (MIT) Zili Yang (MIT)	MIT (1994), Yang et al (1996)
PAGE (Policy Analysis of the Greenhouse Effect)	Chris Hope (Cambridge University) John Anderson/Paul Wenman (Env. Res.)	Commission of European Communities (1992)
PEF (Policy Evaluation Framework)	Joel Scheraga/Susan Herrod (EPA) Rob Stafford/Nathan Chan (DFI)	Cohan, et al (1994)
ProCAM (Process Orientated Global Change Assessment Model)	Jae Edmonds (Pacific Northwest Lab) Hugh Pitcher/Norm Rosenberg (PNL) Tom Wigley (UCAR)	Edmonds, et al (1995)
RICE (Regional DICE)	William Nordhaus (Yale University) Zili Yang (MIT)	Nordhaus and Yang (1996)
SLICE (Stochastic Learning Integrated Climate Economy Model)	Charles Kolstad (Uni. California, Santa Barbara)	Kolstad (1993, 1994a, 1994b)
TARGETS (Tool to Assess Regional and Global Environmental + Health Targets for Sustainability)	J. Rotmans (RVIM) M. Janssen (RVIM) H.J.M. de Vries (RIVM)	Rotmans et al (1995)

INSIGHTS FROM INTEGRATED ASSESSMENT MODELS

In what follows, we group some of the major insights obtained from integrated assessment models thus far into three main categories: (1) insights from policy evaluation models, that include many linkages and interactions between the several key elements of the climate/biosphere system, (2) insights from policy optimization models that directly consider the costs and benefits of potential climate change policy responses, and (3) insights from decision making under uncertainty oriented models.

There are also large differences in the outputs that individual modelers 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 emissions, 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 land use by activity (e.g., agriculture, forestry, etc.), and/or physical impacts like ecosystem at risk, coastal land area lost, fresh water requirements, and mortality rates.

Insights from Deterministic Policy Optimization Models

In this section we consider results from cost/benefit type integrated assessment models run with all inputs and parameters set at that 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 the 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.

Gradual Phase-In of Emission Reductions. In models that balance the costs of carbon emissions control against the reduced economic impacts of climate change in each region, results generally show that the optimal carbon tax starts at a relatively low level (\$5 to \$15 per ton) and then increases gradually over time generally reaching \$50-\$100 a ton by the end of the next century.

The gradual phase in of the carbon tax results from a number of factors: (1) the cost of emissions reduction are directly related to the emissions rate and, so, are incurred immediately; (2) the impacts of climate change are related to the concentration of CO₂ in the atmosphere, which is related to cumulative emissions over time, which affects the climate system with a lag; (3) the shape of the climate damage function in the models, generally quadratic or cubic in CO₂ concentrations, meaning that early increments to CO₂ concentrations have little effect; and (4) discounting whereby costs incurred in the near term are weighted less than benefits in the distant future because money today can be invested to yield a return in the future - or, in this case, money not spent on emission reductions today can be invested in other ways to yield more money to be used for emission reductions (and other goods and services) in the future.

Where and When Flexibility During the past several years, Stanford University's Energy Modeling Forum has been conducting a study on "Integrated Assessment of Climate Change." One of the most significant elements of this study has been the work of a study group (chaired by Dr. Richels the head of Global Climate Change Research at the Electric Power Research Institute and Dr. Jae Edmonds of Pacific Northwest National Laboratory) which has been examining the costs of emission reduction proposals for the post-2000 time

frame. Results from the preliminary report of this group (Richels, et al., 1996) are summarized here.

While calling for new commitments on the part of developed countries to limit emissions, the Berlin Mandate does not specify what the commitments should be. Rather it seeks further analysis and assessment to guide and inform the decision making process. The Energy Modeling Forum study group addressed a key issue in the analysis and assessment phase - the design of cost-effective mitigation strategies.

The Framework Convention on Climate Change states that "policies and measures to deal with climate change should be cost-effective so as to insure global benefits at the lowest possible costs." Adopting least-cost mitigation strategies will free up valuable resources for further addressing the climate issue or for meeting other societal needs. In our study, we explored ways of promoting this objective. In particular, the EMF study group focused on the importance of providing for flexibility both in the location and the timing of emission reductions. The question addressed by the group was the question of "how best" to reduce emissions. This is very different from the question of "how much" to reduce emissions. To address the latter requires a careful balancing of the costs of climate change management proposals with what such proposals might buy in terms of reducing the undesirable consequences of global climate change.

The insights from the group's analysis can perhaps best be communicated by way of an example. Among the scenarios examined was one that was similar in spirit to the proposal being put forward by the Alliance of Small Island States (AOSIS) and is explicitly included for consideration within the Berlin Mandate. In this scenario, the OECD countries are assumed to agree to reduce emissions by 20% below 1990 levels by 2010, and to hold them at that level thereafter. The group first calculated the costs under the assumption that OECD countries would be required to act independently to meet the proposed targets and timetables. That is, that they would be unable to take advantage of low-cost emission reduction opportunities that may exist in other parts of the world. Rather than rely on a single model, the analysis was based on independent runs of four widely-used energy-economy models. The models were developed by researchers at MIT, Stanford, Pacific Northwest Laboratory and EPRI. Costs are added from today through 2050 and discounted to 1990 at 5% per year. Because the models differed in terms of key inputs, for example, population, per capita productivity trends, the fossil-fuel resource base, etc., they differ in their cost projections. Nevertheless, they all suggest that the costs of adopting an AOSIS-like proposal will be substantial -- between two and eight trillion dollars.

Not surprisingly, OECD countries would be hardest hit. But the analysis also shows that non-OECD countries would also likely incur costs even though the reductions are confined to the OECD. This is because an economic slowdown in the OECD would affect the full range of developing country exports, and hence their economic growth.

The group then examined ways that we might achieve the same amount of emission reduction but at a lower cost. In particular, the benefits of providing what was referred to as "where" and "when" flexibility were examined. In the case of "where flexibility," emissions are reduced by the specified amount, but the reductions may be made where it is cheapest to do so regardless of their geographical location. For example, if emissions can be reduced cost-effectively through energy efficiency programs in developing countries, then these are included in the portfolio of emission reduction measures. In other words, the focus is on identifying the least-cost global solution for meeting each year's emissions targets.

In the case of “when flexibility,” the benefits from providing flexibility in the timing of emission reductions were examined. With regard to atmospheric CO₂ concentrations, the issue is not so much one of year-by-year emissions, but one of cumulative emissions. Because of the long lifetime of carbon dioxide in the atmosphere, CO₂ concentrations are determined by the total amount of CO₂ released over an extended period. Accordingly, a case where a limit was placed on cumulative emissions between now and 2050 was examined. This meant that a country participating in the agreement could emit more in the early years if it were willing to emit less later on. Flexibility in timing has several distinct advantages. A problem with tight near-term targets is that they require premature retirement of energy-producing and energy-using capital stock, for example, power plants, houses, and autos. As a result they are likely to be particularly costly. One advantage of “when flexibility” is it provides more time for an economical turnover of the existing capital stock. A second advantage is that it would provide more time to develop low-cost alternatives to carbon-intensive fuels. There has been substantial progress in lowering the costs of carbon-free substitutes (e.g., solar, biomass, energy efficiency) in the past. With a sustained commitment to R&D, there should be further cost reductions in the coming decades. It would make sense to rely more heavily on fossil fuels in the early years when the marginal costs of emissions abatement are highest. With cheaper alternatives in the future, there will be less need for reliance on carbon-intensive fuels.

The case where OECD countries have no flexibility as to where and when the emission reductions must be made is by far the most expensive case. Allowing emissions to be reduced where it is cheapest to do so cuts costs by nearly 70%. The most efficient strategy is one that provides for flexibility both in the location and the timing of emission reductions. Adding “when flexibility” to “where flexibility” halves costs again.

It is important to note that whereas the three cases differ markedly in terms of mitigation costs, they are likely to be quite similar in terms of environmental impacts. The reason is that they lead to identical levels of atmospheric CO₂ concentrations in the year 2050 and the concentration paths lie very close together prior to 2050. As a result, the differential impacts on temperature are likely to be negligible.

In summary, the analysis suggests that mitigation costs can be substantially reduced by providing for flexibility both in the location and timing of emission reductions. With the first, emission reductions are made where it is cheapest to do so. With the second, they take place when it is cheapest to do so. There are formidable obstacles to both, but the potential benefits are huge. Indeed, our calculations suggest that the potential savings to the international community may be of the order of trillions of dollars in unnecessary mitigation costs.

Insights From Deterministic Policy Evaluation Models

A number of interesting preliminary insights have also emerged from the application of the policy evaluation models. Some of the most interesting of these are described briefly here.

Policy Implications of the Sulfur Aerosols Effect. As discussed at length in the IPCC 1995 Working Group I report, the presence of sulphate aerosols in the atmosphere is presently thought to have a strong local cooling effect. This effect is manifest through three pathways: scattering and absorption of shortwave (solar) radiation effects, cloud reflectivity effects, and cloud persistence effects. The effect of sulphate aerosols on radiative forcing can be represented in a highly simplified manner by assuming a logarithmic relationship between the emissions and the direct forcing. By incorporating this simple relationship in integrated assessment models, a part of the sulfate aerosols can be taken into account. In this way, the sensitivity of the climate system to simultaneous changes in SO₂ and CO₂ 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). Therefore, policies which reduce fossil fuel use are not as effective as a simple greenhouse calculation might imply. The proper treatment of SO_2 is, therefore, an important consideration in the integrated analysis of climate change consequences of technology development and deployment. At the global level the strength of the negative radiative forcing resulting from sulfate aerosols can have a significant impact on the total amount of radiative forcing that results from any particular level of carbon emissions. If the aerosols levels are high, more of the carbon contribution will be offset; if aerosols levels are lower, then less of the contribution of carbon emissions will be offset. Moreover, the amount of sulfate aerosols in the atmosphere will depend on how much coal is burned, how much sulfur is in the coal that is burned, and how much of the sulfur in the coal that is burned is removed through sulfur control technologies.

Implications of the CO_2 Feedback Effect for Policy. It is anticipated that one of the main drivers of climate change will be the accumulation of carbon dioxide in the atmosphere caused primarily by fossil fuel combustion. On the other hand, numerous laboratory studies have demonstrated the positive effect increased carbon dioxide availability could have on plant growth. Finally, increased plant growth caused by climate change and CO_2 fertilization would lead to more carbon sequestered in plants and less in the atmosphere. This so called “ CO_2 feedback effect” is complicated by the fact that carbon, nitrogen, water, and sunshine are all potentially limiting factors in plant growth. Thus, it is necessary to understand both the nitrogen and carbon cycles, as well as shifts in temperature and precipitation to study the CO_2 feedback effect on the existing plants. In addition, however, the strength of this effect will depend on what is growing where (i.e., on land cover) which is itself difficult to project over a period of many decades. This implies, further, that land use policies may be nearly as significant as emission reduction policies in the short to intermediate term.

Competition for Land Between Biomass and Agriculture. One popular option for large scale substitution of fossil fuels is biomass plantations. A number of early studies based on back of the envelope calculations projected that extremely large amounts of biomass could be introduced at costs not much higher than today's fossil fuel prices and perhaps even lower prices. One concern that was expressed about these early estimates was the amount of land that would be required, especially with world population expected to roughly double by the end of the next century. With more people there would need to be more land for food production unless agricultural productivity can be increased to compensate. Moreover, more land would be required for the additional people to live. Finally, with world income projected to grow by a factor of ten and per capita incomes by a factor of five over the next century, there would be more intense competition for recreational land use, and forestry products. A number of integrated assessment models now include land use models that try to reconcile all these competing uses to which land may be allocated. Calculations done for IPCC 1995 Working Group II (Watson, et al., 1996) have shown that competition for land may limit the extent to which biomass energy can be relied on as an economic substitute for fossil fuels, and that this limit can be severe under certain sets of plausible assumptions about agricultural productivity, population growth, economic growth, and consumer preferences.

A first attempt to integrate the various aspects of the global land-use problem on a geographically-explicit base is done in the IMAGE 2.0 model. In the geographic detail the model represents the transformation of land cover as it is affected by climatic, demographic and economic factors. It links explicitly the changes in land cover with the flux of CO_2 and other greenhouse gases between the biosphere and atmosphere and, conversely, takes into account the effect of changing productivity of 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 which 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 regional and local demands for driving local land cover changes, and that land use rules can be used to represent driving forces of land conversions. Other examples involve the vulnerability of protected areas under shifting vegetation zones and 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 advanced analyses could well assist regional policy-makers in assessing the seriousness of climate change impacts (Alcamo, 1994).

Insights From Decision Making Under Uncertainty Models

Given the large uncertainties inherent in the various elements of the climate system, policy optimization modelers have pursued a number of alternative approaches to incorporating them into their analyses. The discussion here deals with results obtained from these approaches in the following order: (1) sensitivity analyses over key model inputs/parameters, (2) analyses where all model inputs and parameters are treated stochastically, and (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 modeling challenges that have been identified as high priority areas for future improvements in integrated assessment modeling.

Optimal Hedging Strategies. The idea of hedging against potentially adverse, but uncertain, events is well established in decision theory and widely used in corporate decision making and in everyday life. The extension of this idea to the climate change problem is difficult, but the process and its results can yield many useful insights. One example, of the application of this idea to the climate change problem, was an experiment conducted by seven of the models participating in the Energy Modeling Forum 14 study on "Integrated Assessment of Climate Change" (See Manne, 1996).

There are two alternative ways to think about climate policy when there are just two possible outcomes: a favorable and an unfavorable one. In one view the world is represented as though all uncertainties are resolved prior to making a decision about reducing greenhouse gas emissions. In this situation we have the opportunity to learn whether the state of the world is favorable or unfavorable before taking action.

According to the second view, decisions about climate policy must be made before the uncertainty about whether the climate change situation is favorable or unfavorable. For illustrative purposes here, it is assumed that global CO₂ uncertainties are resolved sometime shortly after 2020. Prior to 2020, the energy sector's supply and conservation investment decisions must be made under uncertainty about the importance of limiting carbon emissions. Thereafter, the uncertainties are resolved. This "sequential decision making under uncertainty" approach is pragmatic. Rather than focusing on long term forecasting, it emphasizes the importance of near-term decisions, how they are affected by long-term uncertainties, and how much one should be willing to pay for the timely resolution of those uncertainties.

By focusing on hedging strategies for a low probability, high consequence scenario, the model comparison study adopted a parsimonious design. Just two cases were considered out of many possibilities. One was described as a base (or reference) case; the other a low probability, highly unfavorable case. Uncertainties were defined in a way that could be incorporated in as many of the participating models as possible, and to minimize the computational burden on them. The uncertainties were also chosen in a way that would allow unambiguous interpretation, would be easily understandable by policy makers, and would

have significant impacts upon near-term decisions. In addition, it was desirable to employ variables that had been the subject of surveys of experts.

Upon reviewing the structures of the model and the literature, only two parameters appeared to meet all the criteria: the mean temperature sensitivity factor and the cost of damages associated with global warming. More precisely, climate sensitivity is defined as the equilibrium change in temperature that would result from doubling the CO₂ concentration of the atmosphere relative to the pre-industrial level, and warming damages are defined as the (market and non-market) economic losses that would result from a 3 degree C warming.

The group decided to define the extremely unfavorable case as one where each of these two variables is at the mean of the upper 5% of its probability distribution. In addition, with independence between the two outcomes assumed, this implies a 25% joint probability of the extremely unfavorable outcome. Based on expert surveys by Morgan and Keith (1995) on climate sensitivity and by Nordhaus (1994) on warming damages, the group determined (Nordhaus, 1995) that the upper 5% climate sensitivity value should be 2.3 degrees C above the base value employed in the individual model, and the unfavorable value of warming damages should be 7.8 times its base value. Finally, it was assumed that the two parameter values would remain uncertain through 2020 and be revealed immediately after that date.

The highest projection is that projected to occur if climate damages are ignored. The average "no control" projection of carbon emissions is 25 billion tons of carbon by 2100. Also included in the figure are the projected optimal carbon emissions when the climate sensitivity and climate damages are known in advance to be either both at their expected value or both at their extreme values. Interestingly, the average projection for carbon emissions in 2100 under expected climate sensitivity and climate damages is 40% below those in the "no control" case. On the other hand, if both parameters are known in advance to be at their extreme values, the models project that it is optimal to reduce emissions to about 10% of their baseline value by 2100 on average. The most interesting projection, however, is the case where both parameters are unknown until 2020, which shows that only a modest amount of hedging (about a 10-15% reduction in emissions relative to the baseline) should take place prior to 2020, and after 2020 emissions should be adjusted to quite near to those in the expected or extreme cases depending on which outcome occurs.

Value of Information. Value of information calculations were also performed for the experiment performed by the EMF "Decision Making Under Uncertainty" group. A number of interesting observations can be made regarding these results of these calculations:

(1) The value of information about the uncertain parameters is generally under \$100 billion dollars, because the probability of being wrong in hedging only modestly below the expected level of carbon emissions is small, and the cost of being wrong is generally only about 15% of GDP initially and declines rapidly as emissions are reduced rapidly to the actual climate sensitivity and climate damage parameter values.

(2) The lower the discount rate the higher the expected value of perfect information. This results is obtained because climate damages become significant only after CO₂ concentrations reach levels that will not be reached for several decades, while emission control costs start accruing immediately.

Thus, a reduction in discount rate means that the damages caused by under controlling prior to 2020, when the extreme climate damages turn out to be the actual climate damages, are weighted more heavily relative to the emissions reduction costs saved by controlling less than that case ultimately dictates in the short run.

(3) The later the date of resolution of the uncertainties, the higher the value of perfect information. The later the date of resolution, the greater become the cumulative errors of either too much or too little abatement.

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