INSIGHTS FROM INTEGRATED ASSESSMENT
(Draft #1)

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John P. Weyant

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Terman Engineering Center
Stanford University
Stanford, California

INTRODUCTION

Integrated assessment is defined here 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.

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 the human activities that affect greenhouse gas emissions; 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 socio-political 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 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. While there have been past examples of integrated assessments of major environmental issues (e.g., 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.

ELEMENTS OF AN INTEGRATED ASSESSMENT MODEL

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 therefore 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 (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:

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John P. Weyant
Department of Engineering-Economic Systems
and Operations Research
Stanford University
Stanford, CA 94305-4023

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Energy Modeling Forum
Stanford University
Stanford, CA 94305-4023

1. Human Activities,
2. Atmospheric Composition,
3. Climate and Sea Level, and
4. Ecosystems.

Figure 1 is not a unique depiction of the climate change system. An infinite number of aggregations are possible and a great many "wiring diagrams" already exist. This particular "wiring diagrams" has the virtue of including both human and natural system components. One alternative organization is the "end-to-end" characterization. In this organizational formulation there are also four categories, but the first becomes Emissions and the fourth becomes 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 de-emphasizes the interactive character of the IAMs, in particular the fact that the same human and natural systems which produce emissions suffer impacts.

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.

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, gases which have the capacity to change the radiative balance of the planet need be considered. At present the set consists principally of the following set of gasses: Water vapor (H_2O), Ozone (O_3), Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Sulfur aerosols. and the Chlouroflurocarbons 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 vapor and O_3 are not emitted in sufficient quantities by human activities to matter. Their concentrations are, however affected by the emissions of other greenhouse related gases such as carbon monoxide (CO), odd-nitrogen (NO_x), and non-methane hydrocarbons (NMHC).

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

1. Energy systems
2. Agriculture, Livestock, & Forest systems, and
3. 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 sulfur compounds as well.

Systems which 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 practices are generally linked to land-use as they 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 that are being released into the atmosphere. Most prominent among these are the chlouroflourocarbons (CFCs) 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 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 though 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:

1. agriculture, livestock, & forest systems,
2. energy systems,
3. coastal zones,
4. water systems,
5. human health,
6. the value of local air quality, and
7. the values of unmanaged ecosystems(1).

The second information set that a full scale IAM must generate is the concentrations of greenhouse gases. IAMs deal with the problem of translating the emissions flows generated by human activities into concentrations of greenhouse gases in the atmosphere. This requires dealing with the fact that emissions are the sum of those from natural and anthropogenic sources. 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 predominately by interactions between atmospheric concentrations and the oceans and terrestrial systems.

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(1) The following types of values of unmanaged eco-systems 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, respectively, (2) option value (preserving a species to retain the possibility that it may be of economic use in the future), and (3) existence value (i.e., the value of knowing that there are still blue whales).

Models deal with CO_2 in a variety of ways which range from simple airborne fraction models, which use a proportional approximation method to determine atmospheric concentrations, to interactive processes models of the atmosphere and biosphere. The present understanding of both the carbon cycle and atmospheric chemistry have been surveyed by IPCC Working Group I.

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. This in turn interacts with the economic value of changes in health conditions.

The third information set that a full scale IAM must generate is the state of climate and sea level. These two information sets are interdependent. That is 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. They thus also determine the rate of sea level rise. In addition, interactions between the atmosphere and cryosphere affect climate change and sea level. Sea level calculations must grapple in some way with the major land based ice sheets.

It should also be noted that the ocean which interacts with atmospheric processes in determining climate change and sea level is the same ocean which is absorbing carbon in the atmospheric composition model. Thus, while Figure 1 treats them as if they were separable features, they are not, and more process oriented IAMs will have a single ocean model which determines carbon uptake, sea level rise, and thermal lag in climate change.

In Figure 1, the fourth category of IAM information is ecosystems. This category includes information associated with the natural system emissions of greenhouse related gases, the terrestrial carbon cycle, 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 are uncertain, future physical impacts of climate change are uncertain, and the future valuation of the physical impacts attributable to climate change are uncertain.

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 rationale 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

Prior to 1992, only two integrated assessment of climate change models had appeared in the literature (Nordhaus, 1989, 1991); Rotmans (1990). Since 1992 a host of new models have emerged. Table 1 lists 23 integrated assessment models that are in active use or are under active development; in addition, a number of additional modeling efforts are underway, so the number of existing integrated assessment models might be expected to double or more in the next few years. Even within the group of models listed in Table 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 modeling in this area is so active that even models that are fully operational are continually being refined and updated substantially every 3-6 months. Table 2 summarizes the current development status and most recent documentation available for the 23 models listed in Table 1.

The models included in Table 1 can be compared structurally according to the amount of emphasis they place on each of the blocks shown in Figure 1. The results of this process are shown in Table 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 modeling of economic activity and rely on exogenous greenhouse gas emission trajectories. In addition, more than half of the existing models consider both the physical impacts and their valuation only through aggregate damage functions that relate economic damages directly to mean global temperature change.

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.(2) 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

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(2) An exception is the FUND model (Tol, et al., 1994) which has separate damage functions for each of the damage categories discussed in Chapter 6.

(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. Table 4 places the models listed in Table 1 into the three primary categories, and relevant sub-categories discussed above.

INSIGHTS FROM INTEGRATED ASSESSMENT MODELS

It has only been since 1992 that most of the integrated assessment of the climate change models have been constructed. 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 that have been employed to study the climate change issue make the comparison and reconciliation difficult.

In what follows, we group the available model results into three main categories: (1) results from policy evaluation models, that include many linkages and interactions between the several key elements of the climate/biosphere system, (2) results from policy optimization models that directly consider the costs and benefits of potential climate change policy responses, and (3) results 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 eco-systems 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. Figure 1 shows the carbon tax trajectories that result from the optimal carbon emissions scenario from the EMF 14 study on "Integrated Assessment of Climate Change." In this scenario, the costs of carbon emissions control are balanced against the reduced economic impacts of climate change in each region represented in each of the models. The results show that the optimal carbon tax starts at a relatively low level ($5 to $15 per ton) and is then increased 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 CO_2 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 CO_2 concentrations, which means early increments to CO_2 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 two 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.

Figure 3 summarizes the results of the analysis. The figure is based on the average of the model results. The left-most bar shows the case where OECD countries have no flexibility as to where and when the emission reductions must be made. This is by far the most expensive case. Allowing emissions to be reduced where it is cheapest to do so (the middle bar), cuts cost by nearly 70%. The most efficient strategy is one that provides for flexibility both in the location and the timing of emission reductions. Note that when we add "when flexibility" to "where flexibility" costs are halved 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 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).

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 CO2 fertilization would lead to more carbon sequestered in plants and less in the atmosphere. This so called "CO2 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 CO2 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 is 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 using 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).

Figure 4 shows one way of thinking about hedging against future climate risks. This figure contrasts two alternative ways to think about climate policy when there are just two possible outcomes: a favorable and an unfavorable one. One is an upside possibility, the other is a downside risk. The topmost panel describes a scenario 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. The panel shows the decision tree for this "clairvoyance" assumption. A circle represents a chance node - a point at which the uncertainties are resolved. A square denotes a decision node - a point at which action is taken.

The bottom panel shows an alternative way to look at things. This viewpoint is characterized by the phrase "sequential decision making under uncertainty." For illustrative purposes, it is assumed that global CO_2 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. The "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 CO_2 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.

Figure 5 shows average carbon emission projections for the seven models that participated in the study for several cases. 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 of 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 shown in Figure 5, however, is the case where both parameters are unknown until 2020. This projection 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. Some of these results are tabulated in Table 5. A number of interesting observations can be made regarding these results:

(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.

CHALLENGES FACED BY INTEGRATED ASSESSMENT AND THE WORLD

The biggest challenges facing integrated assessment modelers are: (1) developing a credible way to represent and value the impacts of climate change, (2) developing realistic representations of the dominant processes and policies in the developing countries, (3) getting experts from developing countries directly involved in the process of integrated assessment, (4) determining the most appropriate discount rate(s) to use in the model analyses, and (5) representing technological change realistically and consistently in the models..

Representation and Valuation of Impacts of Climate Change

Existing general circulation models produce mean steady-state global temperature projections that are very uncertain. The process of projecting transient regionalized changes in the key climate variables - e.g., temperature, precipitation, etc., that lead to impacts on economies and ecosystems in a way that is consistent with the operation of the global circulation models is in its infancy, making them subject to considerable additional uncertainties. The climate information required to most effectively project the impacts has in many cases not yet been determined, the most appropriate measures of climate impacts have not yet been determined, and ecosystems may not currently be in equilibrium. Finally, it may be necessary for this information to be input to valuation methods that are still under development and not tightly linked to the natural systems impacts in order to provide policy makers with the information they need to decide what to do.

Critical Issues in Developing Countries

In general, the processes and policy options relevant to climate change are easier to assess in the twenty four industrialized countries of the OECD. This stems from the fact 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 hundred and forty odd non-OECD countries is 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 driven by other more pressing concerns than climate change. 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 impacted by any changes that might occur. Only a few of the operational integrated assessment models (e.g., Alcamo, et al., 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 it 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 on phenomena (the spread of diseases, the level of income, the cultural norms), and policies (e.g., regarding education, health care, and birth control, etc.) than explicit consideration of the implications of population on climate change in the future. Virtually all of the existing integrated assessment models (the TARGETS models, Rotmans, et al., 1994, has recently become the first exception) take future population growth as given. Moreover, the projections used generally all come from one or two international agencies that use very simple projection methodologies.

The extent to which a better understanding and modeling 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 adding detail in these areas would improve the credibility of the models, especially in the developing countries.

Discount Rate (s)

The choice of appropriate discount rates is addressed in the IPCC Working Group III report (Bruce, et al., 1996), but it is also an extremely important parameter in the analysis and design of appropriate climate change policies. Given the residual uncertainty about this parameter and its schizophrenic status as partly an external parameter and partly a (direct or indirect) policy instrument, it would be quite valuable to do more uncertainty analysis on a single rate and ore experimentation with various alternative implementations. For example, some (e.g., Schelling) has proposed that direct assessments of peoples willingness to pay for climate change policies across time and space be employed, while others (e.g., Nordhaus) has suggested that even if one were to move from the current descriptive rate of 5-6% to a normative rate much less than that, because the existing capital stock and mix of inputs to the economy was based on the higher rate and will last for many years, it is optimal to move to the lower rate quite gradually over a number of decades, rather than immediately.

Technological Change

Energy/carbon taxes may stimulate the development of new technologies that use less energy and produce less carbon emissions. But, for both direct support of R&D and that induced by higher taxes, the net benefits of this induced technical change depends on how large the benefits are and whether the opportunity cost of the funds used for the R&D is higher or lower than those benefits. Energy R&D could reduce energy use/carbon emissions. However, the results of R&D in other areas could lead to more or less energy use, and these outcomes could be more important than the energy sector R&D outcomes.

The returns to R&D are very uncertain, but most empirical studies suggest under investment in R&D (see, for example Sakurai, et al, 1996). This under investment is probably the result of private sector's assessment that many of the benefits of the R&D would not be appropriable by them, and government and the public not believing or understanding this rationale for government R&D support. Direct public support for R&D would involve large direct costs to the government, but avoid the indirect market costs (i.e., deadweight costs) resulting from energy/carbon taxation. On the other hand, the public R&D support might simply displace private support for R&D. Moreover, the track record for government selection of large-scale RD&D technologies to fund has not been very good at times, which suggests funding more concepts at the small-scale demonstration level and letting the private sector determine which of the successful ones to fund at the next stage.

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Table 1
Integrated Assessment Models

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

Table 2
DEVELOPMENT STATUS OF INTEGRATED ASSESSMENT MODELS

Model	Status	Reference
AS/ExM	Preliminary Version Operational	Lempert , et al. (1995)
AIM	Preliminary Version Operational	Morita, et al. (1994)
CETA	Operational, With Regional and Uncertainty Variants	Peck and Teisberg (1992)
Connecticut	Operational	Yohe (1994)
CRAPS	Preliminary Version Operational	Hammitt, et al. (1995)
CSERGE	Preliminary Version Operational	Maddison (1994)
DICE	Operational, With Regional and Uncertainty Variants Under Development	Nordhaus (1994)
FUND	Operational	Tol (1994)
GHC	Operational	Grubb, et al.. (1995)
ICAM-2	ICAM-1 Operational, ICAM-2 in Advanced Module Testing	Dowlatabadi and Morgan (1993)
IIASA	Energy, Economy, and Agriculture Modules Operational	Schrattenholzer (1995)
IMAGE 2.0	Operational	Alcamo (1994)
MARIA	Operational	Mori (1994)
MERGE	Operational, With Uncertainty Variant Under Development	Manne, et al. (1993)
MiniCAM	Operational	Edmonds, et al. (1995)
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	Mosts Modules in Testing Phase	Edmonds, et al. (1995)
Rand	Operational	Hammitt, et al. (1992)
RICE	Operational	Nordhaus and Yang (1995)
SLICE	Operational	Kolstad (1993, 1994a, 1994b)
TARGETS	Preliminary Version Operational	Rotmans, et al. (1995)

Table 3: Summary Characterization of Integrated Assessment Models (Adapted from Rotmans, et al, 1995)

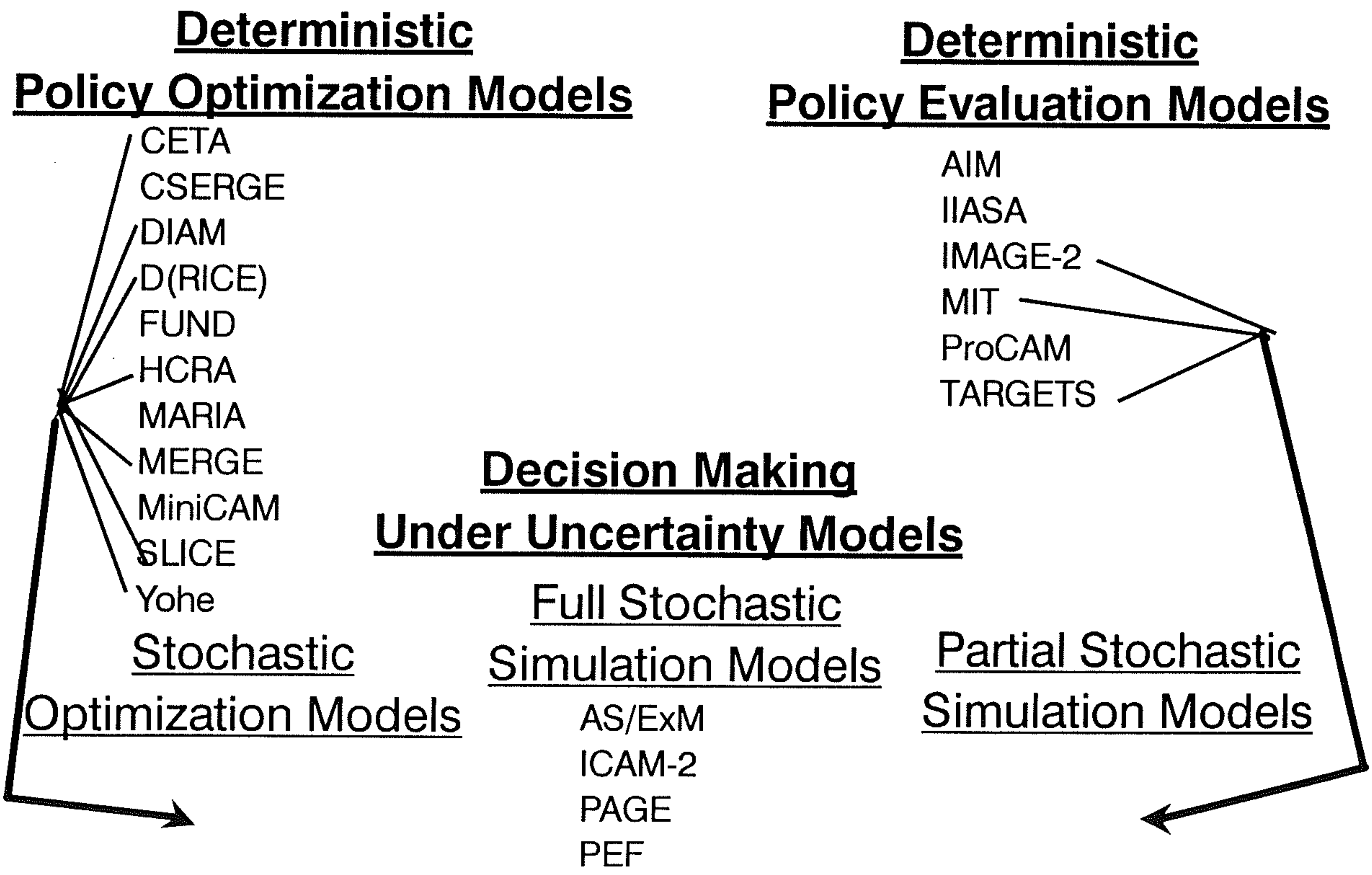
Model	**Forcings** 0. CO_2 1. other GHG 2. aerosols 3. land use 4. other	**Geographic Specificity** 0. global 1. continental 2. countries 3. grids/basins	**Socio-economic dynamics** 0. exogenous 1. economics 2. tech choice 3. landuse 4. demographic 5. cultural perspectives	**Geophysical simulation** 0. ΔF 1. Global ΔT 2. 1-D ΔT, ΔP 3. 2-D ΔT, ΔP	**Impact Assessment** 0. ΔT indexed 1. sea level rise 2. agriculture 3. ecosystems 4. health	**Treatment of uncertainty** 0. None 1. Basic 2. Advanced	**Treatment of decision-making** 0. optimization 1. simulation 2. simulation with adaptive decisions
AS/ExM	0	0	0	1	0	1	2
AIM	0,1,2,3	0 - 1	1,2,3	3	1,2,3	0	1
CETA	0	0 - 1	1, 2	1	0	0 or 1	0
Connecticut	0	0	1	1	0	0	0
CRAPS	0	0	1	1	0	1	2
CSERGE	0	0	1	1	0	0	0
DICE	0	0	1	1	0	0 or 1	0
FUND	1	1	1, 4	1	0, 1, 4	0	0
Grubb et al.	0	0	2	-	0	0	0
ICAM-2	0, 1, 2, 3	1 - 2	1, 3, 4 (no tech choice)	2 - 3	0,1, 3	2	1, 2
IIASA	0	0	1	1	2	0	0
IMAGE 2.0	0, 1, 2, 3	3	0, 2, 3	3	1,2,3	0	1
MARIA	0	0,1	1	1	0	0	0
MERGE 2.0	0, 1	1	1, 2	1	0	0 or 1	0
MiniCAM	0, 1, 2, 3	2 - 3	1, 2, 3	3	0	0	1
MIT	0, 1, 2, 3	2 - 3	1	3	0, 2,3	0	0, 1
PAGE	0, 1	1 - 2 (EEC)	1	1	0 - 4[2b]	2	1
PEF	0, 1	1	0	1	0	2	1
ProCAM	0, 1, 2, 3	2 - 3	1, 2, 3, 4	3	0[3c], 2	0	1
RAND	0	0	1	1	0	1	1
RICE	0	1	1	1	0	0	0
SLICE	0	1	1	1	0	1	2
TARGETS	0, 1, 2, 3, 4	0	1, 2, 3, 4, 5	2	1,2, 3, 4	0	1, 2

[1a] TARGETS includes ozone depletion, soil erosion, acid rain, and toxics and hazardous pollutant releases.

[b] In PAGE the impacts are calculated for each sector as a function of ΔT.

[c] Impacts specific for each sector are calculated separately.

Table 4. Types of Integrated Assessment Models



Deterministic
Policy Optimization Models

- CETA
- CSERGE
- DIAM
- D(RICE)
- FUND
- HCRA
- MARIA
- MERGE
- MiniCAM
- SLICE
- Yohe

Deterministic
Policy Evaluation Models

- AIM
- IIASA
- IMAGE-2
- MIT
- ProCAM
- TARGETS

Decision Making
Under Uncertainty Models

Stochastic
Optimization Models

Full Stochastic
Simulation Models

- AS/ExM
- ICAM-2
- PAGE
- PEF

Partial Stochastic
Simulation Models

Table 5
Expected Value of Perfect Information EMF 14 Decision Making Under Uncertainty Study Group Experiment

Probability of U1 vs. U0 = p(U1)	0.25%	5%	50%
Date of resolution: 2020			
5% discount rate:			
DICE	6		
HCRA	10	185	
MERGE	0	0	0
SLICE	5		
YOHE	5	91	
4% discount rate:			
CETA	48	763	
3% discount rate:			
DIAM	50	946	4849
MERGE			4480
Date of resolution: 2050			
5% discount rate:			
HCRA	28	515	
SLICE	13		
4% discount rate:			
CETA	98	1695	
3% discount rate:			
DIAM	78	1486	7253

Figure 1. Key Components of Integrated Assessment Models

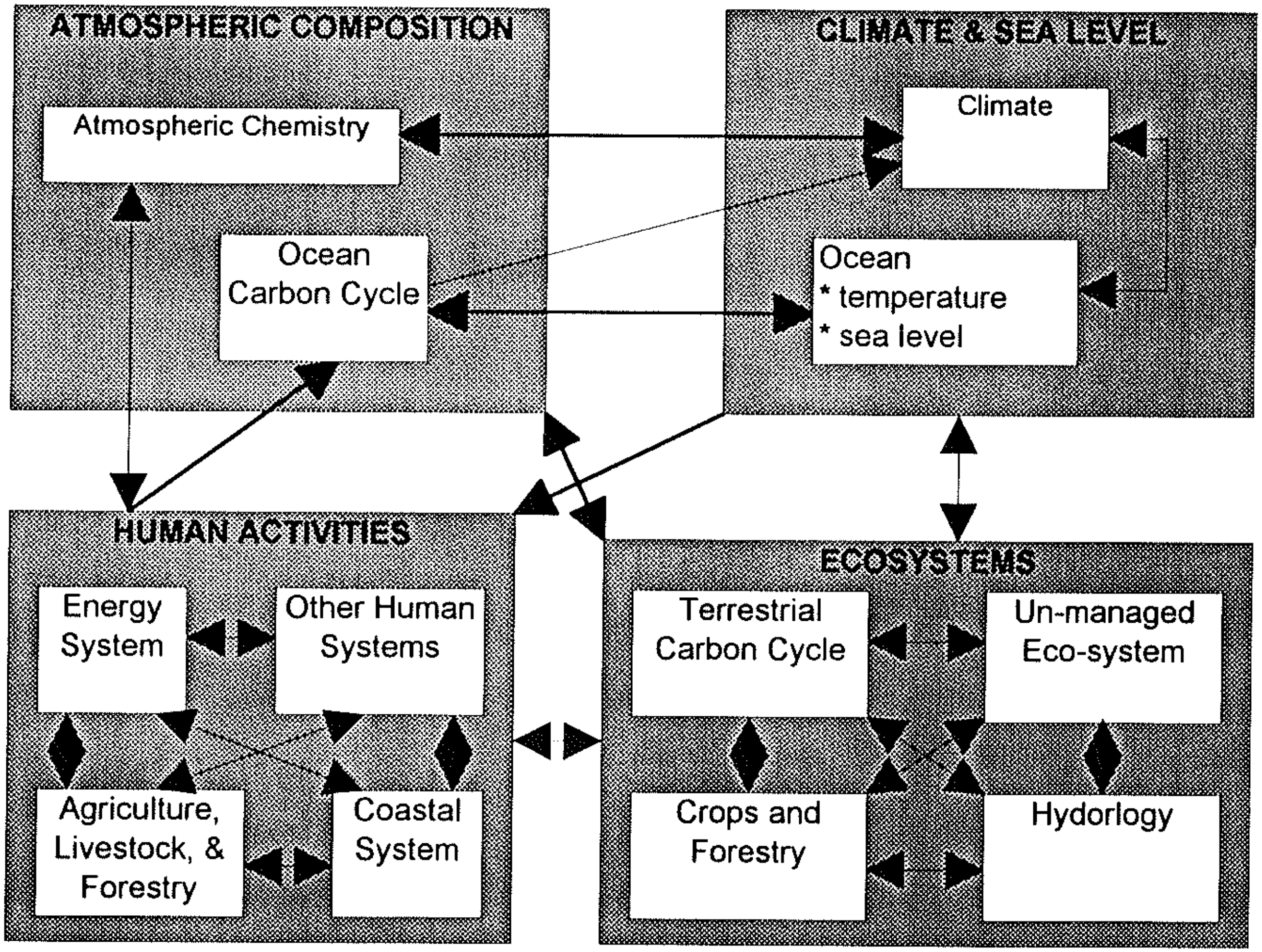


Figure 2
EMF 14 Optimal Carbon Tax Projections

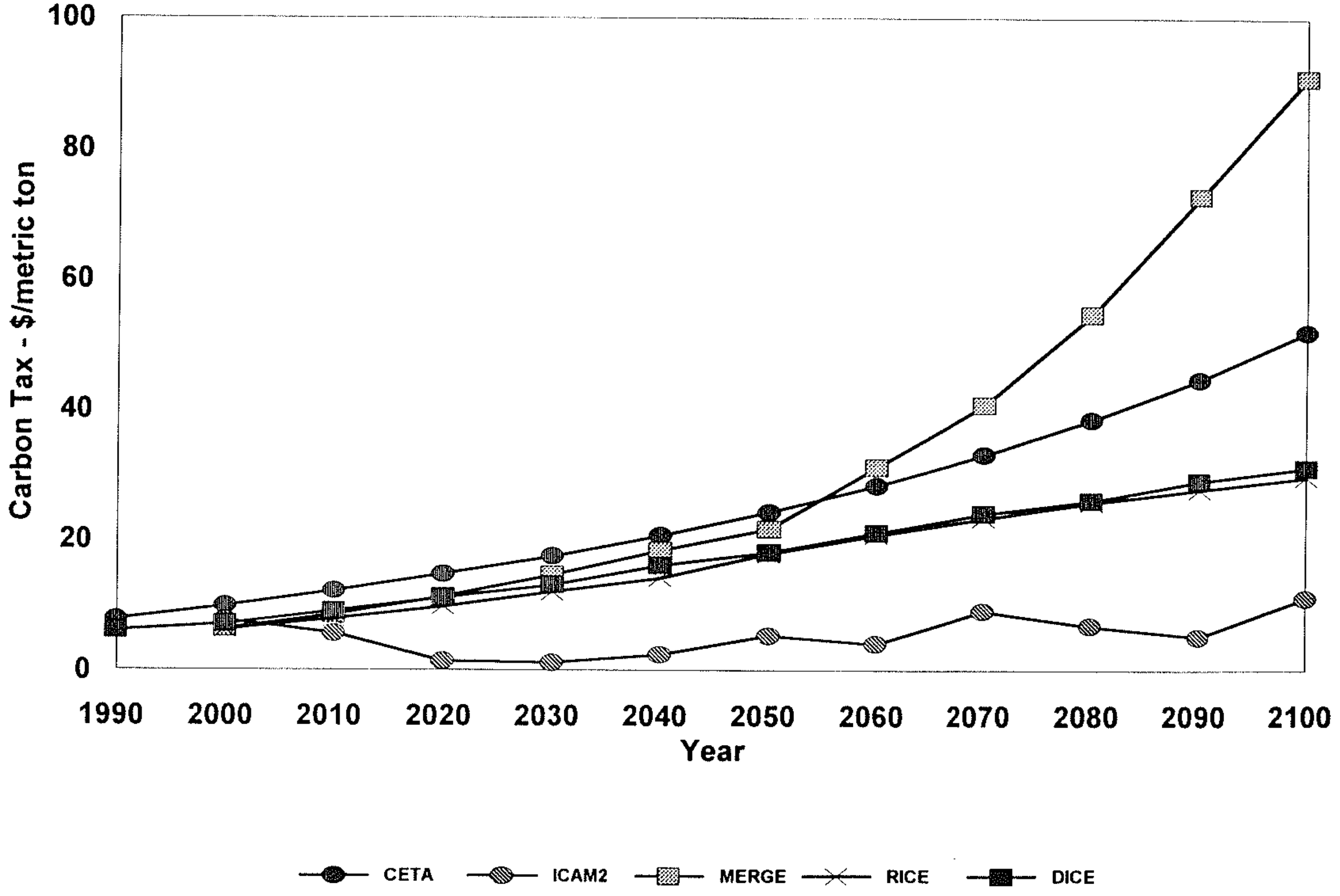
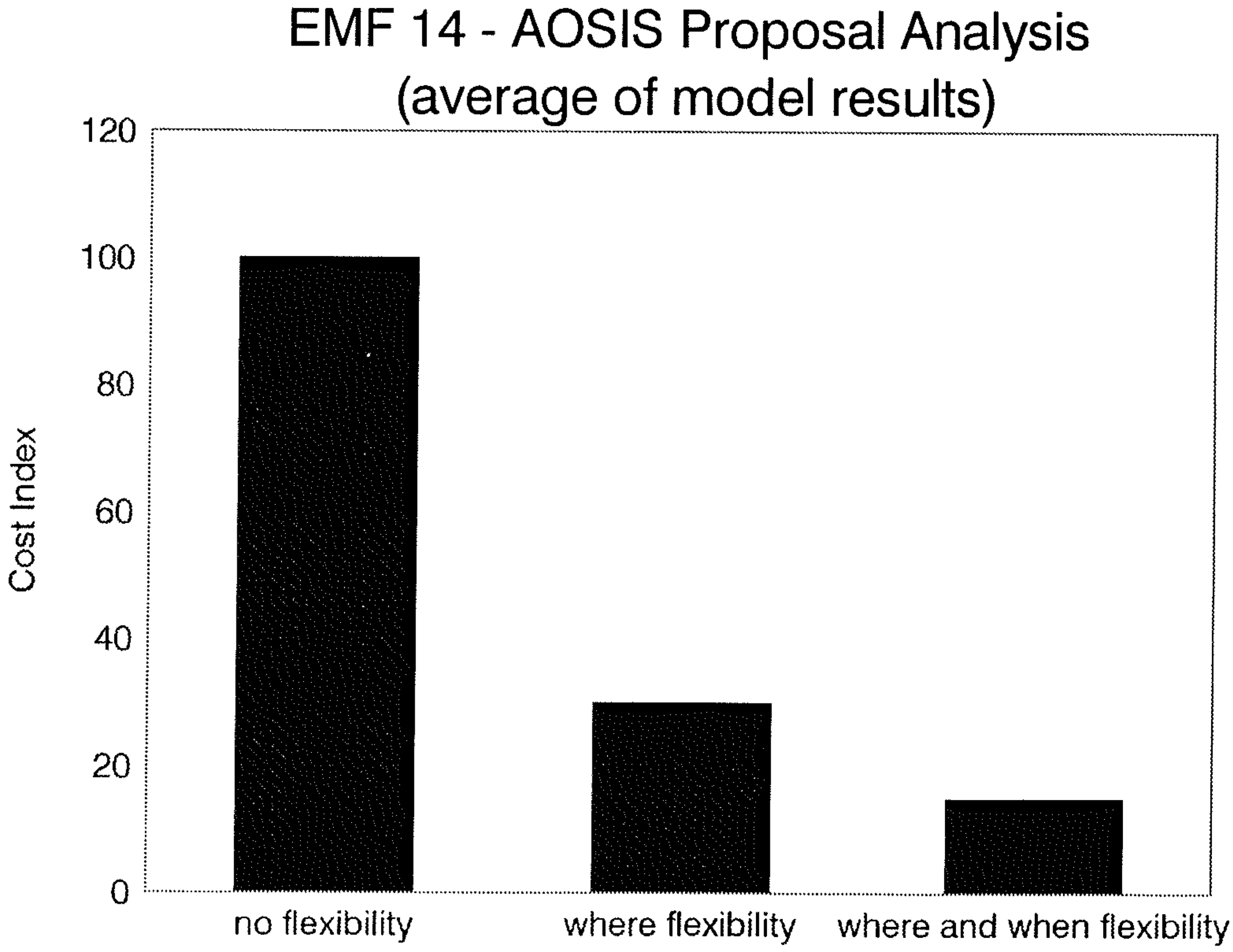
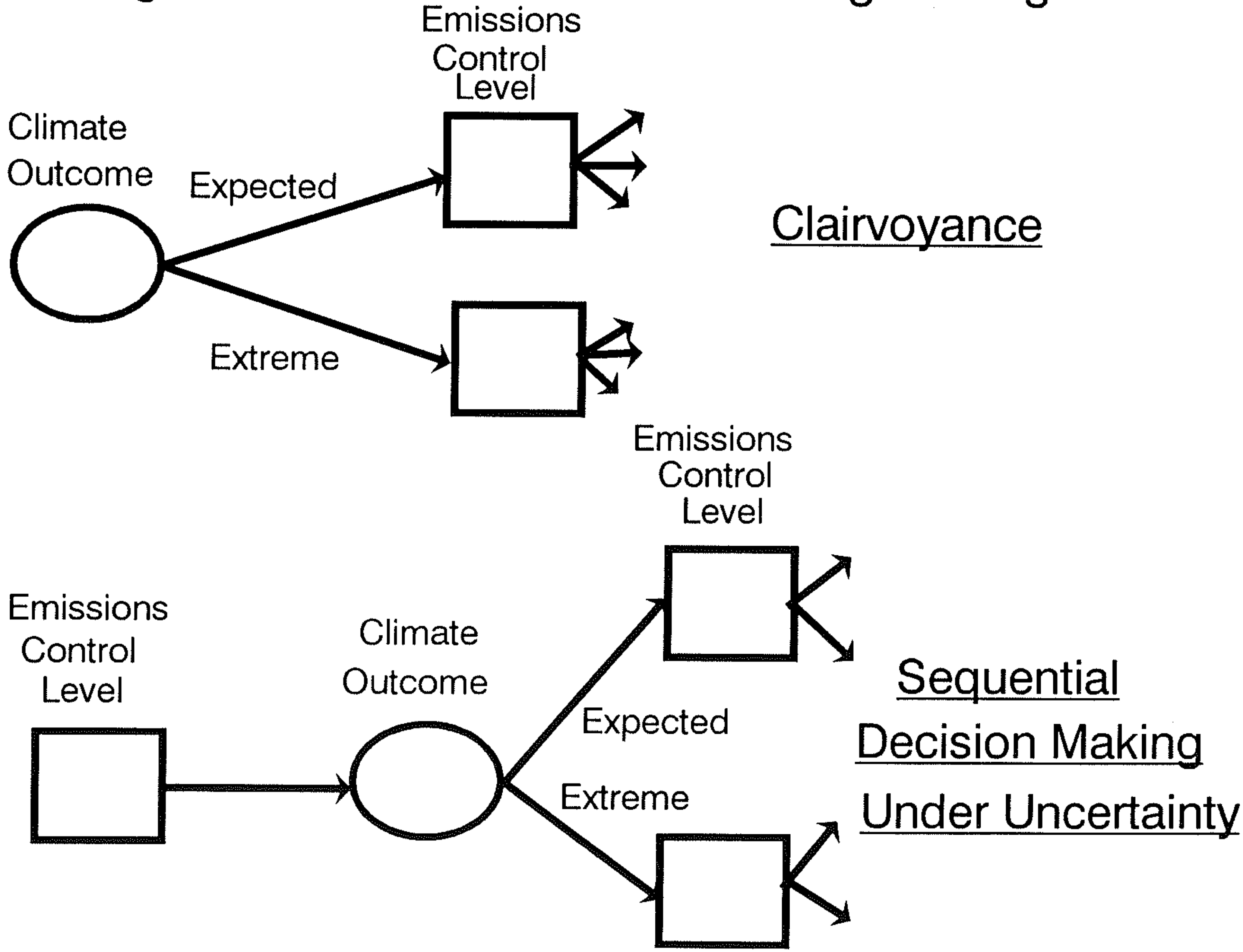


Figure 3. Cost Comparison under Alternative Assumptions about Economic Efficiency



EMF 14 - AOSIS Proposal Analysis
(average of model results)

Figure 4. Alternative Decision Making Paradigms



<u>Clairvoyance</u>

<u>Sequential Decision Making Under Uncertainty</u>

Figure 5. Hedging Against Bad Climate Outcomes

EMF 14 Uncertainty Analysis (Average of Model Results)