PRELIMINARY RESULTS FROM EMF 14 ON INTEGRATED ASSESSMENT OF CLIMATE CHANGE

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John P. Weyant

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EMF 14 STUDY
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WORKING GROUP PARTICIPANTS

NAME	AFFILIATION AT THE TIME OF STUDY
Joseph M. Alcamo	RIVM (The Netherlands)
Arthur Andersen	U.S. Department of Energy
Robert Bidwell	U.S. Department of Energy
Peter Blair	Office of Technology Assessment
Mark A. Boroush	Office of Technology Assessment
Jay Braitsch	U.S. Department of Energy
Robin Cantor	National Science Foundation
Doug Carter	U.S. Department of Energy
William Cline	Institute for International Econ.
David Cohan	Decision Focus, Inc.
Allen Coombs	Natural Resources Canada
Amy Craft	Stanford University
Hadi Dowlatabadi	Carnegie-Mellon University
Ronald Earley	U.S. Department of Energy
James A. Edmonds	Battelle Pacific Northwest Lab
Samuel Fankhauser	GEF Secretariat
Brian Farrell	Edison Electric Institute
Brian P. Flannery	EXXON Research and Engineering Co.
Robert Friedman	Office of Technology Assessment
Yasumasa Fujii	Yokohama National University (Japan)
Michael Grubb	The Royal Institute of International Affairs
Howard Gruenspecht	U.S. Department of Energy
Erik Haites	La Salle Academy (Canada)
James Hammitt	Harvard School of Public Health
Abraham E. Haspel	U.S. Department of Energy
Paul Holtberg	Gas Research Institute
Kazuhiko Hombu	NEDO (Japan)
Chris W. Hope	University of Cambridge (United Kingdom)
John C. Houghton	U.S. Department of Energy
Jean-Charles Hourcade	CIRED/CNRS (France)
Hillard Huntington	Stanford University
Henry D. Jacoby	Massachusetts Inst. of Technology
Russell O. Jones	American Petroleum Institute
Mikiko Kainuma	National Inst. for Environ. Studies (Japan)
Sally M. Kane	Council of Economic Advisors
Charles D. Kolstad	University of California Santa Barbara
Neil Leary	Environmental Protection Agency

Rik Leemans	RIVM (The Netherlands)
Robert Lempert	Rand Corporation
Mark Levine	Lawrence Berkeley Laboratory
David Maddison	University College, London (United Kingdom)
Alan S. Manne	Stanford University
Robert Mendelsohn	Yale University
Shunsuke Mori	Science University of Tokyo (Japan)
Tsuneyuki Morita	National Inst. for Environ. Studies (Japan)
Richard H. Moss	Intergovt. Panel on Climate Change
Roger F. Naill	The AES Corporation
Nebojsa Nakicenovic	IIASA (Austria)
William D. Nordhaus	Yale University
Martin Parry	University College, London (United Kingdom)
Stephen Peck	Electric Power Research Institute
William Pepper	ICF, Inc.
Eric Petersen	U.S. Department of Energy
Ronald G. Prinn	Massachusetts Institute of Technology
Grant Read	University of Canterbury (New Zealand)
John M. Reilly	U.S. Department of Agriculture
Richard Richels	Electric Power Research Institute
Jan Rotmans	RIVM (The Netherlands)
Thomas C. Schelling	University of Maryland
Joel Scheraga	Environmental Protection Agency
Michael E. Schlesinger	University of Illinois, Champaign
Stephen H. Schneider	Stanford University
Leo Schrattenholzer	IIASA (Austria)
Robert Shackleton	Environmental Protection Agency
Susan H. Shaw	U.S. Department of Energy
Michael Shelby	Environmental Protection Agency
Raymond Squitieri	U.S. Department of Treasury
Brandt K. Stevens	California Energy Commission
James L. Sweeney	Stanford University
Tom Teisberg	Teisberg Associates
Richard S.J. Tol	Free University (The Netherlands)
Angelica Tudini	Fondazione Eni Enrico Mattei (Italy)
Robert Watson	Office of Science & Tech. Policy
Rodney Weiher	Nat'l. Oceanic & Atmospheric Admin.
John P. Weyant	Stanford University
Tom M.L. Wigley	UCAR Ofc for Interdisciplinary Studies
Donald J. Wuebbles	University of Illinois
Gary W. Yohe	Wesleyan University

INTRODUCTION

An historic Framework Convention on Climate Change was signed by 154 countries at the United Nations Conference on Environment and Development (UNCED) in Brazil in June 1992. A goal of the convention was to have countries work towards stabilizing concentrations of greenhouse gases in the atmosphere at a level that would prevent undesirable anthropogenically induced effects on the climate system. Ultimately, the appropriate course of action for each country will depend on its assessment of the costs and benefits of policy intervention.

There remain large uncertainties, however, about likely greenhouse gas emission levels in the future, about the relationship between emissions of greenhouse gases and their atmospheric concentrations, about the link between atmospheric concentrations and global climate change, about the changes in climate that will occur, about the impacts of climate change on people and ecosystems, and about how these impacts ought to be evaluated. Over the past few years a number of "integrated assessment" models that represent these links have been developed. The purpose of this EMF study was to compare the various approaches to "integrated assessment" that have been employed to assess their usefulness (and recommend areas for improvement) in policy development and in setting climate change research priorities.

The study brought together representatives of "integrated assessment" modeling teams with experts (with or without models) on each of the key individual components and linkages (e.g., carbon cycle, atmospheric chemistry, climate, energy-economics, physical impacts of climate change, valuation of impacts, etc.). Working with individuals involved in the development of policies for dealing with climate change, these groups have run mutually agreed upon standardized scenarios and have compared key outputs produced. Because of its interdisciplinary nature and the complexities involved, this study required more component-by-component comparisons than previous EMF studies, as well as a closer look at the way model components are currently linked, and an assessment of whether or not improved linkages/component sets can/should be developed in the future.

The full EMF 14 working group met five times: (1) in June of 1994 in Washington, D.C., (2) in December of 1994 at the International Institute for Applied Systems Analysis outside Vienna Austria; (3) in May of 1995 at Stanford University; (4) in March 1996 at IIASA, and (5) in March 1997 in Tokyo, Japan. In addition, numerous study group meetings were convened beween mid-1994 and mid-1997.

ELEMENTS OF INTEGRATED ASSESSMENT MODELS

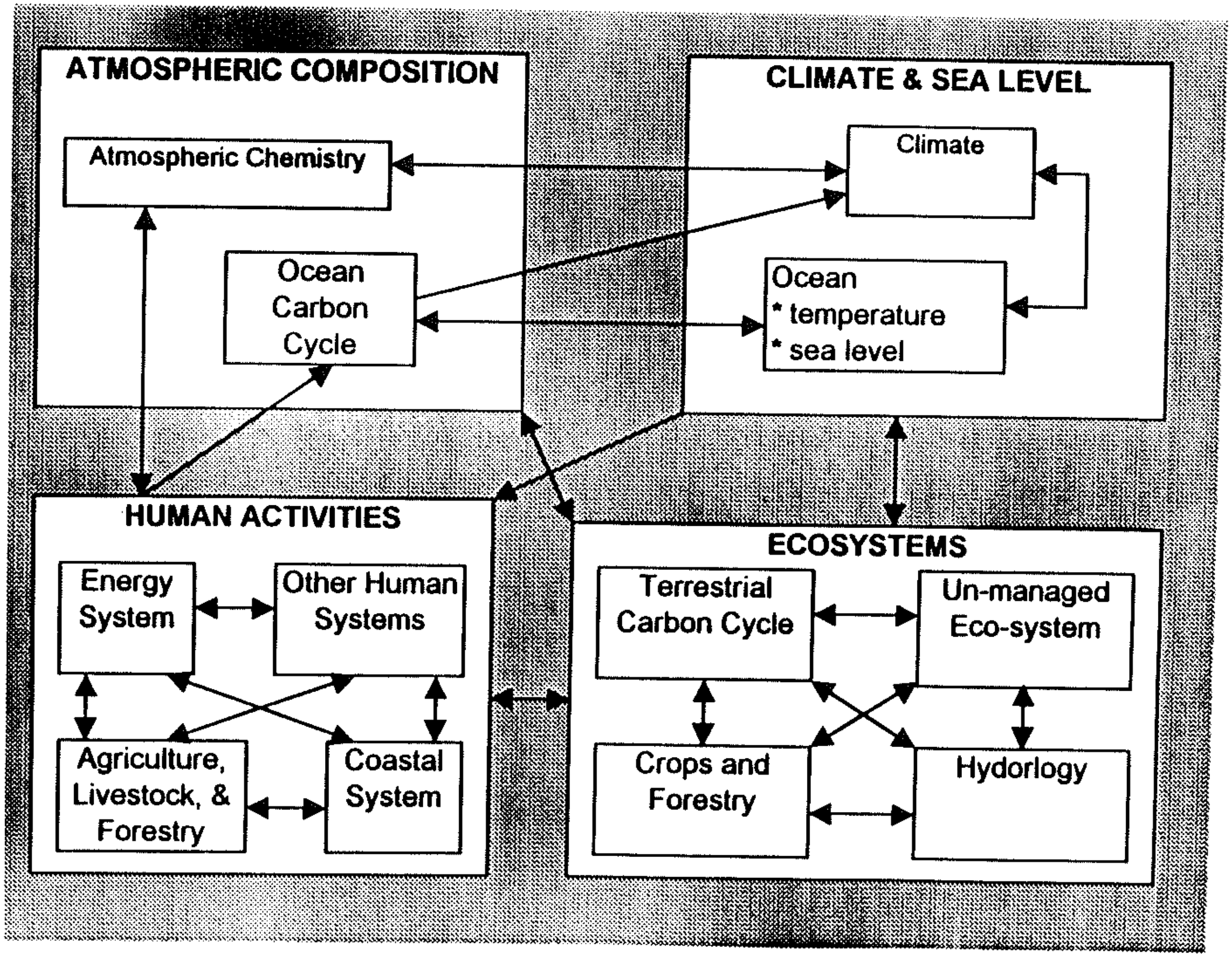
Integrated assessment is defined here as any attempt to integrate information from and across disciplines to help in the process of developing policy responses (Parson, 1994). Assessment is distinguished from disciplinary research by its purpose: to inform policy and decision, rather than to advance 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.

There are a large number of Integrated Assessment Models (IAMs) 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:

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

Figure 1. Key Components of Integrated Assessment Models



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

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.

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).

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

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.(1) 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

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(1)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 in Bruce (1996).

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 1 lists the 23 models that participated in the EMF 14 study. For each model, the principal developers are identified and a representative reference is given. Figure 2 places the models listed in Table 1 into the three primary categories, and relevant sub-categories discussed above.

REFERENCE CASE INPUT ASSUMPTIONS

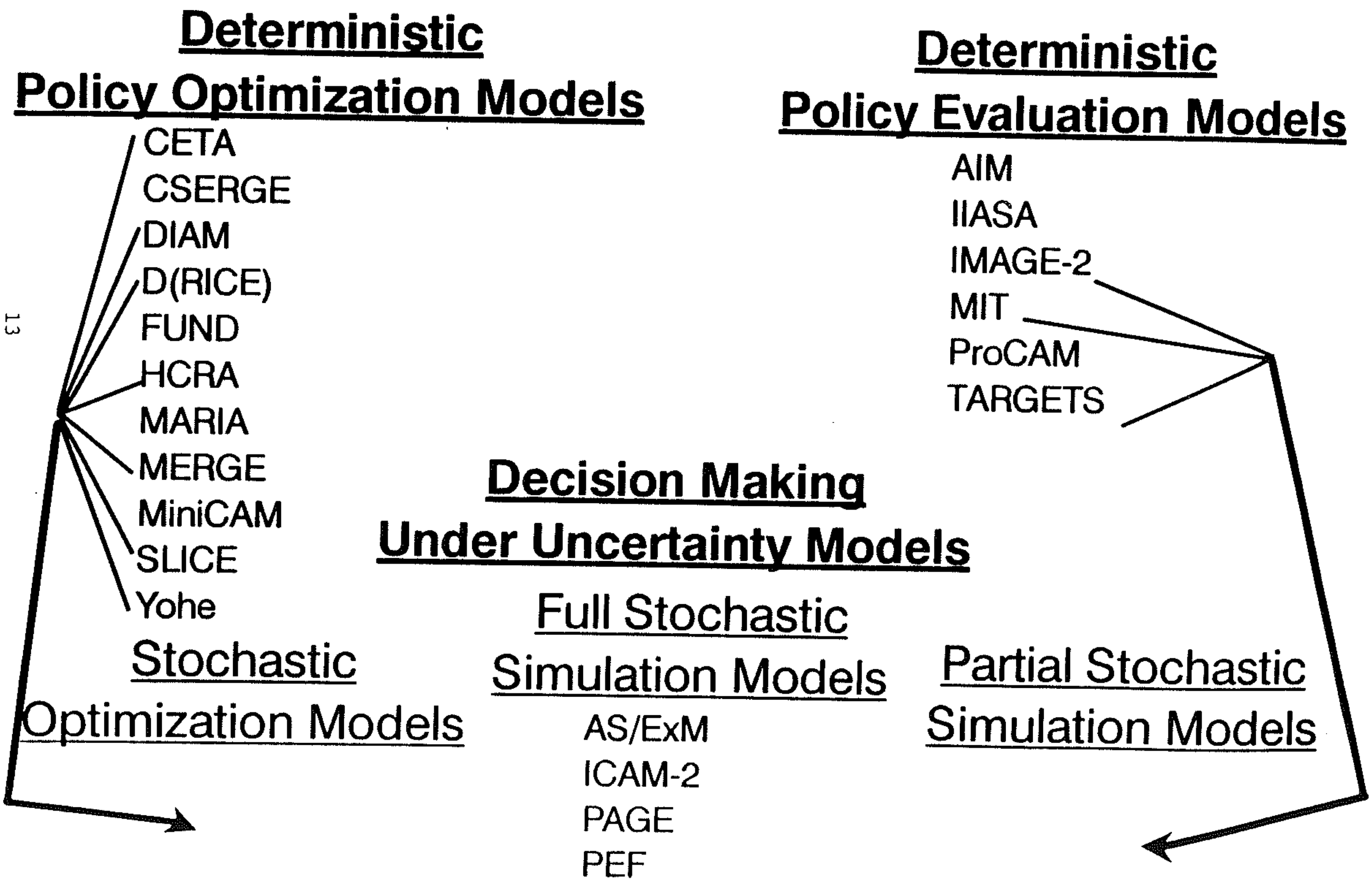
As in all EMF studies, the standardization of input assumptions is accomplished so that important inputs take on common values for each EMF scenario. This process facilitates the interpretation

Table 1
EMF 14 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 Illionois)	Lempert , et al. (1995)
AIM (Asian-Pacific Integrated Model)	T. Morita, M.Kainuma (NIES, Japan) Yuzuri Matsuoka (Kyoto University)	Morita, et al. (1994)
CETA (Carbon Emissions Trajectory Assessment)	Stephen Peck (EPRI) Thomas Teisberg (Teisberg Assoc.)	Peck and Teisberg (1992)
Connecticut (also known as the Yohe model)	Gary Yohe (Wesleyan University)	Yohe (1995)
CSERGE (Center 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 (Dyanamic 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 Hammitt (Harvard) Atul Jain/Don Wuebbles (Univ. Of Ill.)	Hammitt, 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 (1994)
MARIA	Shunsuke Mori (Sci. Univ. of Tokyo)	Mori (1995)
MERGE 2.0 (Model for Evaluating Regional and Global Effects of 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)
PAGE (Policy Analysis of the Greenhouse Effect)	Chris Hope (Cambridge University) John Anderson/Paul Wenman (Env.Res.)	Commission of the European Communities (1992)
PEF (Policy Evaluation Framework)	Joel Scheraga/Susan Herrod (EPA) Rob Stafford/Nathan Chan (DFI)	Cohan, et al. (1994)
ProCAM (Process Oriented 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 (Univ. California, Santa Barbara)	Kolstad (1993, 1994a, 1994b)
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)	Rotmans, et al. (1995)

Figure 2. 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

of the model comparison, allowing one to separate the dependence of key model results on model structure and on specific numerical inputs. However, in instances where a particular model includes an endogenous computation of an input selected for standardization, the modeler is urged to use the internal calculation in lieu of the EMF 14 input assumption. By design this situation arises infrequently, but it is important for the modelers to maintain this flexibility. This avoids producing only "least common denominator" level results from the model comparisons. The standardization described in this preliminary study design pertains primarily to assumptions made to compute the costs of abating climate change, not those used to compute the benefits of avoiding climate impacts. Standardization of some of the key elements included in the calculation of benefits should occur in subsequent model comparison rounds as results of the initial rounds are reviewed and the state of the art in impacts modeling matures. Before discussing specific input values, the time periods and regional breakdown to be used in reporting model results are described. These dimensions of the study design condition the specification of the model inputs.

Time Periods

The global climate change problem is long run in nature. The time horizon for reporting model results needs to be much longer than that typically employed for other energy and environmental policy issues. Thus, the time horizon adopted for this study extends out to the year 2200. On the other hand, the most difficult and costly transitions (especially with discounting of future cash flows) will come in the next 10-50 years. Thus, the time periods adopted for reporting results for this study are shorter (every ten years) during the first 110 years of the study's time horizon than for the 22nd century (every 25 years). Consequently, the reporting years for the study are 1990, 2000, 2010, 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100, 2125, 2150, 2175, and

2200. Not every model will report all these years, nor will they report values for every output specified below. In addition, the working group decided to show comparative results through 2100 only, and to use the results for 2125-2200 solely for help in interpreting model differences through 2100.

Geographical Regions

The main reporting regions for the study take into consideration the present and likely future geographical distribution of greenhouse gas emissions. The main reporting region totals are: (0) World Total, (1) U.S., (2) EEC, (3) OECD total (including the US and the EEC), (4) Former Soviet Union (FSU), (5) China, and (6) Non-OECD total (including the FSU and China). For those who produce estimates for other regions or individual countries, results for these subregions may also be reported.

Population and Economic Growth

The reference case includes assumptions about both population and economic growth. The assumptions chosen here are patterned after those made in the Intergovernmental Panel on Climate Change's (IPCC's) IS92A scenario (IPCC, 1992; Pepper, et al., 1994). As in that scenario, we extrapolate population growth projections contained in a World Bank (1991) report. These population assumptions are shown in Table A-1 in Appendix A.

The economic growth rates for the nineties for all regions represent reasonable extrapolations of actual economic performance from 1990 to 1994. With the exception of China and the Former Soviet Union, the economic growth rate assumptions adopted here from 2000 through 2100 are also drawn from the IPCC's IS92A scenario. The recent collapse of the economies of the Former Soviet Union make projecting future growth there extremely difficult. The projections shown in Table A-2 in Appendix A show a decline in economic output in the FSU from 1990 to 2000, followed by a steady recovery over the first quarter of the next century. As shown in Table A-2, the GDP growth rates assumed here decline gradually after 2000 (after 2025 in the case of the Former Soviet Union) due to structural change and lower population growth.

Also shown in Table A-2 are estimates of GDP for 1990 for the study regions. Except for the FSU and China, these estimates are consistent with a number of published estimates. For the FSU and China, there exists considerable uncertainty regarding the purchasing power parity adjustments necessary to translate economic activity measured in non-convertible currencies into dollars. This conversion is complicated for these two major countries because of the absence of market-based pricing systems. Our approach here for both China and the FSU was to take the average of the official market exchange rate GDP estimates and purchasing power parity estimates. These two sets of estimates appear to span the range of current thinking in this area. Our averaging procedure does, however, result in much higher GDP estimates for China and than FSU than those computed at market exchange rates (about a factor of three higher for China and a factor of two higher for the FSU). The GDP per capita projections are plotted in Figure 1, which shows that the non-OECD countries achieve a much higher percentage of average OECD per capita GDP by 2200 than today, but that large differences remain. For example, the U.S. GDP per capita is a factor of almost 19 larger than that in China in 1990, but only a factor of two larger in 2200.

Oil Prices and Fossil Fuel Resource Base

For modelers requiring exogenous oil price inputs the world price of oil should be assumed to be $20/barrel through the year 2000 in 1990 dollars and then to increase $6.00 per barrel each decade until 2050 (reaching the backstop level of $50/barrel in that year). For modelers requiring oil and gas resource base estimates, the 95th percentile estimates from Masters, Attanasi, and Root (1994), summarized here in Table A-3 in Appendix A were recommended. Recommended estimates for ultimately recoverable coal resources are also shown in Table A-3.

These oil, gas, and coal sector assumptions should be employed in all first round scenarios.

Technology Costs

New coal-fired power plants are assumed to be able to generate electricity for 50 mills/kwH, with an overall efficiency of 34%, and a carbon emission coefficient of .25 metric tons carbon per thousand kilo-watt hours. It is assumed that four advanced "backstop" technologies will become available:

(1). A liquid synthetic fuel derived from coal or shale at $50/barrel of crude oil equivalent, and a carbon emission coefficient of .04 metric tons carbon per billion joules (or 40 million tons per exajoule) available for the first time in 2010.

(2). A non-carbon based liquid fuel at $80/barrel of crude oil equivalent, available for the first time in 2010.

(3). A non-carbon based electric option at 75 mills/KwH first available in 2010.

(4). A non-carbon based electric option at 50 mills/KwH first available in 2030.

Energy Efficiency Improvements

In many of the models a key determinant of future energy demand is the rate at which energy use per unit of economic activity is projected to trend down independently of any future energy price changes. This trend, which includes the effects of both technological progress and shifts in economic structure, is often represented with a single aggregate parameter referred to as the Autonomous Energy Efficiency Improvement (AEEI) rate. Recent expert opinion polls report an AEEI of about .7 percent per year for the U.S. (e.g., Manne and Richels, 1994) in the near term. The regional and longer term U.S. AEEI values shown in Table A-4 in Appendix A result from a simple formula suggested by Arnulf Grubler of IIASA. The formula assumes that AEEI improvements are a constant fraction of the projected GDP per capita growth rates. Dividing the short-run AEEI projection for the U.S. by the U.S. GDP per capita projection for 1990-2000 of 2.18% yields .32; the per capita GDP projections for each time period in each period are multiplied by this factor to get the AEEI values shown in Table A-4. This approach insures some degree of consistency among the AEEI assumptions made across time periods and regions. These AEEI projections should be used by models that use this approach to energy demand modeling. In addition to these AEEI assumptions, there may be additional energy efficiency improvements that are independent of world energy price changes in models where energy subsidies in certain countries (which have been substantial in the FSU and many developing countries) are reduced from their 1990 levels.

Discount Rates

If a model does not calculate a discount rate internally, the near-term marginal product of capital was to be set at 5 percent. This concept is often used as the discount rate for discounting goods and services. If you use some other method for computing a discount rate internally, please provide a description with your results.

SCENARIOS

The EMF 14 baseline model comparison scenarios are generic policy excursions rather than detailed model structure investigations or policy implementation excursions. Two separate reference cases were considered:

(0) a modelers reference case with no changes in existing policies assumed and each modeling team using its preferred set of population, economic growth, natural resource and technology assumptions,

(1) a standardized reference case with no climate change impacts and no changes in existing policies assumed and the reference case assumptions described above used at inputs to each model.

In addition to these two reference scenarios the following scenarios were included in the study:

(2). (1)+ Limit Carbon Emissions to No More Than 1990 Levels.

(3). (1) + Limit CO_2 Concentrations to No More Than 550 ppmv.

(4). (1) + Limit Temperature Increase to No More Than 2°C wrt 1990

(5). (1) + Pareto Optimal Emissions
(Balance Costs and Benefits of CO_2 Control)

(6). (1) + Accelerated Technology

(7). (1) + Modelers Choice Policies
(Each Modeler Picks Favorite Scenario)

Scenarios (8)-(12) are identical to (2)-(6), but are to be run using the Modelers Reference Case assumptions rather than the Standardized Reference Case Assumptions.

(8). (0) + Limit Carbon Emissions to No More Than 1990 Levels.

(9). (0) + Limit CO_2 Concentrations to No More Than 550 ppmv.

(10). (0) + Limit Temperature Increase to No More Than 2°C wrt 1990

(11). (0) + Pareto Optimal Emissions
(Balance Costs and Benefits of CO_2 Control)

(12). (0) + Accelerated Technology

In the accelerated technology scenario it is assumed that:

(I) 400 Exajoules of low-cost biomass resources are first available in 2020.

(ii) 20% of this resource is available at $1.40 per exajoule, and the remaining 80% at $2.40 per exajoule.

(iii) A prohibition on the re-introduction of a technology once it has been abandoned.

Limits on the atmospheric concentration of CO_2 scenario have been studied extensively by Working Group I (the science assessment working group) of the IPCC. The accelerated technology scenario (scenario 6) was developed by the energy supply mitigation options team of IPCC Working Group III, based on work on biomass energy by Williams (1994).

The policies to be used to achieve the emission reductions are left up to the discretion of the modeling teams. It was argued that this type of scenario design would be most useful to policy makers and would reveal a great deal about the policies under consideration, the representation of these policies in the models, and model behavior. We will, however, ask each modeling team to specify the policies they have employed to achieve the specified emission reductions. If your model does not consider trading in carbon emission rights between regions, vary emissions in each region as you see fit to meet the various scenario targets.

Diagnostic Scenarios. The next three scenarios (13, 14, and 15) involve fixing the carbon emissions (13), CO_2 concentrations (14), and (15) global mean temperature trajectories input to the models, respectively (this type of scenario was originally proposed by Rob Mendelsohn of Yale University). This should enable us to isolate differences in the carbon cycle, climate, and damage components of the models, and to compare results with more elaborate component models developed by discipline specialists:

(13). Input Carbon Emissions From IPCC Scenario IS92A shown in the first column of Table A-5 in Appendix A.

(14). Input Carbon Dioxide Concentrations Projected by the MAGICC Model With the IS92A emissions as input shown in the second column of Table A-5.

(15). Input Global Mean Temperatures Projected by the MAGICC Model With the IS92A emissions as input shown in the third column of Table A-5.

The emissions trajectory in (13) is an extrapolated version of the emissions trajectory contained in Pepper, et al. (1992, p. 101) for the IS92A scenario, while the concentration and temperature trajectories are those produced by the MAGICC model (Wigley, 1994) for the IS92A scenario with the "default" set of gas cycle, climate and sea level parameter assumptions. Available information on other greenhouse gas emissions are shown in Appendix Table A-6, for other gas concentrations in Appendix Table A-7, and for other climate variables in Appendix Table A-8, for those who need it.

Impact Scenarios. Policy makers are ultimately interested in much more complex scenarios than those described above. Much of what is of interest to them goes beyond what the current integrated assessment models can examine, but this situation is improving rapidly. Joel Scheraga and Susan Herrod of EPA have formulated a set of five generic "impact" scenarios, to demonstrate some of the things that may be of most interest to domestic policy makers and international negotiators. Modelers should run as many of these scenarios as they can and assess what it would take to be able to the remaining ones in the future. The impact scenarios should ideally be considered with respect to the impacts on economic sectors and ecosystem types over time resulting from a range of climate scenarios:

Scenario (16): Examination of mitigation and/or adaptation strategies that help insure that various ecosystems maintain the ability to adapt naturally to alternative rates of climate change, while not exceeding acceptable rates (or levels) of net economic loss.

Policy Issue: Should a metric for determining policy be sensitive to the rate at which ecosystems and/or economic systems are able to adapt to climate change? This is relevant for meeting the objectives of Article 2 of the Framework Convention on Climate Change.

Scenario (17): Examination of the effect of potential discontinuities or irreversibilities in physical, biological or economic systems on the choice of policies.

Policy Issue: How important might the existence of discontinuities or irreversibilities be for climate policy? How important is it to consider the probabilities of different outcomes occurring?

Scenario (18): Compare preferred policies for achieving some "equity" in the distribution of impacts across different countries/regions to preferred policies for minimizing total global impacts.

Policy Issue: The development of international protocols -- and the acceptability of those protocols to different countries -- will require an examination of the distributional impacts of climate change across different countries.

Scenario (19): Examination of mitigation and/or adaptation strategies that would ensure that an acceptable level of loss of agricultural production is not exceeded.

Policy Issue: Article 2 of the Framework Convention on Climate Change also requires that dangerous anthropogenic interference in the climate system be avoided in order to ensure that food production is not threatened Hence it is useful to have a scenario which examines global agricultural production in particular.

Scenario (20): Effect of increases in the frequency and severity, and changes in the distribution of, extreme weather events (including drought, storms, and floods) on ecosystem types and economic sectors under alternative climate scenarios and policy options.

> Policy Issue: A key uncertainty is the potential effect of climate change on the frequency of extreme events. As countries consider making investments to "insure" against uncertain future climate impacts, inclusion of extreme events is warranted.

Since it is unlikely that many of the models can presently run many of these scenarios, it is pleasing to note that the "Analysis for Decisions Under Uncertainty" study group (see below) is exploring issues related to scenario #17, and the "Distribution of Costs and Benefits" study group is starting to investigate the issues included in scenario #18.

The EMF 14 baseline scenarios are displayed in Table 2 (developed by James Sweeney), which shows two dimensions to the model comparisons - a vertical "policy" dimension and a horizontal "model diagnostic" dimension. The additional lines shown for scenarios 2, 3, and 4 illustrate that these generic policy option scenarios also provide some diagnostic information as carbon emissions, carbon dioxide concentrations, and temperatures, respectively, are limited in these scenarios. Thus, to the extent that the limits are binding (usually the case) these scenarios provide another source of diagnostic information regarding the carbon cycle, climate, and impacts modules of the models, albeit one far from the reference case operating points of these modules.

Table 2

EMF 14 Scenario Map

(a.k.a. Sweeney Diagram)

Generic Policy	Level at Which Standardization is Imposed				
	Modelers Reference	EMF Reference (Standardize Econ. & Technology Drivers)	Standardize CO_2 Emissions	Standardize CO_2 Concentrations	Standardize Global Temperatures
No Intervention	**0**	**1**	**13**	**14**	**15**
Limit Carbon Emissions (1990 Level)	**8**	**2**	2	2	
Limit CO_2 Concentrations (550 ppmv)	**9**	**3**		3	3
Limit Global Temperatures (+2°C wrt 1990)	**10**	**4**			4
Pareto Optimal CO_2 Emissions	**11**	**5**			
Accelerated Technology	**12**	**6**			
Other Policy Scenarios	**16-20**	**7**			

OUTPUTS REQUESTED

Table 3 shows the output variables being requested from each model for each reporting year and region for each scenario. For the energy variables, the format is patterned after that used in the BP Statistical Review of World Energy, (British Petroleum, p.l.c, June 1992), primary energy includes commercially traded fuels only. Excluded therefore are fuels such as wood, peat and animal waste which, though important in many countries, are unreliably documented in terms of consumption statistics.

Also shown in Table 3 are our best estimates for values for the reporting variables for 1990. Actual reporting of data will be implemented in Lotus format via floppy disks to be provided by EMF headquarters. There will be alphanumeric labels for each data series, but blank data fields to be filled in by participating modelers.

Energy quantities should be expressed in terms of "net" calorific value. The difference between the "net" and the "gross" calorific value for each fuel is the latent heat in condensation of the water vapor produced during combustion of the fuel. For coal and oil, net calorific value is about 5 percent less than gross. For most forms of natural and manufactured gas, the difference is 9-10 per cent, while for electricity there is no difference. The use of net calorific value is consistent with the practice of the Statistical Offices of the European Communities and the United Nations.

Table 3
EMF 14 Output Reporting Form
(estimated 1990 values shown)

Variable	USA	EEC	OECD Total	FSU	China	Non-OECD Total	World Total
PRIMARY ENERGY CONSUMPTION (Exajoules)							
Coal/Shale	20.1	11.9	39.4	11.8	21.7	52.8	92.2
Total Fossil Fuels	73.2	43.6	148.2	52.9	26.9	149.6	297.8
Total Primary Energy	82.7	50.9	176.3	57.7	28.2	165.6	341.9
ELECTRIC GENERATION (Trillion KwH)	2.80	1.96	6.90	1.73	.62	4.75	11.65
ATMOSPHERE/CLIMATE							
Total Carbon Emissions[a] (million metric tons)	1417	863	2902	960	623	2962	5864
Total Sulfur Emissions (million metric tons)							
CO_2 Concentration (ppmv)							353
CH_4 Concentration (ppbv)							1720
ΔT (°C wrt 1990)							-
Sea Level Rise (cm wrt 1990)							-
ECONOMICS (Bil. 1990$s)							
Gross Domestic Product	5520	5710	16,200	1310	1330	5750	21950
Climate Change Costs							
Control Costs[b]							
Carbon Tax (1990$/metric ton carbon)							
LAND USE (million hectares)							
Agricultural Area							
Forest Area							
PHYSICAL IMPACTS							
Ecosystem Under Stress (million hectares)							
Area Lost to Sea Rise (mil.hectares wrt 1990)							
Mortality (deaths per 1000 people)							
Fresh Water Supply (Fraction of 1990)							

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[a] Not corrected for non-energy uses of fossil fuel. Following Marland and Boden, Statement before the Senate Committee on Energy and Natural Resources, July 26, 1989, computed by assuming emissions' coefficients of 19.94 million metric tons of carbon per exajoule of primary oil consumption, 13.74 for natural gas and 24.12 for coal.

[b] Relative to the appropriate reference scenario (scenario 0 or 1).

Sources: Primary Energy - British Petroleum (1992).
Fuels for Electric Generation - International Energy Agency (1992).
Atmospheric Concentrations - IPCC (1992).

RESULTS FROM BASELINE MODEL COMPARISONS

Twenty three modeling teams submitted results for the baseline model comparison scenarios although no team submitted all the outputs requested for all scenarios. Rather than give a complete review of all the results obtained here, a few key observations are emphasized and further details are left to a forthcoming paper (Weyant, 1997). In this section we: (1) look at the trends projected in GDP, energy use per unit of GDP (often referred to as energy intensity), and carbon emissions per unit of energy consumed for the reference and emissions stabilization scenarios, (2) review results for how the models compare in translating carbon emissions into atmospheric concentrations, concentrations into temperature change and temperature change into climate damages, and (3) summarize the cost estimates for various scenarios designed to limit carbon emissions through carbon emission reductions.

Reference Projections

The projections of carbon emissions for the reference scenarios vary widely. Projections of global carbon emissions in the year 2100 for the Standardized Reference Scenario range from about 16 billion tons to about 60 billion tons, with a mean of 28 billion tons and a standard deviation of 13 billion tons (see Figure 3). For the Modelers Reference Scenario (where each team can use its own preferred set of socio-economic drivers) the range of projections of world carbon emissions in the year 2100 is 16 billion tons to 71 billion tons, with a mean of 28 million tons and a variance of 14 billion tons (see Figure 4).

Figure 3. Standardized Reference Case
World Carbon Emissions

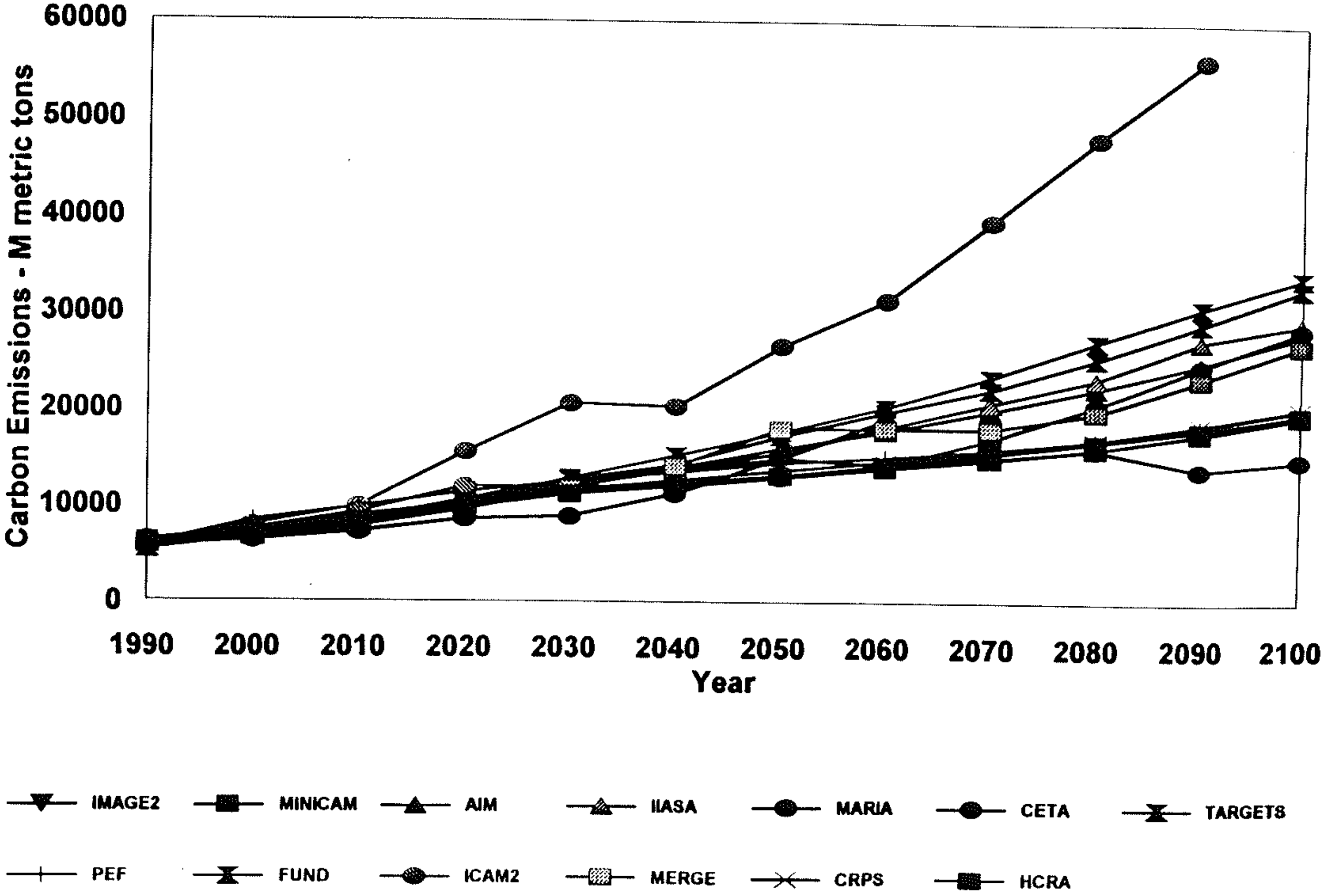
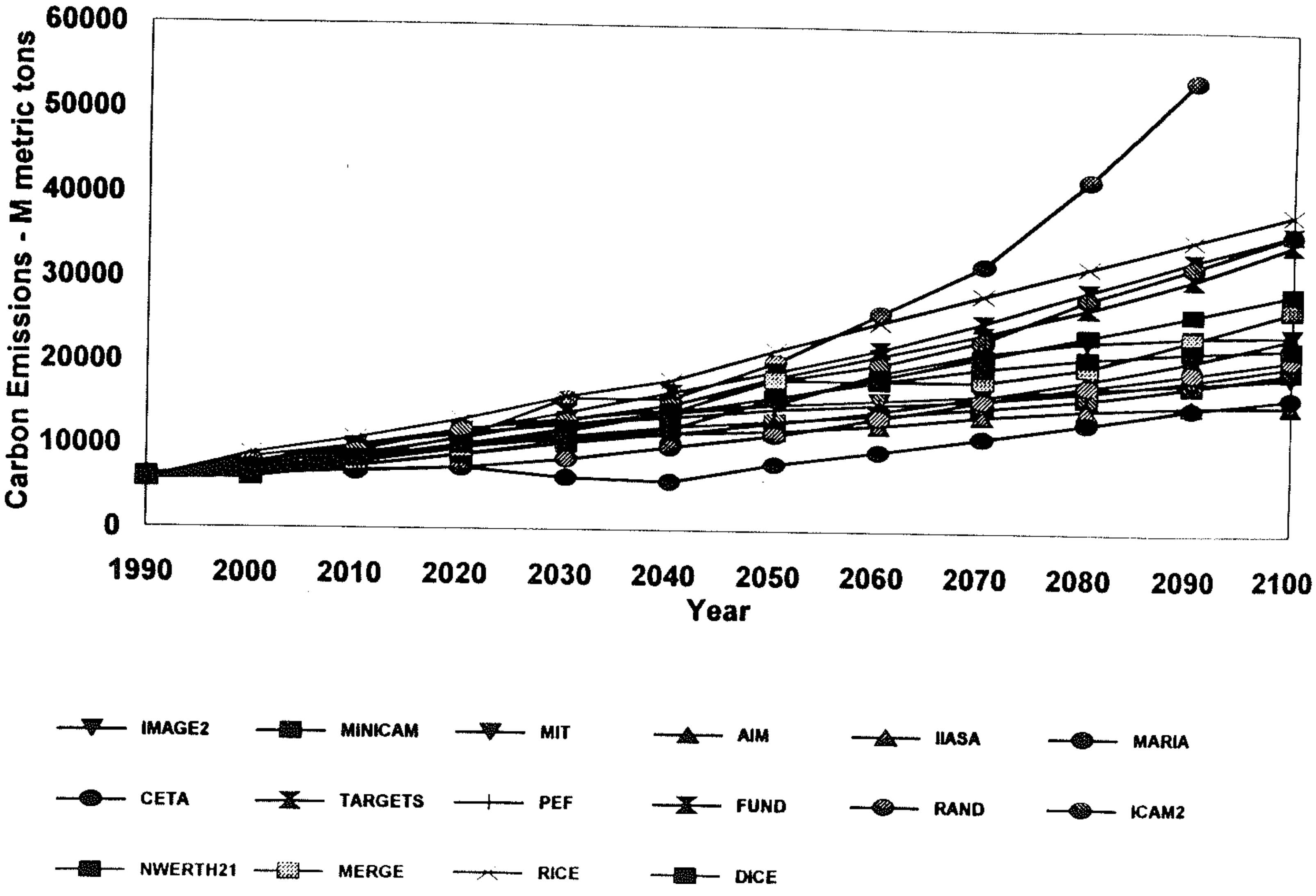


Figure 4. Modeler's Reference Case
World Carbon Emissions



It is also of interest to look at the projections of Gross National Product and primary energy use associated with the carbon emissions. For the Standardized Reference scenario projections of total primary energy use in 2100 range from about 1350 Exajoules up to about 300 Exajoules, with a mean of 2100 Exajoules and a standard deviation of about 700 Exajoules. For the Modelers Reference Scenario the range of primary energy projections range from 1100 to about 3500 Exajoules for the year 2100, with a mean of 1900 Exajoules and a standard deviation of about 800 Exajoules.

For the Standardized Reference scenario projections of world GDP in 2100 range from about $185 to $ 300 Trillion 1990 U.S. dollars, with a mean of $260 Trillion 1990 U.S. dollars and a standard deviation of about $25 Trillion dollars. For the Modelers Reference Scenario the range of world GDP projections range from $120 to $ 385Trillion 1990 U.S. dollars, with a mean of about $230 Trillion 1990 U.S. dollars and a standard deviation of about $50 Trillion 1990 U.S. dollars.

The differences in carbon emission projections can be decomposed into differences in economic growth projections, differences in energy use per uint of economic output and differences in carbon emissions per unit of energy use. Table 4 shows year 2100 projections of GDP, energy, and carbon emissions as multiples of their 1990 values for each model for the Standardized Reference and Modeler's Reference scenarios. Generaly, the models project about a 50% reduction in the energy/GDP ratio by 2100 relative to 1990, and a small reduction in the carbon intensity of energy use. This decomposition also enables us to see whether a model that produces

Table 4
DECOMPOSITION OF EMISSION PROJECTIONS
(Year 2100 Multiples of 1990 Values)

Model	Standardized Reference			Modelers Reference		
	GDP	Energy	Carbon	GDP	Energy	Carbon
AIM	12.8	5.5	4.8	17.6	4.8	4.0
CETA	12.2	6.6	4.9	7.7	4.3	2.8
CRPS	12.5	-	3.4			
DICE				10.1	-	3.8
FUND	10.4	-	5.6	5.7	-	3.7
HCRA	12.5	-	3.3			
ICAM-2	11.7			12.4	5.8	5.6
IIASA	14.3	7.0	4.9	14.8	4.8	2.6
IMAGE-2	12.3	7.8	5.7	13.9	5.5	3.9
MARIA	14.6	10.9	11.2	13.8	11.3	11.9
MERGE	12.8	8.0	4.6			
Mini-CAM	12.3			11.7	4.3	3.4
MIT				7.0	3.0	3.1
NewE-21					4.0	5.0
PAGE	-	-	2.6			
PEF	13.1	-	3.5	13.1	-	3.5
RAND				-	-	2.6
RICE				9.3	-	6.5
TARGETS	9.7	5.8	5.3	9.3	5.7	5.5
YOHE				4.1	-	2.7

Table 5

DECOMPOSITION OF EMISSION PROJECTIONS

(Year 2100 Multiples of 1990 Values)

Model	Standardized Reference			Stabilize Emissions wrt Std. Ref.		
	GDP	Energy	Carbon	GDP	Energy	Carbon
AIM	12.8	5.5	4.8	16.6	3.0	1.0
CETA	12.2	6.6	4.9	12.1	5.4	1.0
CRPS	12.5	-	3.4	12.5	-	1.0
DICE						
FUND	10.4	-	5.6	5.7	-	3.7
HCRA	12.5	-	3.3	12.5	-	1.0
ICAM-2	11.7	3.1	2.3	11.9	2.4	1.0
IIASA	14.3	7.0	4.9	13.9	7.4	1.0
IMAGE-2	12.3	7.8	5.7			
MARIA	14.6	10.9	11.2	13.7	3.8	1.0
MERGE	12.3	8.0	4.6			
Mini-CAM				11.4	3.2	1.0
MIT						
NewE-21						
PAGE	-	-	2.6			
PEF	13.1	-	3.5	13.1	-	1.0
RAND						
RICE						
TARGETS	9.7	5.8	5.3			
YOHE						

higher or lower projections of carbon emissions than average does so because of higher or lower GDP growth projections, energy intensity projections, or carbon intensity projections. This same type of decomposition can also be used to see how a particular model implements carbon emssion reductions, i.e., the extent to which it is projected that GDP, energy intensity or carbon intensity are reduced to meet a specific carbon emission limitation. For example, Table 5 compares the values for the Standardized Reference scenario and the Stabilize Carbon Emissions at 1990 levels with Repect to the Standardized Reference scenario assumptions. Thus, the AIM model achieves the required carbon emission reduction through a combination of energy efficiency improvements and reductions in the carbon intensity of energy use, while the IIASA model relies primarily on carbon intensity reductions. Table 6 shows the same decomposition for the Stabilize Emission With Respect to the Modelers Reference Scenario. Further decompositions are possible as well. For example, Table 7 shows total primary fossil fuel use and primary coal use multiples between the energy and carbon multiples shown previously. In both the Standardized Reference Scenario and the Modelers Reference Scenario. Generally the model projections show a reduction in the total fossil fuel share of primary energy, but an increase in coal use, with some models increasing coal use enough to maintain the sahre of fossil fuels in total energy despite the exhaustion of much of the world's oil and gas.

Component Model Comparisons

Figures 5 and 6 show how the projections of CO2 concentration in the atmosphere for the Stabilize Emisssions at 1990 levels for the standardized reference and modelers reference assumptions, respectively. These results show very similar CO2 concentration projections,

Table 6
DECOMPOSITION OF EMISSION PROJECTIONS
(Year 2100 Multiples of 1990 Values)

Model	Modelers Reference			Stabilize Emissions wrt Mod. Ref.		
	GDP	Energy	Carbon	GDP	Energy	Carbon
AIM	17.5	4.8	4.0			
CETA	7.7	4.3	2.8	7.6	3.6	1.0
CRPS						
DICE	10.1	-	3.8	9.7	-	1.0
FUND	5.7	-	3.7			
HCRA						
ICAM-2	12.4	5.8	4.6	11.0	2.1	1.0
IIASA	14.8	4.8	2.6	14.6	4.6	1.0
IMAGE-2	13.9	5.5	3.9			
MARIA	13.8	11.3	11.9			
MERGE						
Mini-CAM	11.7	4.3	3.4			
MIT	7.0	3.0	3.1			
NewE-21		4.0	5.0			
PAGE						
PEF	13.1	-	3.5	13.1	-	1.0
RAND	-	-	3.6			
RICE	9.3	-	6.5	8.8	-	1.0
TARGETS	9.3	5.7	5.5			
YOHE	4.1	-	2.7	3.4	-	1.0

Table 7
DECOMPOSITION OF CARBONIZATION PROJECTIONS
(Year 2100 Multiples of 1990 Values)

Model	Standardized Reference				Modelers Reference			
	Energy	Fossil	Coal	Carbon	Energy	Fossil	Coal	Carbon
AIM	5.5	-	10.7	4.8	4.8	-	9.0	4.0
CETA	6.6	4.0	10.8	4.9	4.3	2.3	6.6	2.8
CRPS	-	-	-	3.4				
DICE					-	-	-	3.8
FUND	-	-	-	5.6	-	-	-	3.7
HCRA	-	-	-	3.3				
ICAM-2	3.1	1.8	5.8	2.3	5.8	5.5	8.0	5.6
IIASA	7.0	4.3	11.8	4.9	4.8	3.3	1.6	2.6
IMAGE-2	7.8	5.2	6.1	5.7	5.5	4.0	4.7	3.9
MARIA	10.9	8.0	26.1	11.2	11.3	7.7	26.3	11.9
MERGE	8.0	-	-	4.6				
Mini-CAM	4.3	-	9.1	4.6	4.3	-	8.1	3.4
MIT					3.0	3.2	2.6	3.1
New Earth 21					4.0	4.1	12.7	5.0
PAGE	-	-	-	2.6				
PEF	-	-	-	3.5	-	-	-	3.5
RAND					-	-	-	2.6
RICE					-	-	-	6.5
TARGETS	5.8	5.2	6.1	5.3	5.7	5.5	6.1	5.5
YOHE					-	-	-	2.7

Figure 5. Stabilize Emissions at 1990 Levels - Standardized Inputs

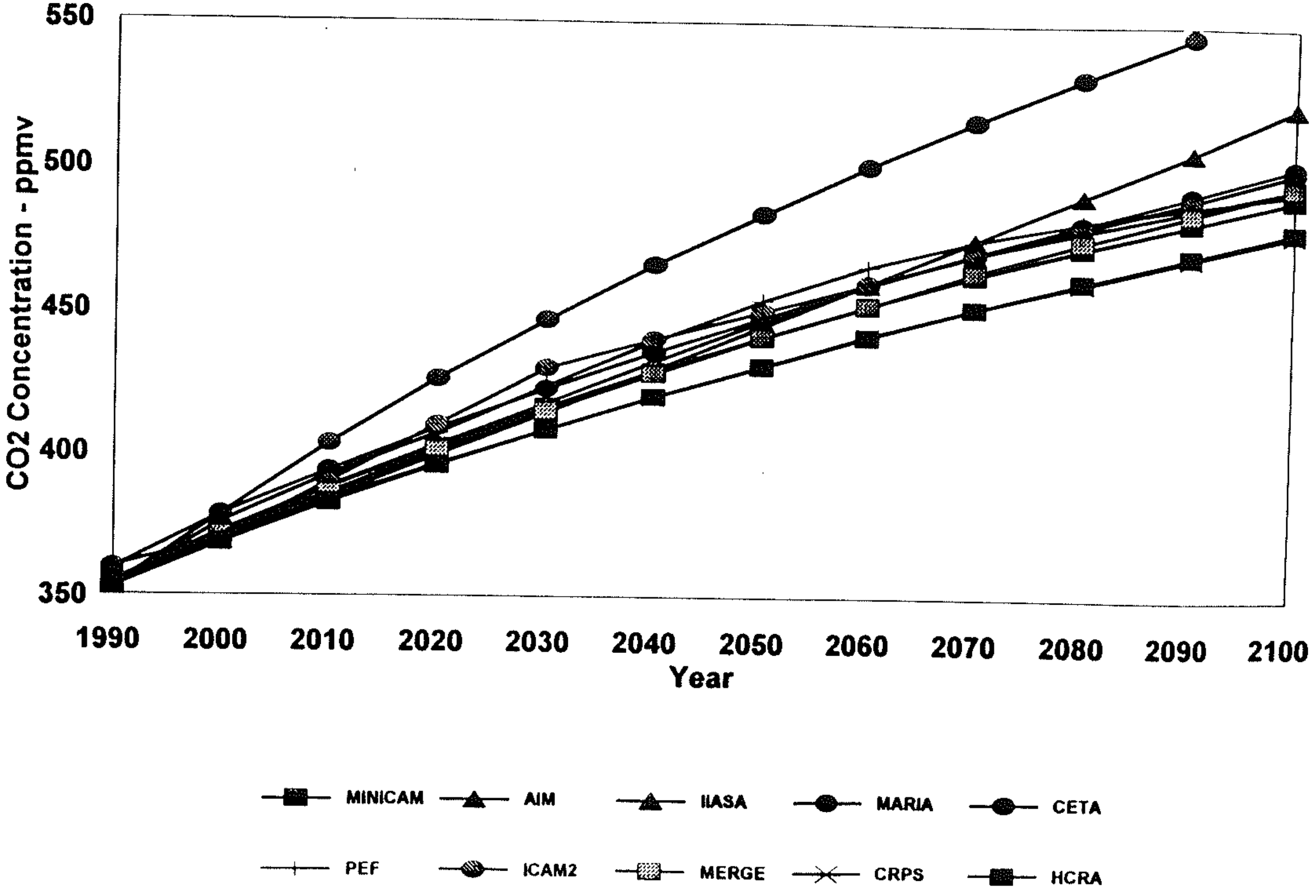


Figure 6. Stabilize Emissions at 1990 Levels - Modelers Input

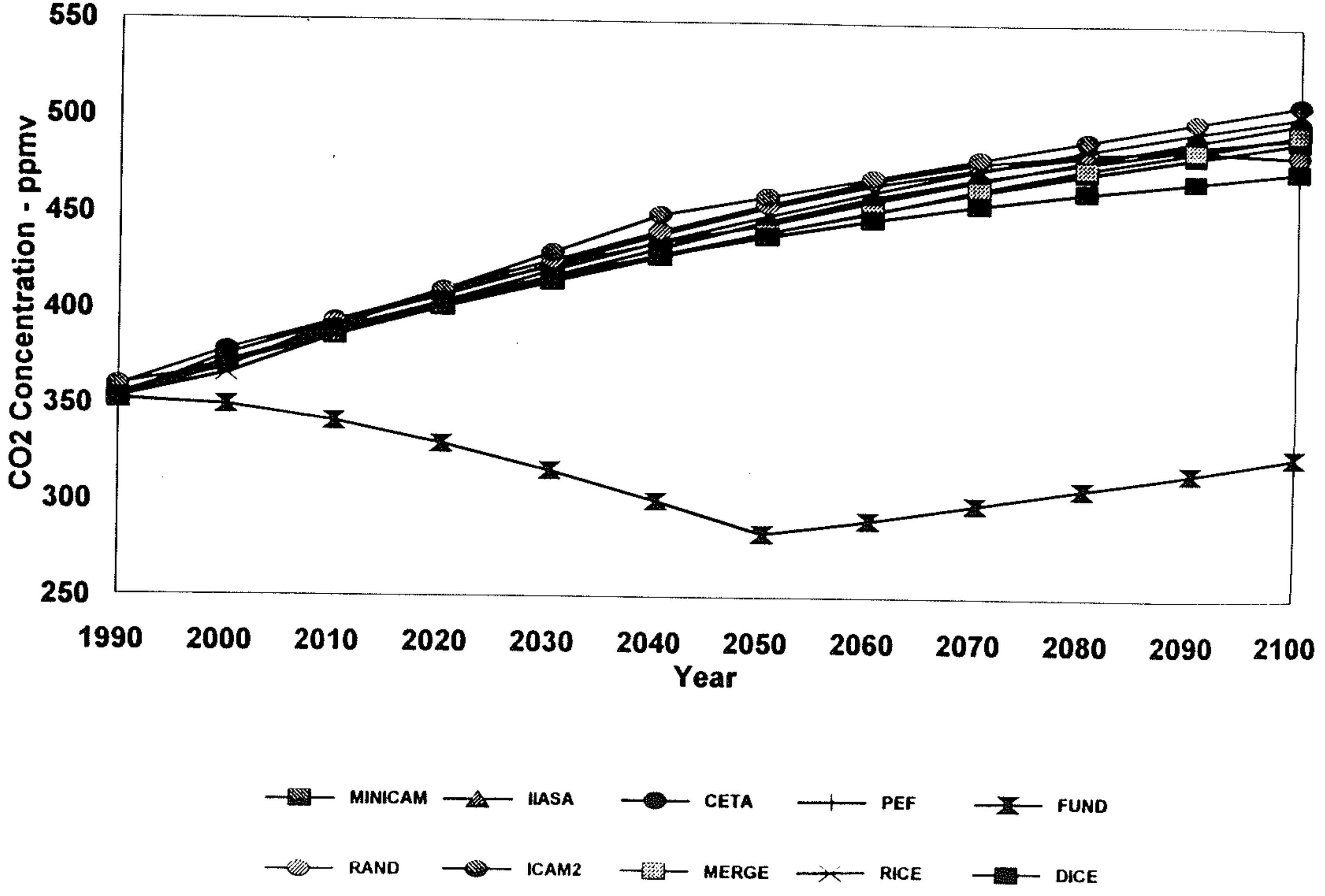


Figure 7. Limit CO2 Concentration to 500 ppm - Standardized Inputs

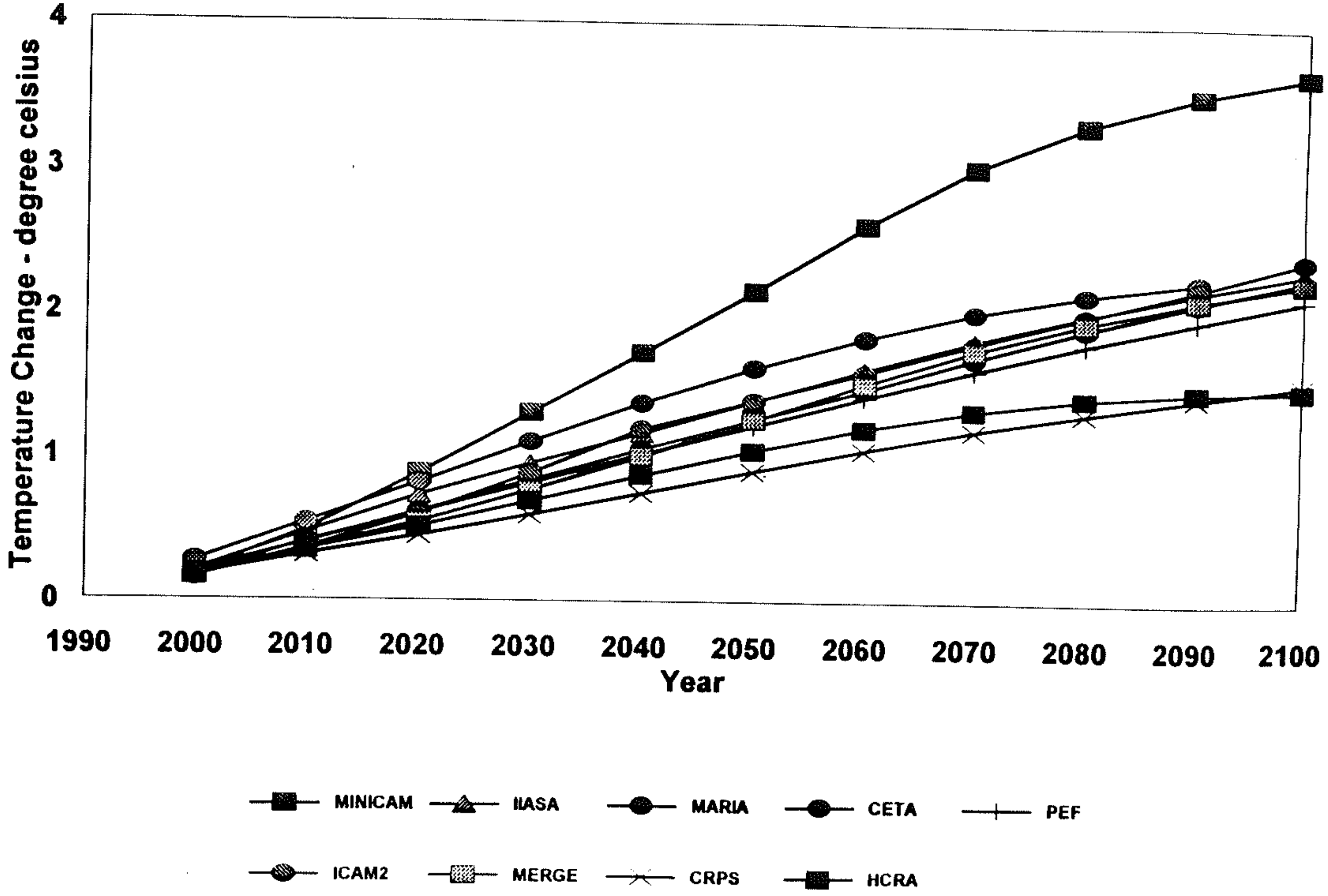
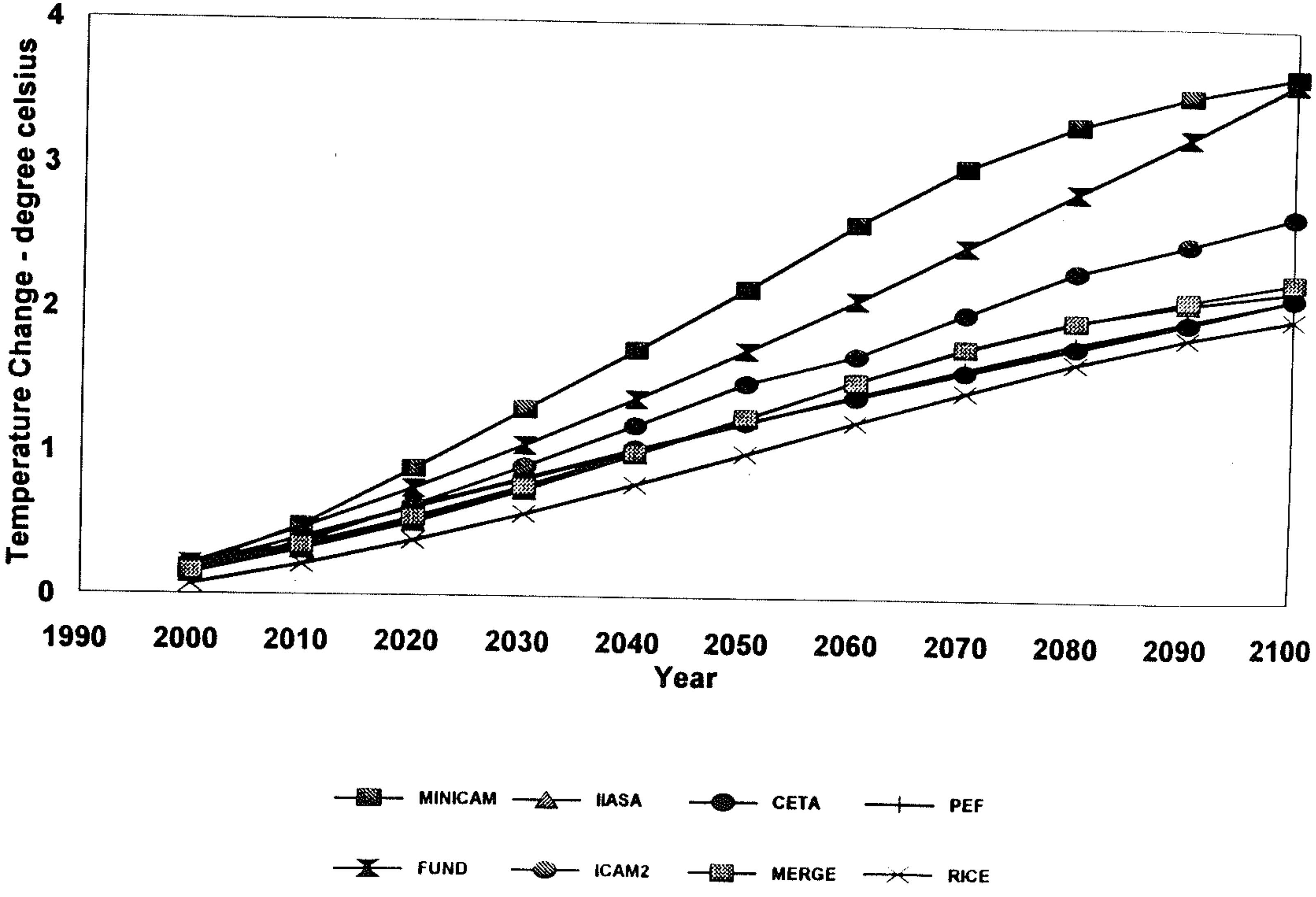


Figure 8. Limit CO2 Concentration to 500 ppm - Modelers Inputs



primarily because most models use the same reduced form carbon cycle model due to Meyer-Reimer and Hasselman. The projections of temperature change for the scenarios in which carbon concentrations are limited to 550 parts per million are shown in Figures 7 and 8. Here there is more dispersion in the ressults, but this may be because the modeling teams are using different climate sensitivities (equilibrium temperature increase for a doubling of atmospheric CO2 concentrations) as inputs.

Emissions Versus Concentration Limits

It is of interest to compare the effectiveness of emissions limits versus concentration limits in limiting CO2 in the atmosphere. Figure 9 shows the projections of the carbon taxes required to stabilize carbon emissions at 1990 levels for the modelers reference case assumptions, while Figure 10 shows those required to limit CO2 concentrations to less than 500 parts per million. The cost of implementing the emissions limits are much greater than for observing the concentration limit. As shown in Figures 11 and 12, CO2 concentrations by 2100 are approximately equal (about 550 ppm) in the two scenarios, but the CO2 concentrations are slightly higher in the concentration limit case prior to 2100.

STUDY GROUPS

Five study groups have been established to investigate issues relevant to integrated assessment, but not necessarily considered in the existing set of models. Table 8 lists the groups and their Chairmen/Co-ordinators.

Table 8
EMF 14 Study Groups & Chairman Co-ordinators

Study Group	Co-ordinators/Chairmen
Decision Making Under Uncertainty	Phase I: Alan Manne (Stanford University) Phase II: Hadi Dowlatabadi (Carnegie-Mellon)
International Distribution of Costs and Benefits	Jae Edmonds (Pacific Northwest National Lab.) Richard Richels (Electric Power Research Inst.) Erik Haites (IPCC) Howard Gruenspecht (U.S. Dept. of Energy) Tom Wigley (Univ. Consortium on Atmos. Research)
Climate Change Impacts and Integrated Assessment	EMF 14 Interface: John Reilly (U.S. Dept. Agric.) Sally Kane (NOAA) Snowmass Chairs: Jerry Melillo (Marine Biology Lab.) Rob Mendelsohn (Yale Univ.) Case Studies: Jae Edmonds (PNNL) John Houghton (U.S. Dept. Of Energy)
Valuation/Discounting	Bob Lind (Cornell) Paul Portney (RFF) Alan Manne (Stanford University) Ferenc Toth (Potsdam Institute)
Technology Innovation and Diffusion	John Houghton (U.S. Department of Energy)

Figure 9. Stabilize Carbon Emissions
at 1990 Levels - Modelers Inputs

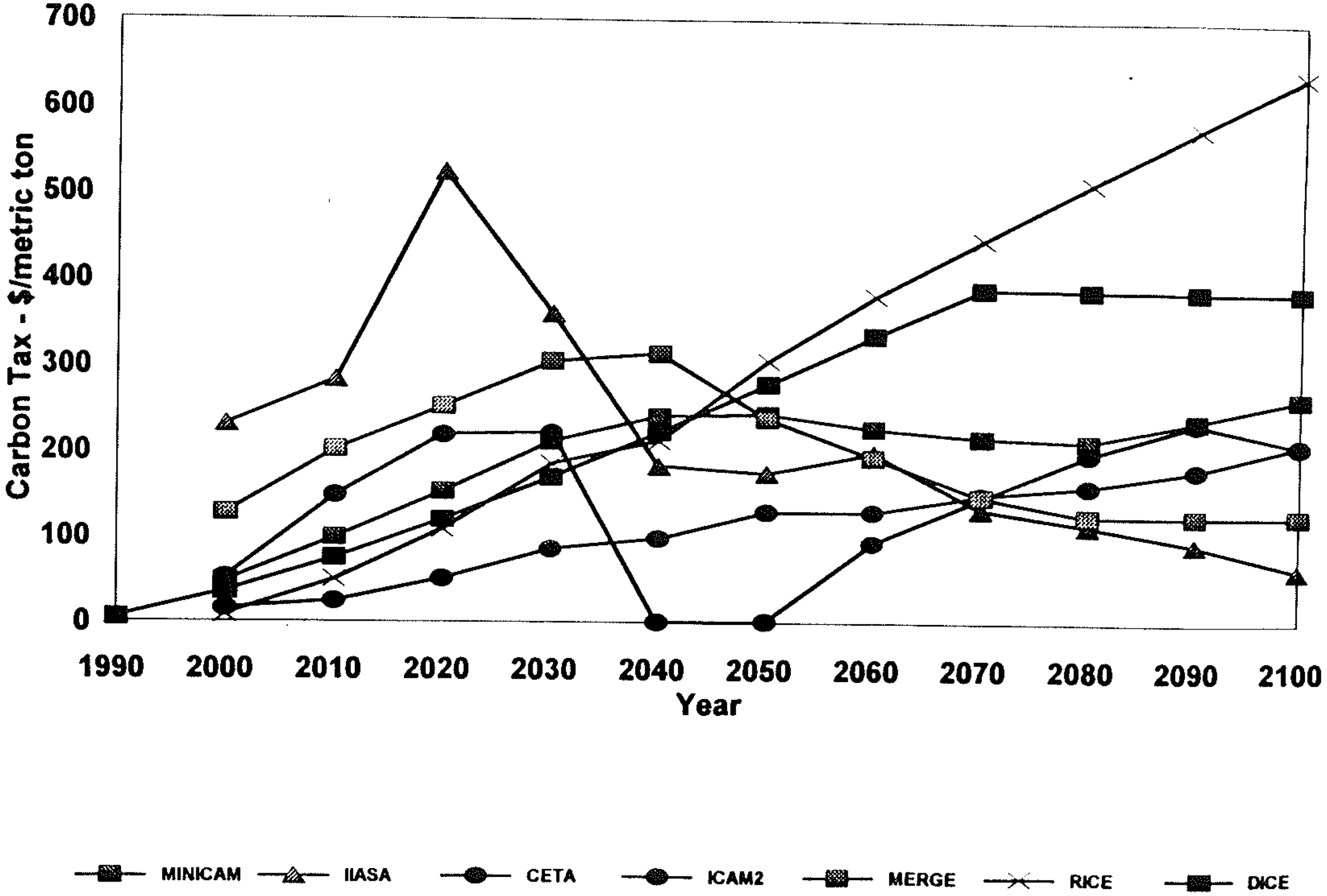


Figure 10. Limit CO2 Concentration to 500 ppm - Modelers Inputs

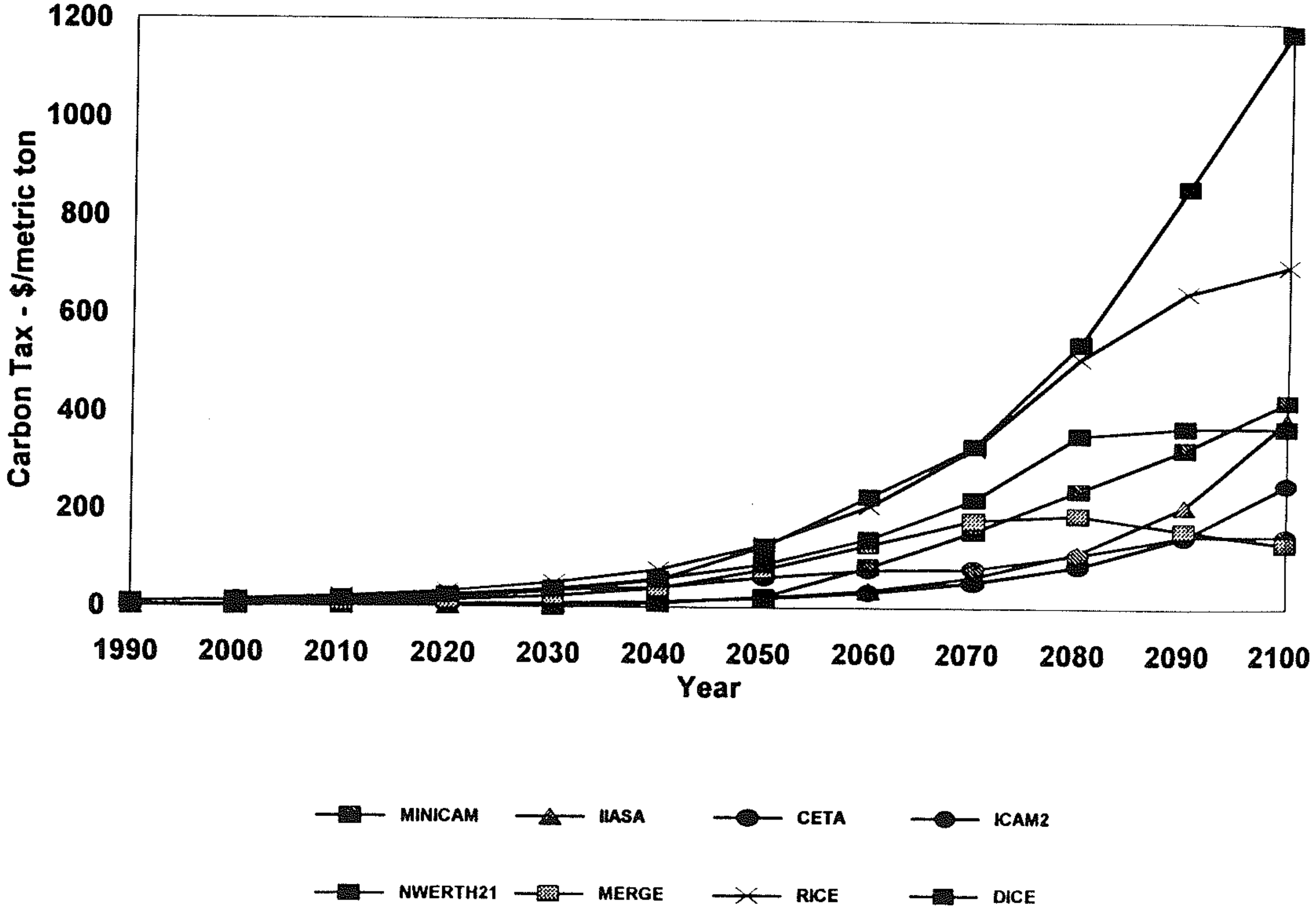


Figure 11. Stabilize Carbon Emissions at 1990 Levels - Modelers Inputs

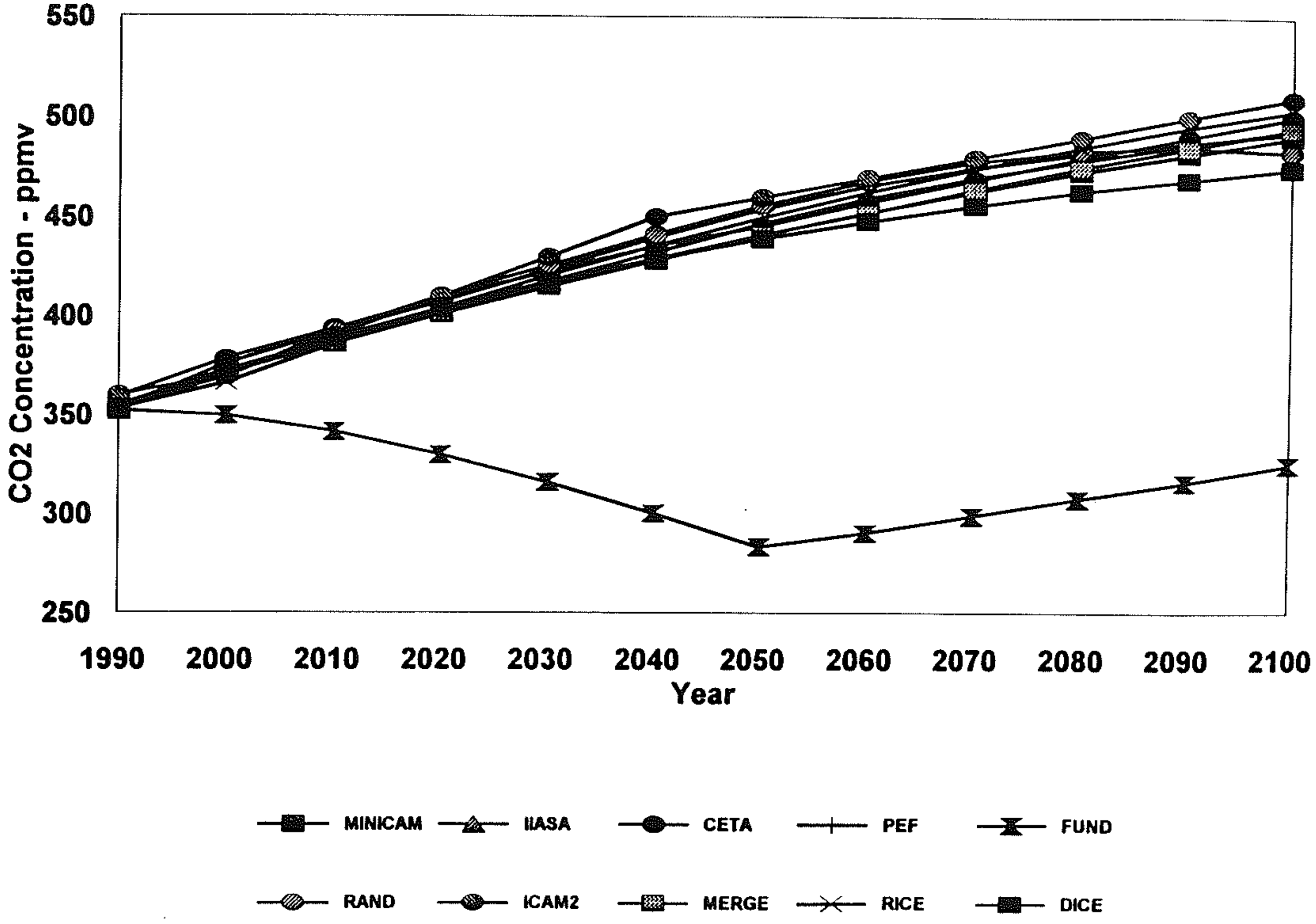
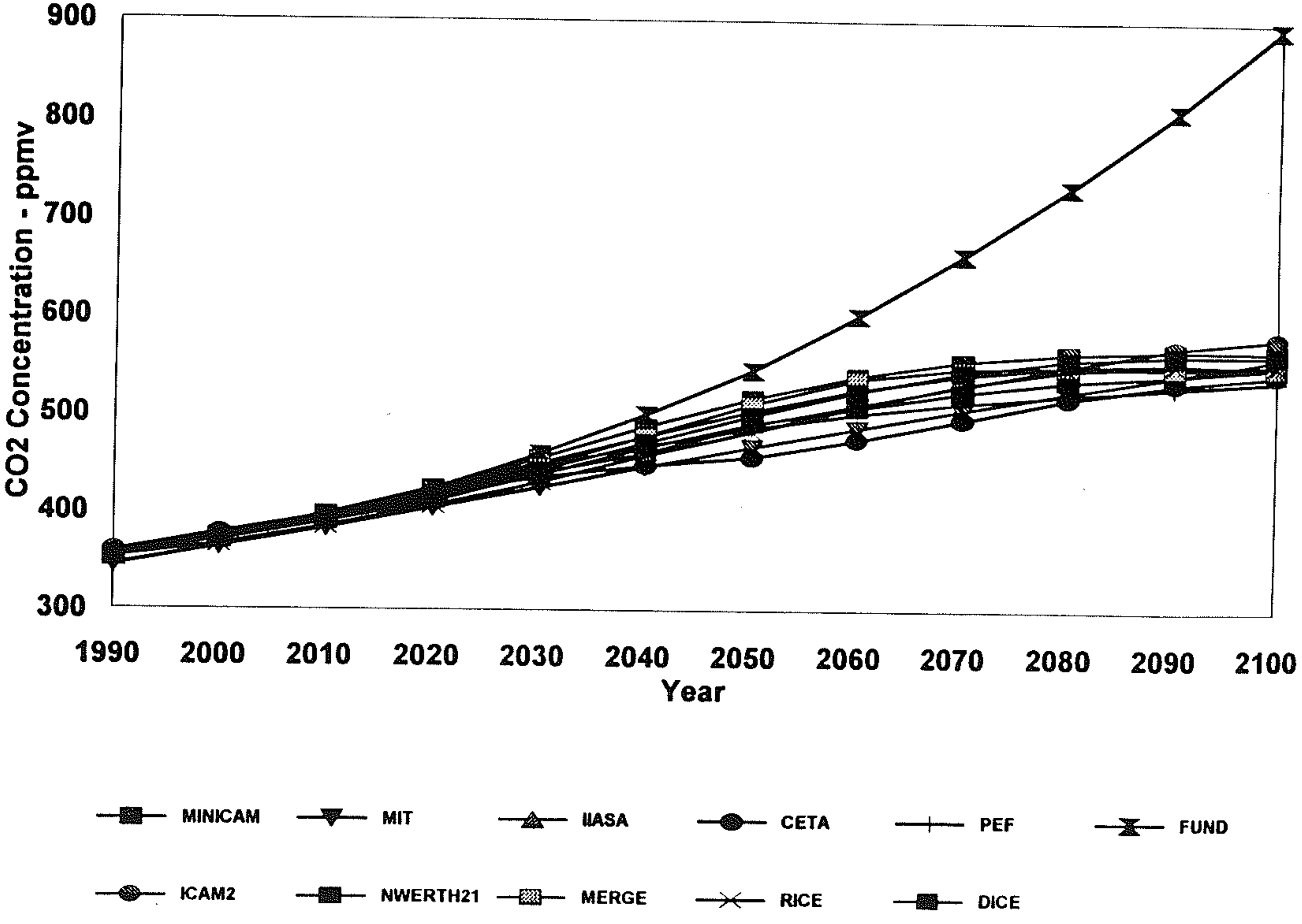


Figure 12. Limit CO2 Concentration to 500 ppm - Modelers Inputs



The Impacts of Climate Change Study group is assessing how climate impacts are represented in integrated assessment models and the extent to which recent research from the relevant disciplines could improve the state of the art. The work of this group has significantly augmented by summer workshops on "Climate Change Impacts and Integrated Assessment" organized by the EMF during the past two summers. During the summer of 1995, the EMF organized a workshop on climate change impacts and integrated assessment of climate change on behalf of the United States Global Change Research Program (USGCRP), the U.S. Department of Energy, and the U.S. Environmental Protection Agency. The purpose of this workshop was to bring researchers studying the likely impacts of climate change together with researchers working on developing methods and models for integrating the atmospheric, ecological and economic dimensions of climate change and potential policy responses to it. This workshop was successful in stimulating dialog between the several disciplines involved in climate change research, in identifying new joint research projects for the individual researchers who participated, and in setting up the structure for a collaborative research project among all the participants and anyone else who might chooses to participate.

During this workshop, it was concluded that the analysis of climate change impacts has progressed significantly over the past 2-3 years and is better than what is included in most of the integrated assessment models. On the other hand, both the impacts analysts and the integrated assessment modelers recognized that they could improve the current state-of-the-art in integrated climate impacts analysis significantly by working together over the next few years. For example, the new climate impact studies generally are based on better data and methods and do a more thorough job representing the adaptation of human, animal, and eco-systems to climate change, but most studies are based on analysis of two times CO_2 equilibrium conditions. However, one of the major goals of integrated assessment is the analysis of alternative transition paths to a lower-carbon world, where the dynamics of the adjustment of natural and anthropogenic systems are crucial. Thus, there appears to be a large potential payoff from getting the researchers involved in climate impact assessment research to work together with the integrated assessment modelers on appropriate specifications and projections of the dynamics of the climate change impacts. In response to to this realization, a small number of "case studies" of integrated climate impacts that the group could work on together subsequent to the workshop.

Although the participants were enthusiastic about these initial case studies, it was recognized that that the results from these case studies will constitute only a first step in the process of producing more credible integrated climate impact projections for a number of reasons. First, only two countries - the U.S. and China, only three scenarios - a baseline and two ways of achieving a 550 ppm limit on CO_2 in the atmosphere are being considered, and only certain impacts categories - agriculture and forestry, eco-system, and human health impacts - are being considered. Second, for the most part the results we obtain will be integrated, and co-ordinated across sectors, but necessarily "once through" in the sense that interactions and feedbacks among the sectors considered and between them and the climate and overall economic system will not be explicitly considered. Third, work on a number of critical methodological issues is in its infancy: e.g., valuation of non-market impacts, modeling adaptation under uncertainty, and scaling from experimental ecology results to larger geographical areas. Thus, it was proposed that additional workshops be convened for the summers of 1996, 1997 , and 1998, with an option to continue after 1998. In addition, it was concluded that it would be desirable to diversify funding into the international community and the private sector to insure the broadest possible participation in the activity. With support from the USGCRP, the Environment Agency of Japan, the Australian Bureau of agriculture and energy resource economics, the Electric Power Research Institute, and Exxon Research and Engineering. The 1996 Workshop took place from July 25 to August 1 in Snowmass, Colorado. It was very successful in pushing the case studies forward and surfacing new research on climate change impacts. Planning for the 1997 workshop is now in the active planning stage.

The Decisions Under Uncertainty study group is employing some of the models participating in the base model comparison exercise - CRAPS, DICE, ICAM-2, MERGE, PAGE, and SLICE - as well as a half dozen additional smaller-scale research models that focus explicitly on uncertainty and learning to explore the potential impact of uncertainties in key model inputs and structural assumptions on climate change policy decisions. The results of the first phase of the work of this group is summarized in Appendix B (1996). In Phase II, the Decision Making Under Uncertainty study group will; (1) extend the Phase I analysis, especially in refining the value of improved information regarding key demographic, economic, and scientific parameters, (2) design and implement a methodology for characterizing the amount of uncertainty surrounding the modelers reference case produced with each model, and (3) systematically examine the impact of learning and adaptive behavior on optimal policies through a model comparision of the models that include imperfect information and learning.

The International Distribution of Costs/Benefits study group is exploring what the models say about the international allocation of emissions rights and responsibilities for paying for emission reductions as a precursor to international negotiations on these issues. The first experiments performed by this group involved alternative levels of participation in programs designed to reduce global carbon emssions and alternative timing of carbon emssion reduction leading to the achievement of a gloabl carbon ceiling for global carbon emissions. These results are summarized in Appendix C. Work planned for this group over the coming year will involve further investigation of the so-called "spill-over effects" of actions to reduce carbon emissions in the OECD countries on economic activity in the non-OECD countries, as well as more work on alternative schemes for participation in - and burden sharing of the costs of - a global carbon emissions reduction program.

The Valuation/Discounting study group is exploring a number of valuation issues that are fundamental to assessments of the magnitude of the climate change problem and potential policy responses to it, including initially the discount rate and ultimately the valuation of non-market impacts. A high level meeting jointly sponsored by the EMF and Resources for the Future was held on November 14 and 15th, 1996 at the headquarters of Resources for the Future in Washington, D.C. to discuss the merits of altenative ways of thinking about the appropriate discount rate for making very long term decisions.

In June of 1995 a group of about 30 relevant experts was convened for John Houghton at the Department of Energy to review work on representing technical change and its implications for integrated assessment. Researchers were drawn from within the integrated assessment community as well as from outside of it. A follow-up meeting on timining optimal emssions reductions was held in Paris in June of 1996. The meeting was co-sponsored by the EMF, the International Center for Research in Environment and Development, the Royal Institute of International Affairs and the Electric Power Research Institute. Additional efforts in this area are being discussed and should also benefit from joint sponsorship.

ADDITIONAL INSIGHTS FROM INTEGRATED ASSESSMENT MODELS

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. Many of these insghts were first identified by one of the EMF 14 study groups.

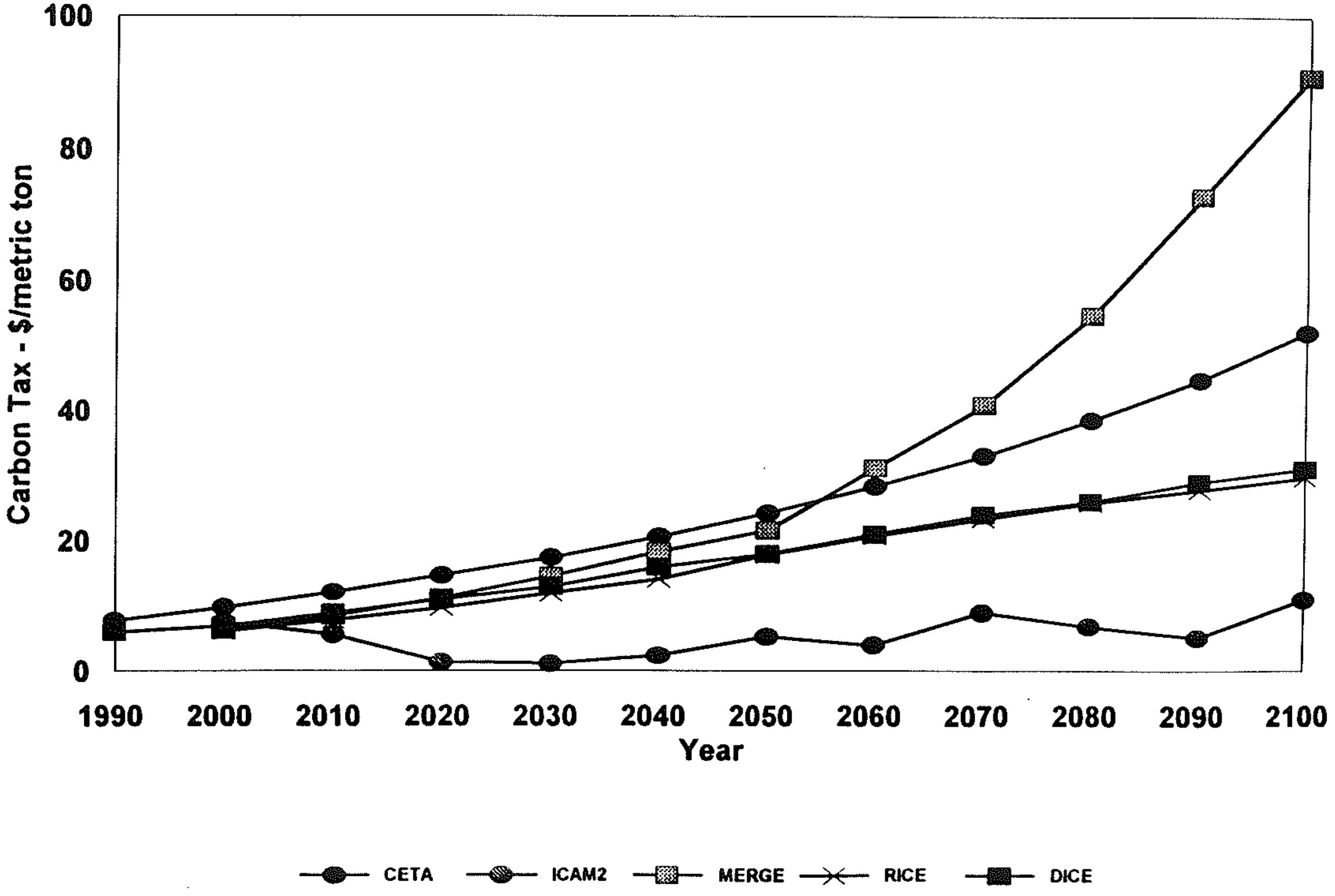
There are also large differences in the outputs that individual modelers report from their integrated analyses, and the time periods for which those outputs are reported. Some of the more common outputs from the policy optimization models are projections of the cost of controlling greenhouse gas emissions, 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 13 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.

Figure 13. Pareto Optimal Emissions
Modelers Inputs



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 Results from the preliminary report of The International Distribution of Costs and Benefits study group are included here in Appendix C and 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.

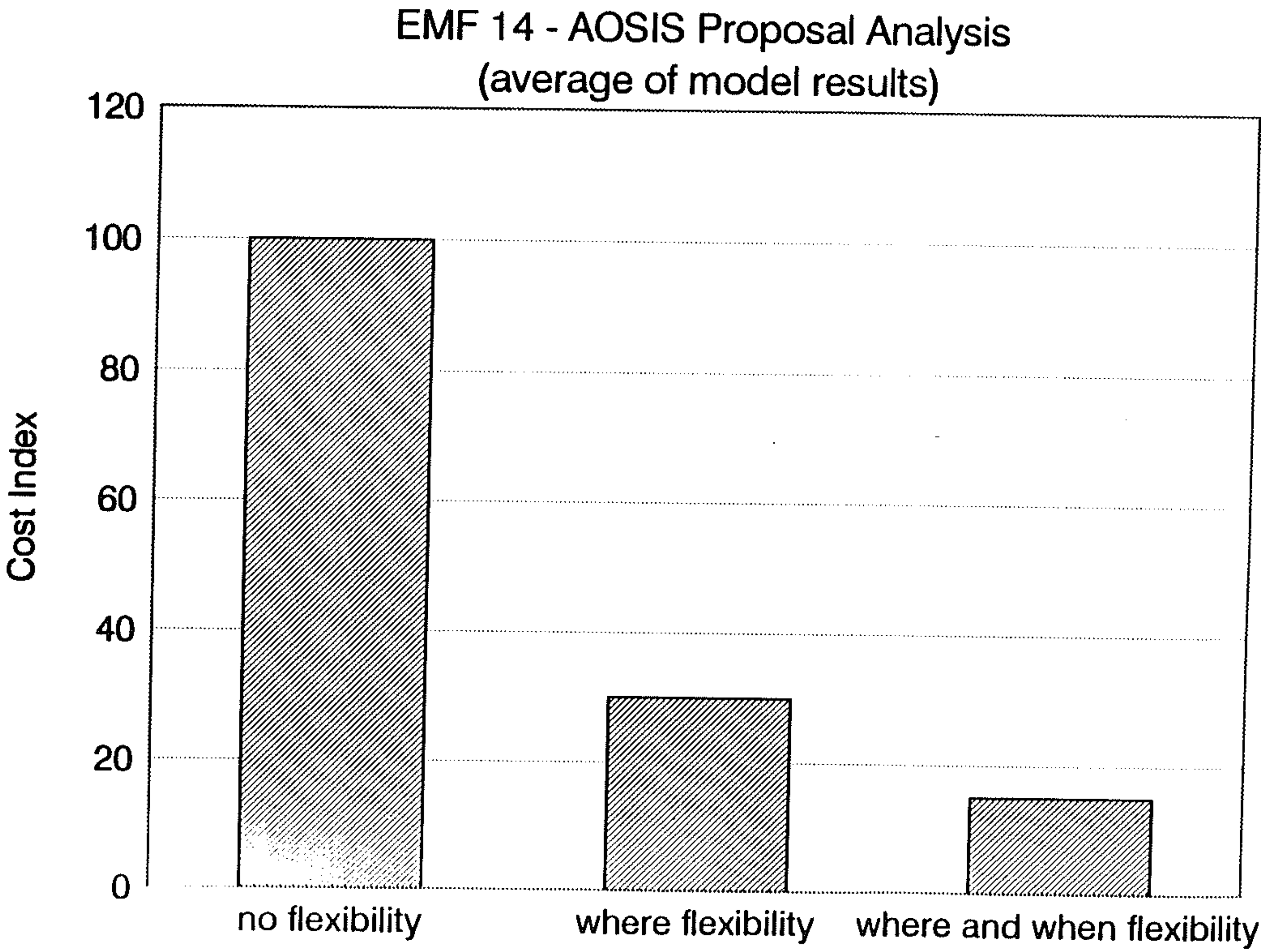
The group then examined ways that we might achieve the same amount of emission reduction but at a lower cost. In particular, the benefits of providing what was referred to as "where" and "when" flexibility were examined. In the case of "where flexibility," emissions are reduced by the specified amount, 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 14 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

Figure 14, Cost Comparison under Alternative Assumptions about Economic Efficiency



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 inital experiments designed by the Decision Making Under Uncertainty study group discribed in Appendix B and summarized here.

Figure 15 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.

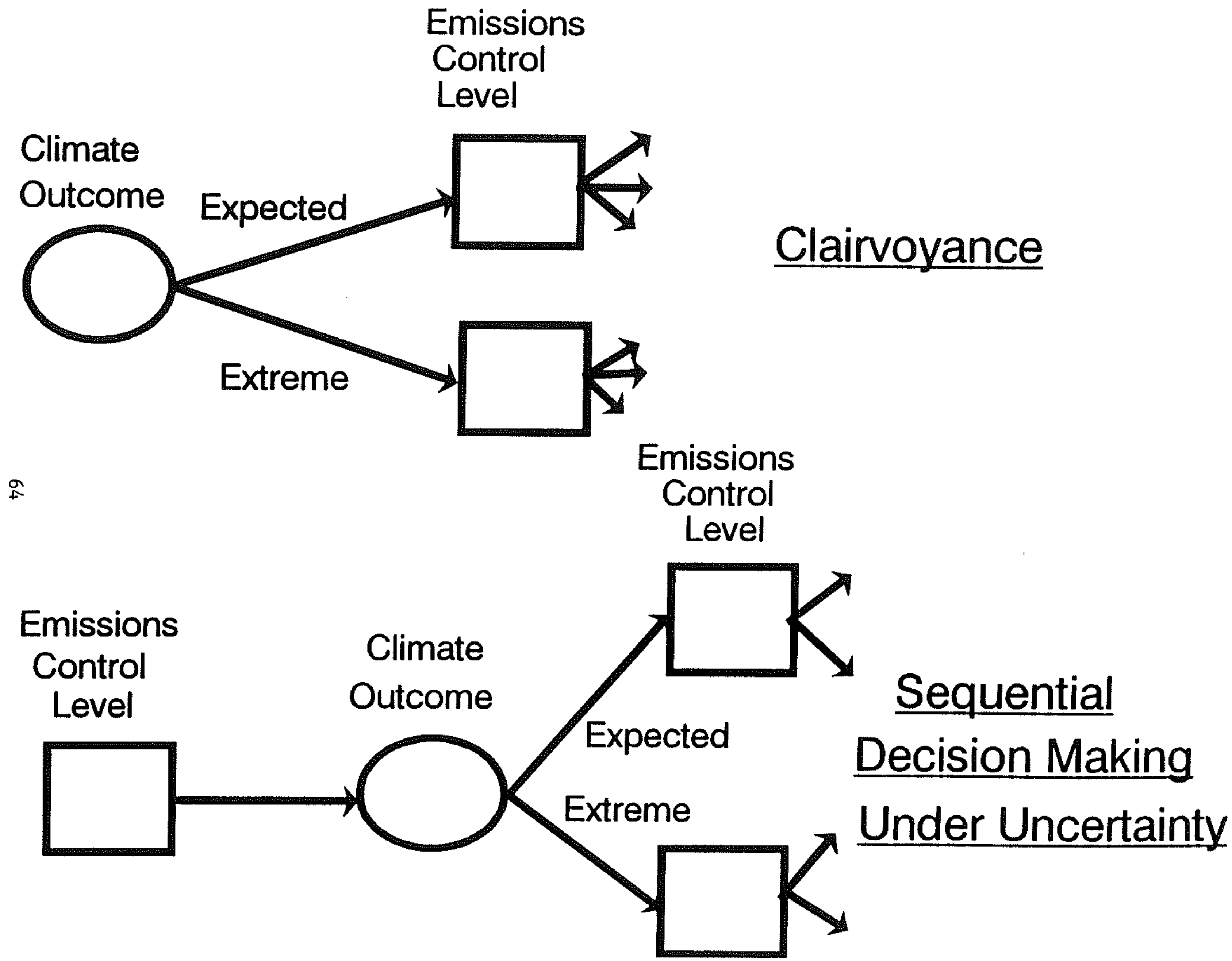


Figure 15. Alternative Decision Making Under Uncertainty Paradigms

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.

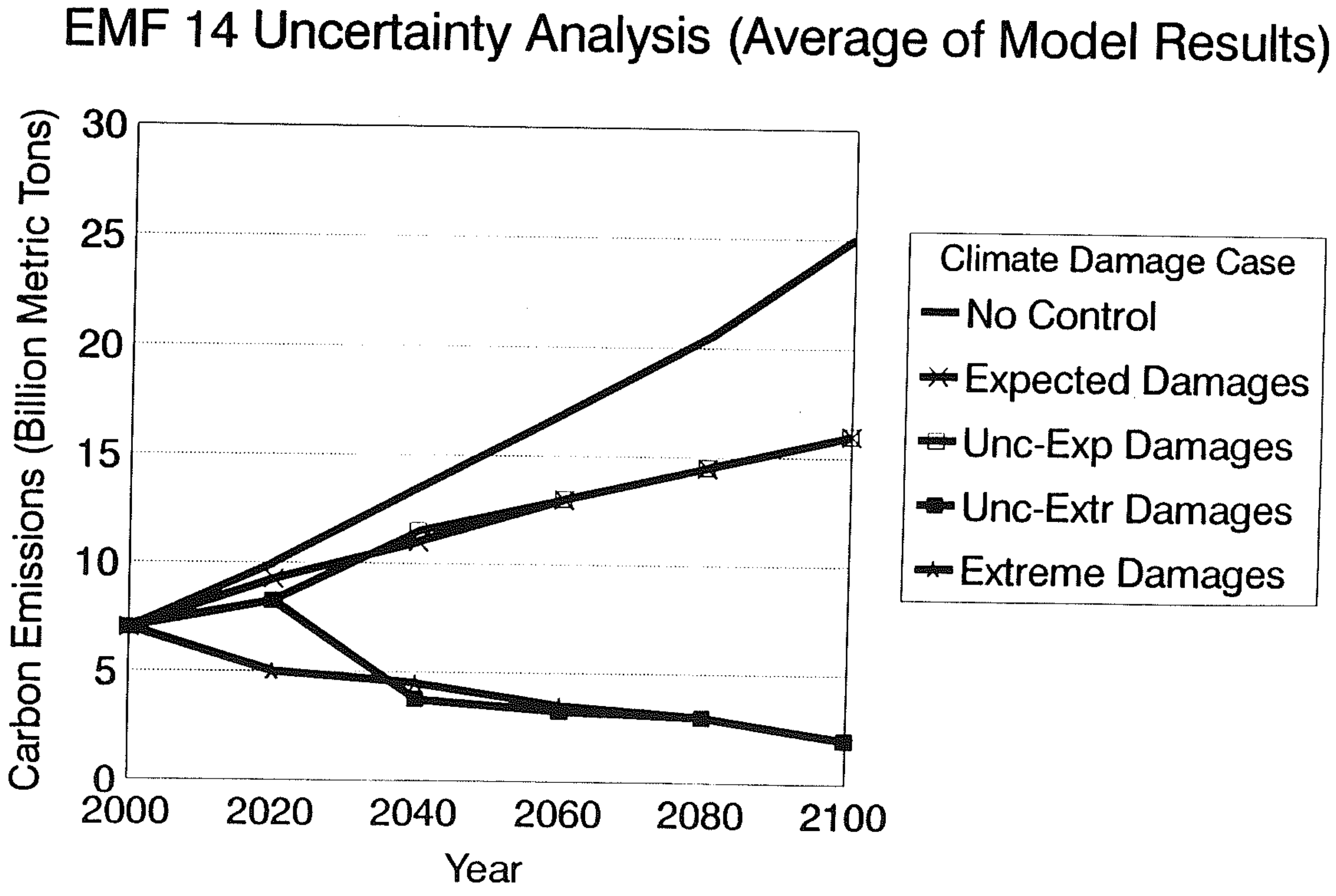
Upon reviewing the structures of the model and the literature, only two parameters appeared to meet all the criteria: the mean temperature sensitivity factor and the cost of damages associated with global warming. More precisely, climate sensitivity is defined as the equilibrium change in temperature 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 16 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 16, 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.

Figure 16. Hedging Against Bad Climate Outcomes



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: (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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APPENDIX A
Additional Standardized Assumptions

Table A-1

Population Assumptions

Region	1990 Level (10^6)	Projections (Millions)				
		2000	**2025**	**2050**	**2075**	**2100-2200**
USA	250	258	280	272	269	268
EEC	344	356	375	366	362	361
Other OECD	259	271	284	278	276	274
FSU	289	306	337	351	361	367
China	1134	1285	1576	1703	1750	1817
Other Non-OECD	2976	3729	5562	7061	7831	8225
World Total	5252	6205	8414	10031	10,849	11,312

Table A-2

Economic Growth Rate Assumptions

Region	**1990 GDP** Trillions (per capita)	**GDP Growth Rates** (per capita growth rates)						
		1990-2000	2000-2025	2025-2050	2050-2075	2075-2100	2100-2150	2150-2200
USA	5.52 (22,080)	2.50% (2.18)	2.30% (1.97)	1.50% (1.62)	1.10 (1.14)	1.10% (1.12)	.80% (.80)	.60% (.60)
EEC	5.71 (16,599)	2.50% (2.15)	2.30% (2.09)	1.50% (1.60)	1.10% (1.14)	1.10% (1.11)	.80% (.80)	.60% (.60)
Other OECD	4.97 (19,189)	2.70% (2.24)	2.30% (2.11)	1.50% (1.59)	1.10% (1.13)	1.10% (1.13)	.80% (.80)	.60% (.60)
FSU	1.31 (4533)	-1.50% (-2.0)	4.30% (3.90)	3.50% (3.33)	2.00% (1.89)	2.00% (1.93)	1.00% (1.00)	.80% (.80)
China	1.33 (1173)	4.00% (2.71)	3.50% (2.66)	3.25% (2.93)	3.00% (2.89)	3.00% (2.85)	2.00% (2.00)	1.00% (1.00)
Other non-OECD	3.11 (1045)	3.75% (1.44)	4.20% (2.55)	3.40% (2.42)	2.80% (2.38)	2.80% (2.60)	2.00% (2.00)	1.00% (1.00)
World Total	21.95 (4179)	2.63% (.93)	2.84% (1.59)	2.27% (1.55)	1.94% (1.62)	2.11% (1.94)	1.60% (1.60)	.90% (.90)

Table A-3
Resource Base Assumptions
(Exajoules of Economically Recoverable Resources)

Resource	Category	USA	EEC	Other OECD	FSU	China	Other Non-OECD	World
Crude Oil + Nat. Gas Liquids	Reserves	398	166	229	916	230	5423	7362
	Undiscovered resources, 95th[*] percentile	455	166	511	1709	534	3458	6833
	TOTAL	853	332	740	2625	764	8881	14,195
Natural Gas	Reserves	365	198	343	1673	42	2916	5537
	Undiscovered resources, 95th[*] percentile	415	144	1099	4703	460	3984	10,805
	TOTAL	780	342	1442	6376	502	6900	16,342
Coal	Ultimately Recoverable Resources	45,000	5,000	10,000	60,000	60,000	120,000	300,000

Source: Masters, Charles D., Emil D. Attanasi, and David H. Root, "World Petroleum Assessment and Analysis," Proceedings of the 14th World Petroleum Congress Stavanger, Norway, John Wiley and Sons, Ltd. 1994.

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[*] These values are referred to as 5th percentile values in Master's, et. al.. Here we use standard probability theory cumulative distribution convention. Thus, there is a 95% probability that the actual amount of undiscovered resources will turn out to be less than the values shown in the table.

Table A-4

Autonomous Energy Efficiency Improvement Rate Assumptions

Region	AEEI Rates (percent per year rates)						
	1990-2000	2000-2025	2025-2050	2050-2075	2075-2100	2100-2150	2150-2200
USA	.70%	.63%	.52%	.37%	.36%	.26%	.19%
EEC	.70%	.67%	.51%	.37%	.36%	.26%	.19%
Other OECD	.72%	.67%	.51%	.36%	.36%	.26%	.19%
FSU	-.66%	1.25%	1.07%	.60%	.62%	.32%	.26%
China	.87%	.85%	.94%	.92%	.91%	.64%	.32%
Other Non-OECD	.46%	.81%	.77%	.76%	.83%	.64%	.32%

Table A-5
Inputs for Diagnostic Scenarios

	Scenario #13	Scenario #14	Scenario #15
Year	Carbon Emissions (BMt Carbon)	CO_2 Conc. (ppmv)	Temp.Change (°C)
1990	6	355	0
2000	7	374	0.16
2010	8.3	396	0.32
2020	9.8	422	0.48
2030	11.2	452	0.66
2040	12.1	482	0.85
2050	13.2	515	1.05
2060	14.3	549	1.28
2070	15.5	584	1.52
2080	16.8	622	1.77
2090	18.2	665	2.01
2100	19.8	714	2.27
2125	23.8	837	2.92
2150	27.8	959	3.57
2175	31.8	1082	4.22
2200	35.8	1204	4.87

Draft: comments welcomed

APPENDIX B

Hedging Strategies for Global Carbon Dioxide Abatement:

A Summary of Poll Results

EMF 14 Subgroup -- Analysis for Decisions under Uncertainty

Alan S. Manne
Stanford University

February 1996

* This report summarizes a collective effort. William Nordhaus was the principal architect of the guidelines for scenarios. Other active participants included: Minh Ha Duong, James Hammitt, Charles Kolstad, Stephen Peck, Thomas Teisberg, and Gary Yohe. Helpful comments have been received from Richard Richels and John Weyant. The author is much indebted to Fehmi Ashaboglu and Joel Singer for research assistance. Financial support was provided by the Center for Economic Policy Research of Stanford University.

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1. Introduction - hedging strategies

The global warming problem resembles the dilemma faced by a driver on a foggy road. It is desirable to move rapidly toward one's destination, but one's speed must be governed by the distance that one can see ahead, and by the ability to make rapid changes in direction. Reasonable people will differ in their estimates of these factors. A driver does not automatically determine his speed on the basis of worst-case scenarios such as brake failure.

A prudent decision maker allows for the possible costs of rapid mid-course corrections, and hedges his bets against both upside and downside risks. Any of the current projections can be wrong. The extremely pessimistic outcomes are headline-grabbing, but they are not a sure thing. Their probabilities need to be considered in the design of global emissions strategies.

This report compares the application of these ideas within seven of the models participating in Energy Modeling Forum Study 14, Integrated Assessment of Climate Change. The acronyms of these models and the most recent documentation for each is shown in Table 1. They differ in terms of the degree to which they include details concerning regions, energy supply and conservation technologies, the carbon cycle and climate impacts. They all, however, share a common approach: the belief that policy-relevant results can be obtained by comparing the abatement strategies associated with a favorable versus an unfavorable (low probability, high consequence) scenario.

For a general overview of hedging strategies, see Figure 1. This contrasts two alternative ways to think about the greenhouse issue 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 were resolved prior to decision-making. In a "scenario" approach such as this one, 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 "learn-then-act" (LTA) viewpoint. A circle denotes a chance node - a point at which the uncertainties are resolved. A square denotes a decision node - a point at which actions are required.

The bottom panel shows an alternative way to look at things. This viewpoint is characterized by the phrase "act-then-learn" (ATL). For illustrative purposes, 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. The ATL approach is a pragmatic one. It is *not* designed for producing accurate long-range forecasts. Rather, 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.

Table 1. References to the seven participating models

CETA S. Peck and T. Teisberg, "CETA: A Model for Carbon Emissions Trajectory Assessment", *The Energy Journal*, 13:1, 1992.

DIAM T. Chapuis, M. Ha Duong and M. Grubb, "DIAM: a Model for Studying the Dynamics of Inertia and Adaptability in the Climate Change Issue", working paper, November 1995. Modified by A. Manne for analyzing decisions under uncertainty.

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MERGE A. Manne and R. Richels, "The Greenhouse Debate -- Economic Efficiency, Burden Sharing and Hedging Strategies", *The Energy Journal*, 16:4, 1-37, 1995.

SLICE C. Kolstad, "George Bush vs. Al Gore: Irreversibilities in Greenhouse Gas Accumulation and Emission Control Investment", *Energy Policy*, 22: 771-78, 1994.

YOHE G. Yohe, "Exercises in Hedging against Extreme Consequences of Global Change and the Expected Value of Information", working paper, August 1995.

2. Guidelines for scenarios

By focusing on hedging strategies for low probability, high consequence scenarios, this model comparison study has adopted a deliberately parsimonious design. We contrast just two out of many possibilities. One is described as a base (or reference) case; the other is a low probability, highly unfavorable case. At some point, it would be instructive to do a systematic analysis of more than two scenarios.

In designing the two alternatives, we took advantage of preliminary work that had been undertaken by several of the participants in the EMF 14 study. These enabled us to screen out several plausible sources of uncertainty and to focus on those that were likely to have a major impact on near-term decisions. For example, differences in GDP growth rates during the mid- to late 21st century could have major impacts on carbon emissions during that period, but not prior to 2020.

The meaning of the underlying probabilities must be carefully defined. They refer to "judgmental" and "subjective" distributions, and are not derived from empirical observations of relative frequencies. For a readable overview of these issues, see Raiffa (1968).

For reasons of practicality, we had to define uncertainties in a way that could be incorporated in as many of the participating models as possible, and to reduce the computational burden upon them. The uncertainties had to be 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 expert opinion. In this way, we hoped to reduce the arbitrariness of the probability judgments that are central to this type of decision analysis.

After reviewing the earlier work, it appeared that there were only two parameters that appeared to meet all of these criteria: the mean temperature sensitivity factor and the cost of the damages associated with global warming. More precisely, *climate sensitivity* is the equilibrium temperature change that would occur if atmospheric CO2 concentrations were to double from their preindustrial level of around 275 ppmv (parts per million, by volume). ***Warming damages*** are defined as the economic losses that would occur if CO2 doubling in the late 21st century were to produce, say, a 3 degree C. warming from the preindustrial level. These losses include both market damages and the willingness-to-pay for avoiding non-market damages. Inherently, there is a good deal of uncertainty if we are to allow for all the potential surprises and adaptive measures that might be taken in response to this rate of global warming.

The next question to be decided was the numerical values of the two parameters being investigated. The group discussed alternative values and eventually concluded that it would be useful to define the unfavorable cases as the top 5 percent of each of these two distributions. The values of the unfavorable variants are therefore the conditional means of each variable in the top 5 percent of the subjective distribution. For example, if the distribution is uniform over the range [0,1], then the unfavorable top 5 percent would be represented by .975, the mean of the distribution between 0.95 and 1.0.

In choosing the distributions of the two variables, we relied upon two surveys of expert opinion. These are by no means fully satisfactory. They do, however, have the advantage of having been undertaken systematically, and they were subject to peer review prior to publication. For the opinion survey on climate sensitivity, see Morgan and Keith (1995). For warming damages, see Nordhaus (1994).

For further details on the design of this model comparison, see Nordhaus (1995). The following is a summary of these guidelines.

1. To implement the uncertainty scenarios, the models are to employ both a "base" and an "unfavorable" case for the climate sensitivity and for the warming damage parameters.

2. The unfavorable value of the climate sensitivity factor is 2.3 degrees C above the base value employed by the individual model. The unfavorable value of warming damages is 7.8 times its base value.

3. For identification purposes, the following abbreviations are convenient:

U0: base value of both parameters
U1: unfavorable value of both parameters
U2: unfavorable value of climate sensitivity; base value of warming damages
U3: unfavorable value of warming damages; base value of climate sensitivity

4. The probability of the unfavorable outcome is 5 % when either U2 or U3 is being compared with U0. The probability of the unfavorable outcome is 0.25 % when U1 is being compared with U0. That is, the standard assumption is statistical independence of the two parameters. Modelers are encouraged to explore probabilities other than these standard values, and to report the results.

5. For calculating the expected value of perfect information, the modeler should first perform an LTA (learn, then act) analysis in which all uncertainties are resolved during the 1990's. This is to be compared with an ATL (act, then learn) analysis in which the two uncertain parameter values remain unknown through 2020. Recall the hedging strategy concepts illustrated by Figure 1.

After completing the study reported here, we realized that a third uncertain parameter had a major impact on near-term decisions: the rate at which future costs and benefits are to be discounted. Because of its controversial nature, the overall EMF 14 study had not attempted to standardize its value. The only guidance is to be found in a single sentence that appears in the guidelines: "If your model does not calculate a discount rate internally, assume that the near-term marginal product of capital is 5 percent." In our model comparisons, we will see that the discount rate can make a major difference in near-term decisions and in the value of information.

3. Four LTA scenarios - average model results

In order to perform a controlled comparison between the base case and the three unfavorable scenarios, we begin with the LTA (learn, then act) approach. Figure 2 is a conventional sensitivity analysis. It shows how an economically efficient carbon emissions trajectory might be affected by the climate and damage parameters, and it reports the average carbon emissions projected by the seven participating models.

Under U0 (the base case), emissions rise steadily throughout the 21st century. According to the other cases, climate sensitivity has a smaller impact than the warming damage parameter. Even under U2 (high climate sensitivity), emissions rise during the next 50 years. It is only when we incorporate a high value for the warming damage parameter (cases U1 and U3) that it becomes desirable to stabilize or reduce global emissions during the next few decades. As might be expected, the greatest difference in emissions occurs when we compare the base scenario U0 with the low probability, high consequence unfavorable scenario U1. For this reason, we will concentrate on these two alternatives when we turn to the ATL (act, then learn) view of the world.

Figures 3-5 show the average model projections of concentrations, temperature change and the value of emission rights. Except for carbon emissions, not all of these values were reported by all seven models. For details on the coverage and for the actual values reported by each model, see the attached spreadsheet tables.

Carbon inflows are a small fraction of atmospheric stocks, and there is a long time lag before concentrations are translated into equilibrium temperature changes. This is why changes in emissions (Figure 2) make their way only slowly into changes in concentrations (Figure 3) and even more slowly into temperature changes (Figure 4).

The value of carbon emission rights (alternately termed "carbon taxes") are indicators that could be useful for the decentralized implementation of globally efficient abatement scenarios. These values suggest how the payoffs might vary from different research and development strategies. According to Figure 5, they represent the most volatile series reported by the participants in this study. Each model has a somewhat different approach for determining the optimal mix between the costs and the benefits of abatement. The inter-scenario differences are so great that the only satisfactory way to compare cases is through a semi-log scale.

For the year 2000, the typical model indicates that the carbon price might be only $10 per ton in U0 (the base case), but could be worth ten times that amount in U1 (the low probability, high damage case). In all scenarios, there is a rising value over time -- somewhat along the lines suggested by the Hotelling rule for the price of exhaustible resources. When one adopts a long-term benefit-cost perspective, the abatement problem becomes one of determining the optimal cumulative volume of emissions, not the quantity in any one year. The year-by-year carbon prices are then linked by what one assumes with respect to the rate of return on capital in alternative forms of investment.

4. ATL scenarios - U0 vs. U1 comparisons

Figures 6-10 report on ATL scenarios in which U0 and U1 are the only alternatives considered, and the uncertainties are resolved just after 2020. According to the guidelines, the probability is only 0.25% for the unfavorable outcome.

Figure 6 provides an average of the carbon emission results reported by all seven models. It compares two possible futures: the base case U0 and the unfavorable outcome U1. The dashed lines show what happens when we are endowed with perfect foresight and can make today's decisions in full knowledge of which of these outcomes will occur. The upper dashed line shows the path corresponding to the base case. The lower dashed line shows the path when we are told today that the unfavorable scenario will definitely occur. That is, both climate sensitivity and warming damages are high. These perfect foresight projections are repeated directly from the LTA scenarios shown in Figure 2. The lower of the two dashed lines is the scenario to be followed if we were to ignore the numerical value of the probabilities and governed our near-term decisions solely by worst-case considerations.

The solid lines indicate the average results for an economically efficient hedging strategy. Note that there is a fork at 2020, the date of resolution of uncertainties. The best hedging strategy consists of adopting an emissions path that lies somewhere between the two cases shown along the dashed lines. Somewhat surprisingly, this optimal hedging strategy lies quite close to the LTA reference (U0) scenario throughout the 21st century. Taking account of both the costs and benefits of abatement, it is desirable to wait until 2020, and at that point begin to reduce emissions rapidly - but only in the unlikely event of the unfavorable scenario. The world would then have to change course abruptly, and move to rapid decarbonization.

There is a range of ATL estimates obtained from the individual models. Figures 7 and 8 report on carbon emissions for the U0 and U1 scenarios, respectively. During the decades through 2020, *none* of the models indicate that it is economically efficient to aim for global emissions stabilization. The increases are modest in the case of DIAM, but substantial in the case of DICE. These two models are distinguished by dashed lines.

Beyond 2020, there is no simple way to characterize the differences between models. Under the favorable U0 scenario (Figure 7), all but one of them (MERGE) indicate that emissions will continue to rise after 2020.

Figure 8 shows how the models react to the unfavorable U1 scenario. The only valid generalization is that in 2020 (upon the resolution of uncertainties), there is an abrupt change in the trend of carbon emissions. DICE, SLICE and YOHE report that it is optimal to stabilize emissions from the middle of the century onward, but the other four models show a decline to virtually zero by the end of the century. Opinions will differ on whether these are reasonable estimates of decarbonization rates. The answer will depend upon what one assumes with respect to the system's inertia and the costs of abrupt changes in direction. In terms of the foggy road analogy, these models provide alternative estimates of how rapidly a driver might attempt to apply the brakes under unfavorable circumstances.

Figures 9 and 10 report the value of carbon emission rights under the two scenarios. For the year 2000, most of the models indicate a modest but positive carbon tax ($5 - $10 per ton). There is a general tendency for these values to increase over time. By definition, the value of carbon emission rights is identical for scenarios U0 and U1 between 2000 and 2020. Immediately thereafter, there is a bifurcation - a decline in the favorable scenario U0 and a sharp jump in the unfavorable scenario U1. (See Figure 10.) Carbon values then exceed $100 per ton, and in some cases exceed $1000. CETA is the only model in which carbon values are limited by a backstop assumption ($465 per ton).

5. The value of information

Individual observers will assign very different subjective probabilities to scenarios such as U0 and U1. For this reason, it is useful to compare results at a single point in time, but with differing values of these probabilities. For concreteness, Figure 11 compares the ATL and LTA projections of carbon emissions in 2020 - just before the date at which the climate and impact uncertainties are resolved.

The horizontal axis indicates the relative likelihood of U0 and U1. Let p(U0) denote the probability of the base scenario. When this is close to 100%, the ATL results virtually coincide with those for U0-LTA. Conversely, when p(U0) is close to zero, the ATL results coincide with those for U1-LTA. If one took a very different position than the guidelines adopted by the EMF 14 Uncertainty Subgroup, one might assign equal probabilities to the U0 and U1 scenarios, and p(U0) would then be 50%.

With a high value of p(U0), all but one of the models indicate that the optimal level of global emissions is in the range of 8-9 billion tons. This would represent a 30-50% increase over the 1990 level of about 6 billion tons of carbon. DICE is the exception. It projects still higher emissions - nearly 11 billion tons in 2020. To date, we have not identified the reasons for the inter-model differences. It is possible that DICE employs more optimistic assumptions on economic growth or less optimistic assumptions on autonomous energy conservation than the others.

With a low value of p(U0), all but one of the models (SLICE) indicate that it would be optimal to reduce 2020 emissions below the 1990 level of 6 billion tons. When p(U0) is changed from a high to a low value, the largest *percentage* difference in the optimal policy occurs in the case of DIAM. This model employs a 3% annual discount rate, whereas most of the others employ a real rate of about 5% for the first few decades of the 21st century.

DIAM employs not only a low discount rate, but also a low long-term cost of emissions abatement. One of its distinctive features is that it attributes much of the cost of abatement to inertia in the economic system, rather than to intrinsic long-term costs of low-carbon scenarios. Accordingly, it should come as no surprise that DIAM's optimal solution for 2020 is to lower carbon emissions drastically below 1990 levels - provided that we are reasonably sure of being in a high climate sensitivity and high damage scenario. DIAM is the model for which the 2020 level of emissions is the most dependent on the assumptions about the relative likelihood of the two alternative scenarios.

Accordingly, it is useful to take a close look at the expected value of information within DIAM. (See Figure 12.) The horizontal axis again refers to p(U0), the probability of the base scenario. The vertical axis indicates DIAM's maximand - the expected value of macroeconomic consumption discounted throughout the planning horizon to 1990 at 3% per year. It ranges from about $1625 to $1675 trillions. The difference of $50 trillions is 3% of the total.

With an LTA characterization of the problem, the expected value of the maximand is obtained by *linear interpolation* between the U1 and U0 outcomes. E.g., with p(U0) = 50%, the expected value of the DIAM maximand would be $1650 trillions. With the ATL characterization, we cannot attain this high a value of the maximand. If scenario U0 occurs and there has been a low level of emissions prior to 2020, we will have made one type of error - too much abatement. If scenario U1 occurs and there has been a high level of emissions prior to 2020, we will have made a different type of error - too little abatement.

In an ATL world, we cannot avoid making one or the other type of error. This is why the ATL curve (solid line) lies uniformly below the LTA dashed line. The vertical difference is termed the "expected value of perfect information" - for short the EVPI. E.g., with p(U0) = 50%, the vertical distance is about $5 trillions. This is the amount that informed decision makers would be willing to pay for an immediate determination of whether they were in a U0 or a U1 world. A perfect forecast would enable them to avoid both types of errors during the decades prior to 2020. The EVPI has an analogy within the game of bridge. There this principle is known as "one peek is worth two finesses". That is, additional information can often help, and it never hurts.

According to Figure 12, the EVPI is virtually zero when p(U0) is either very low or very high. It is at its maximum when the uncertainty is greatest - a 50% probability of each scenario. Accordingly, it should come as no surprise that all of our models report the EVPI at under $100 billion dollars when employing the study group's guideline probabilities. That is, p(U1) = 0.25%. (See Table 2.) Even when undertaking a sensitivity analysis and assuming that p(U1) = 5%, all of the models reported an EVPI of less than a trillion dollars. In the case of MERGE, the EVPI was too small to be detected by the optimization algorithm, and accordingly this value was reported as zero.

Several additional observations on the EVPI results reported in Tables 2 and 3:

(1) The lower the discount rate, the higher become the expected benefits of taking immediate steps to reduce emissions. This is why the one model that employs a 3% discount rate (DIAM) tends to show a higher EVPI than those models that employ discount rates of 5%. When MERGE is modified to allow for a 3% discount rate, the EVPI becomes comparable with that of DIAM.

2) CETA, DIAM, HCRA and SLICE reported EVPI results for a 2050 as well as a 2020 date of resolution of the uncertainties. The later the date of resolution, the greater become the cumulative errors of either too much or too little abatement. This is why the EVPI grows with the length of time prior to the resolution of uncertainty.

(3) When comparing U0 with the U2 scenario, there is not a great potential for costly errors in the choice of abatement strategies. (Recall the similarity between the U0 and U2 carbon emission paths prior to 2020 in Figure 2.) This is why both CETA and SLICE show low EVPI values for this pair of scenarios in Table 3. There is a somewhat higher potential for costly errors when comparing the U0 and U3 emission paths. Accordingly, CETA and SLICE both show higher EVPI values for the U0-U3 scenario comparison. (Again see Table 3.)

(4) In a separate report, Chang (1995) has shown that when MERGE is modified to allow simultaneously for all four possibilities (U0, U1, U2 and U3) instead of just two contrasting scenarios, there can be a considerable increase in the EVPI.

Table 2. Expected value of perfect information (discounted $ billions).

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

Table 3. Additional EVPI results (unit: billion dollars)

Resolution date	2020	2050
SLICE (5% discount rate):		
U0 (95%) vs. U2 (5%)	1	2
U0 (95%) vs. U3 (5%)	38	101
CETA (4% discount rate):		
U0 (95%) vs. U2 (5%)	12	27
U0 (95%) vs. U3 (5%)	136	267

6. Concluding comments

This paper has emphasized the concept of hedging strategies for dealing with uncertainty. It is misleading to interpret such strategies as an argument for a do-nothing policy. Delay should not be confused with inaction. There is widespread agreement that we need to maintain a broad portfolio of options for dealing with global climate change. According to most of the participating models, it would be desirable to institute a modest carbon tax in the near future ($5 - $10 per ton in the year 2000), and to have that tax increase over time.

During the next few decades, we will learn how far we can get with "no regrets" energy conservation policies. It is important to continue intensive science research to reduce climate and impact uncertainties. Our energy research and development efforts must be directed toward cost-effective conservation and to low-carbon supply technologies. Immediate reduction of emissions is only one among several competing possibilities. The issue is not one of either-or, but of finding the right mix of policies.

Additional references

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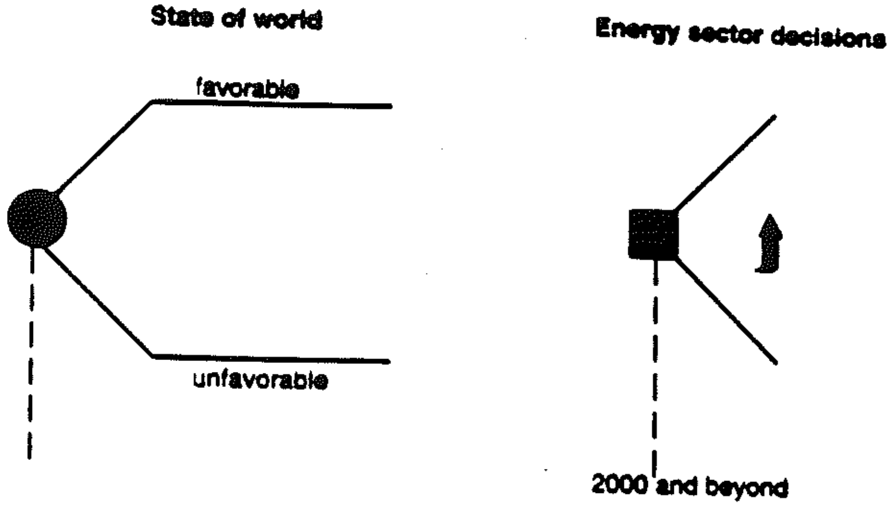
W. Nordhaus, "Notes on Scenarios for Uncertainty Group", working paper, Yale University, June 1995.

H. Raiffa, *Decision Analysis: Introductory Lectures on Choices under Uncertainty*, Random House, New York, 1968.

Figure 1.

Alternative Characterizations of Decision Problem
Learn-Then-Act (LTA)



Alternative Characterizations of Decision Problem
Act-Then-Learn (ATL)

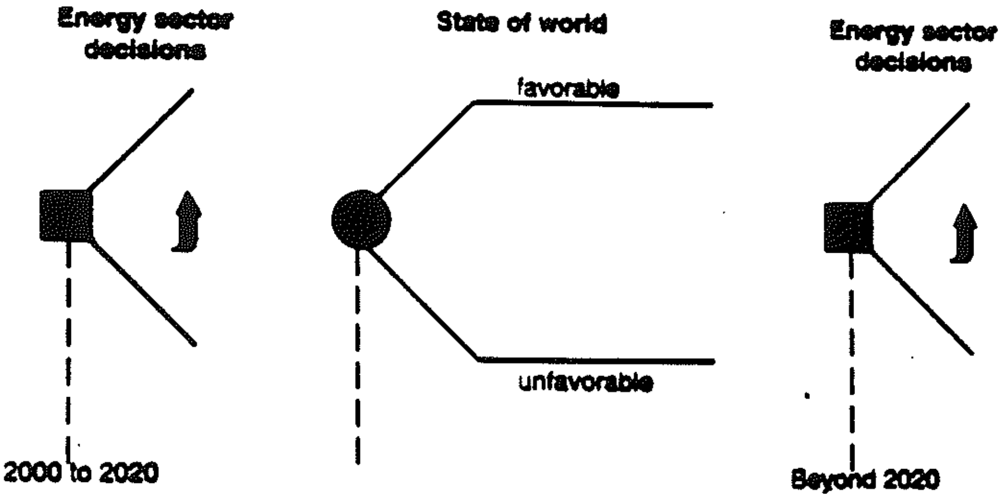


Figure 2. Carbon Emissions
(average of all models, LTA)

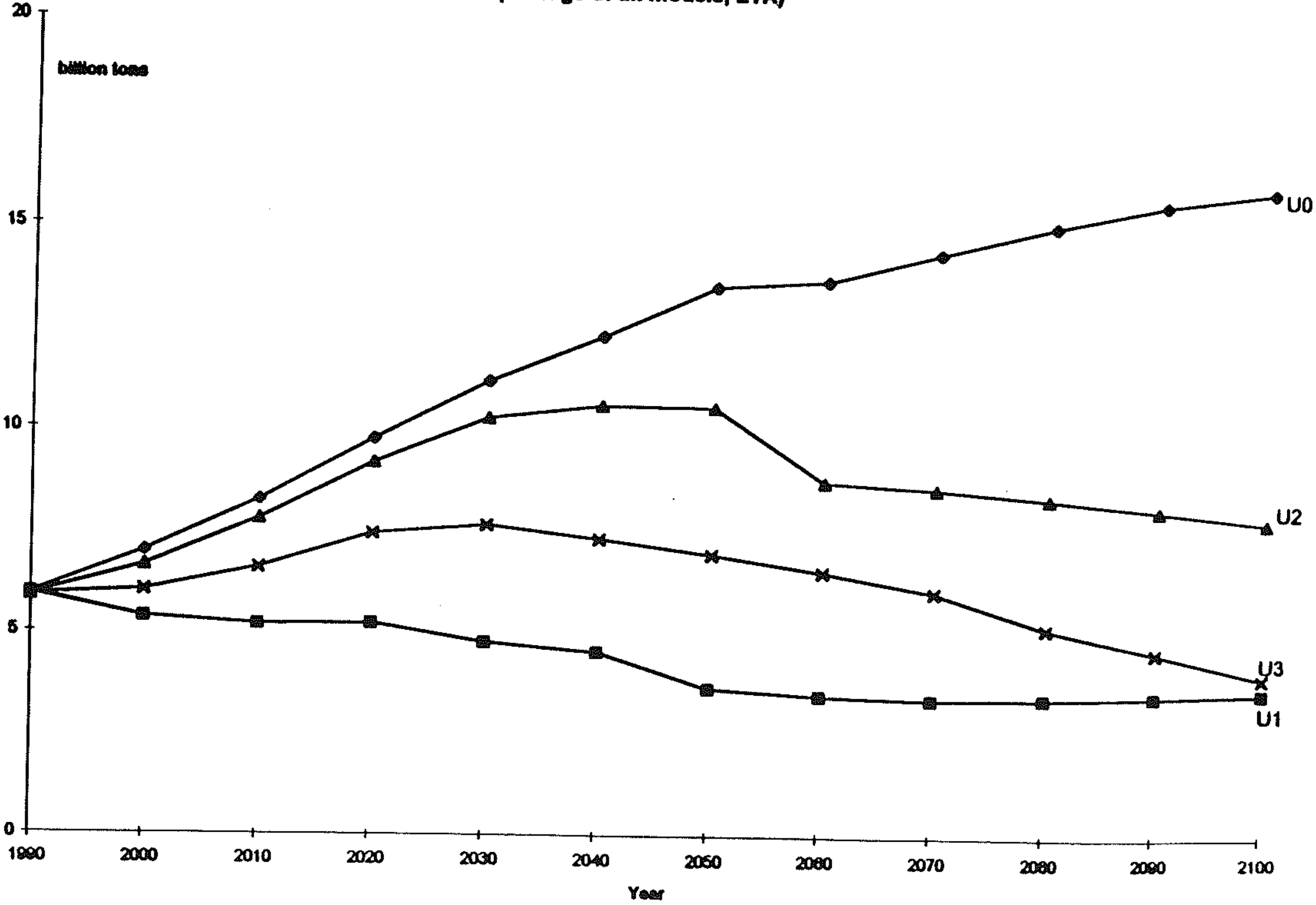


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Figure 3. Carbon Concentrations
(average of all models, LTA)

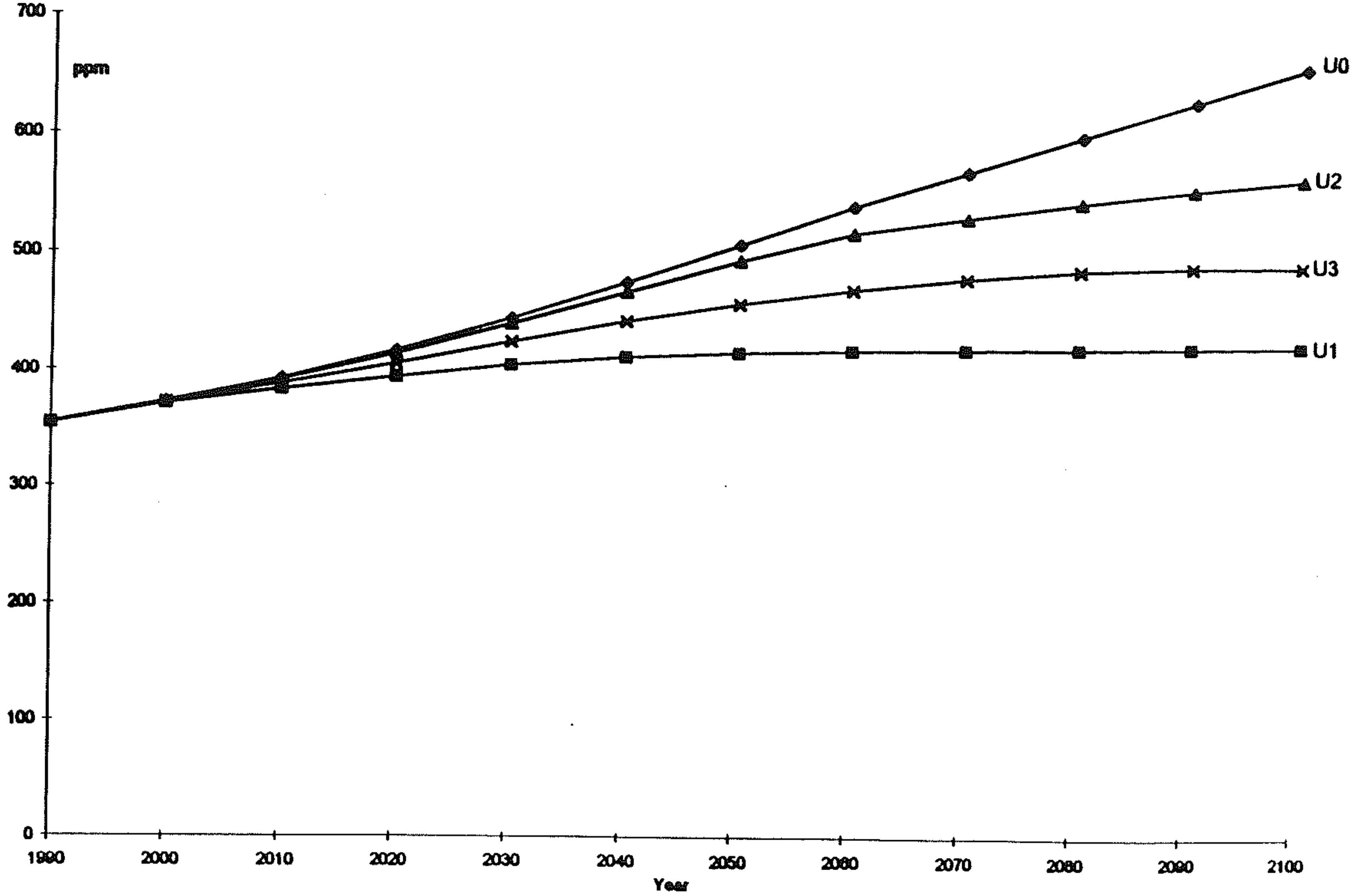

Figure 4. Temperature Change
(average of all models, LTA)

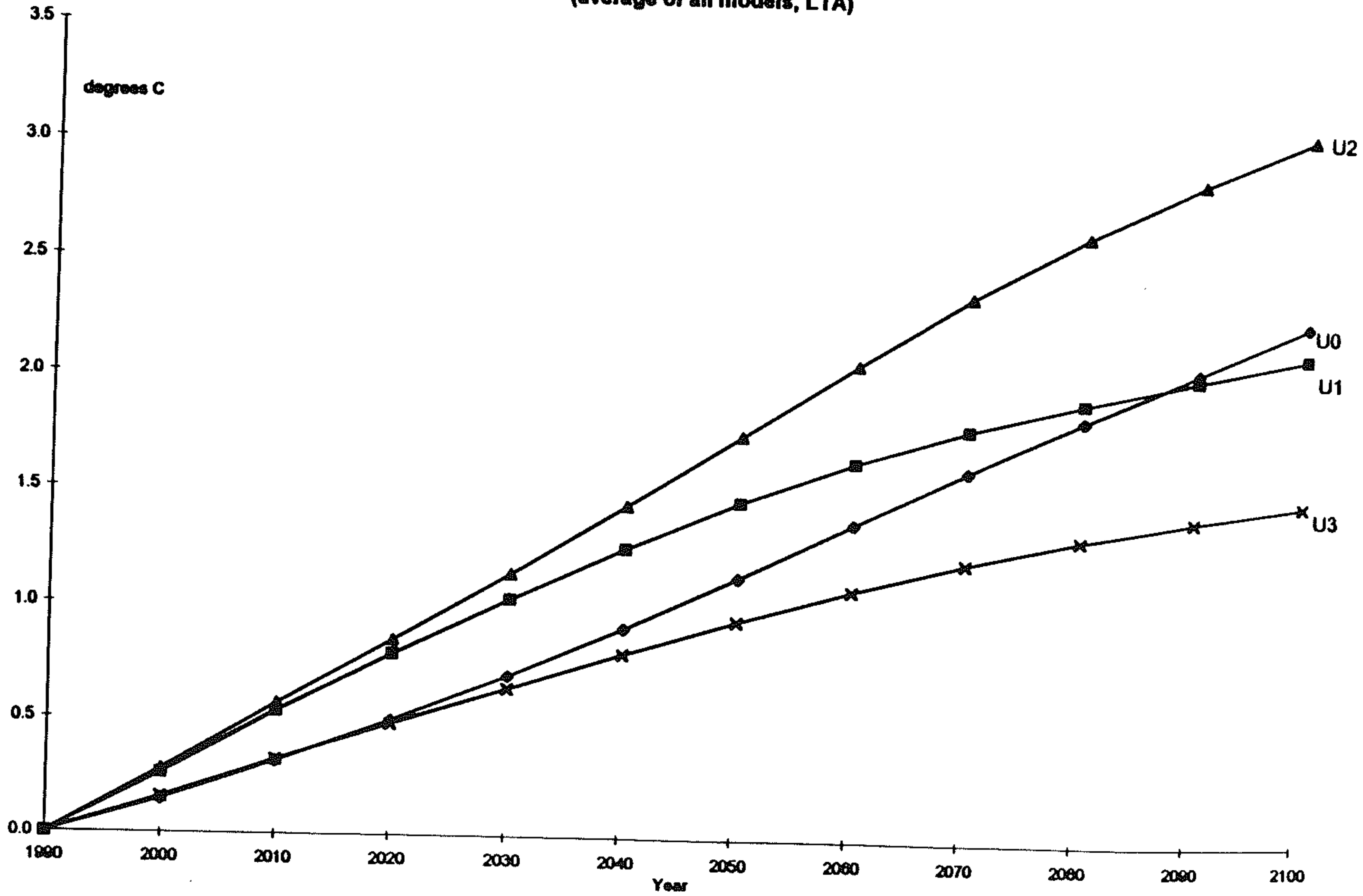

Figure 5. Value of Carbon Emission Rights
(average of all models, LTA)

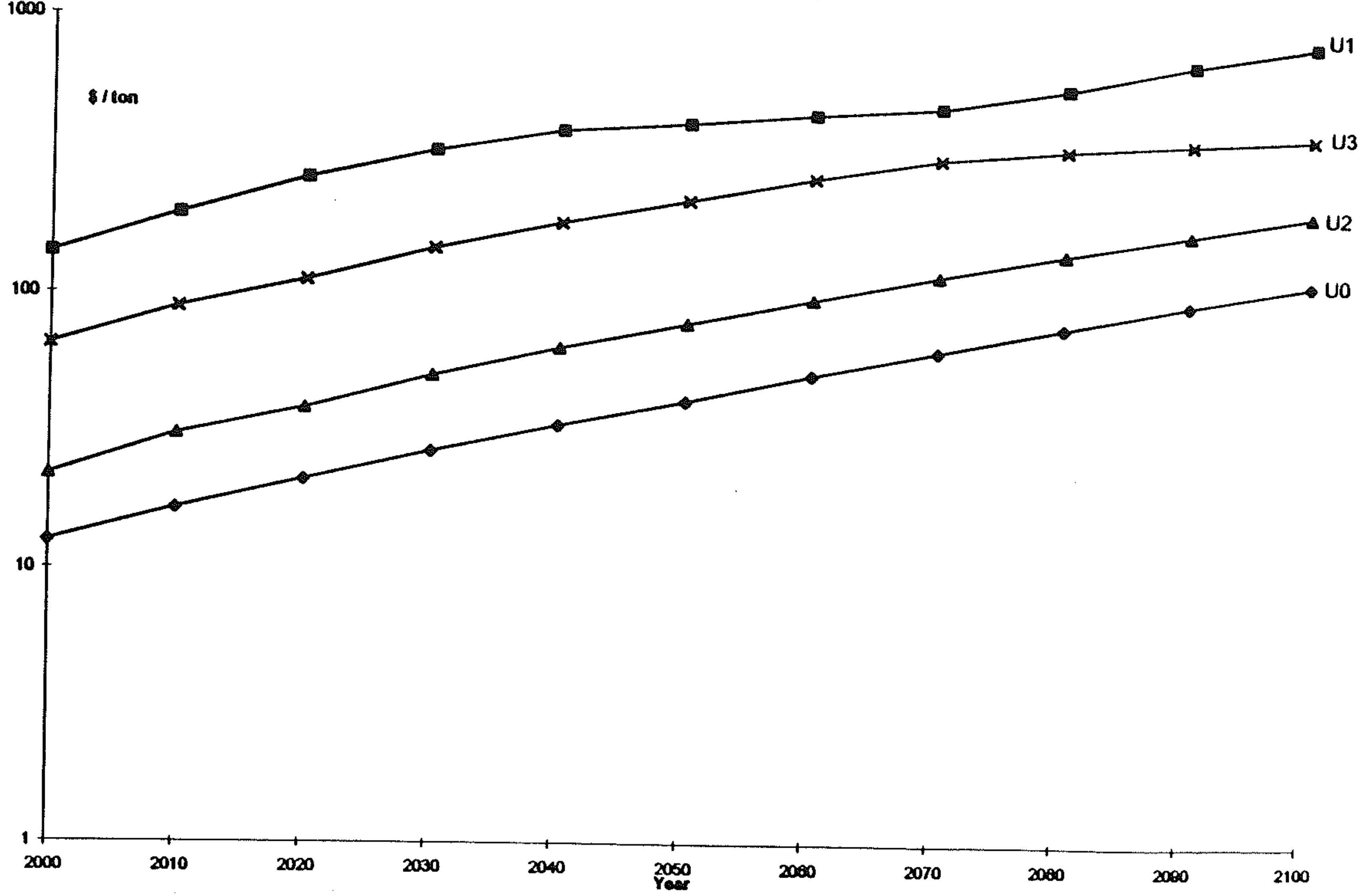

Figure 6. Carbon Emissions
(average of all models)

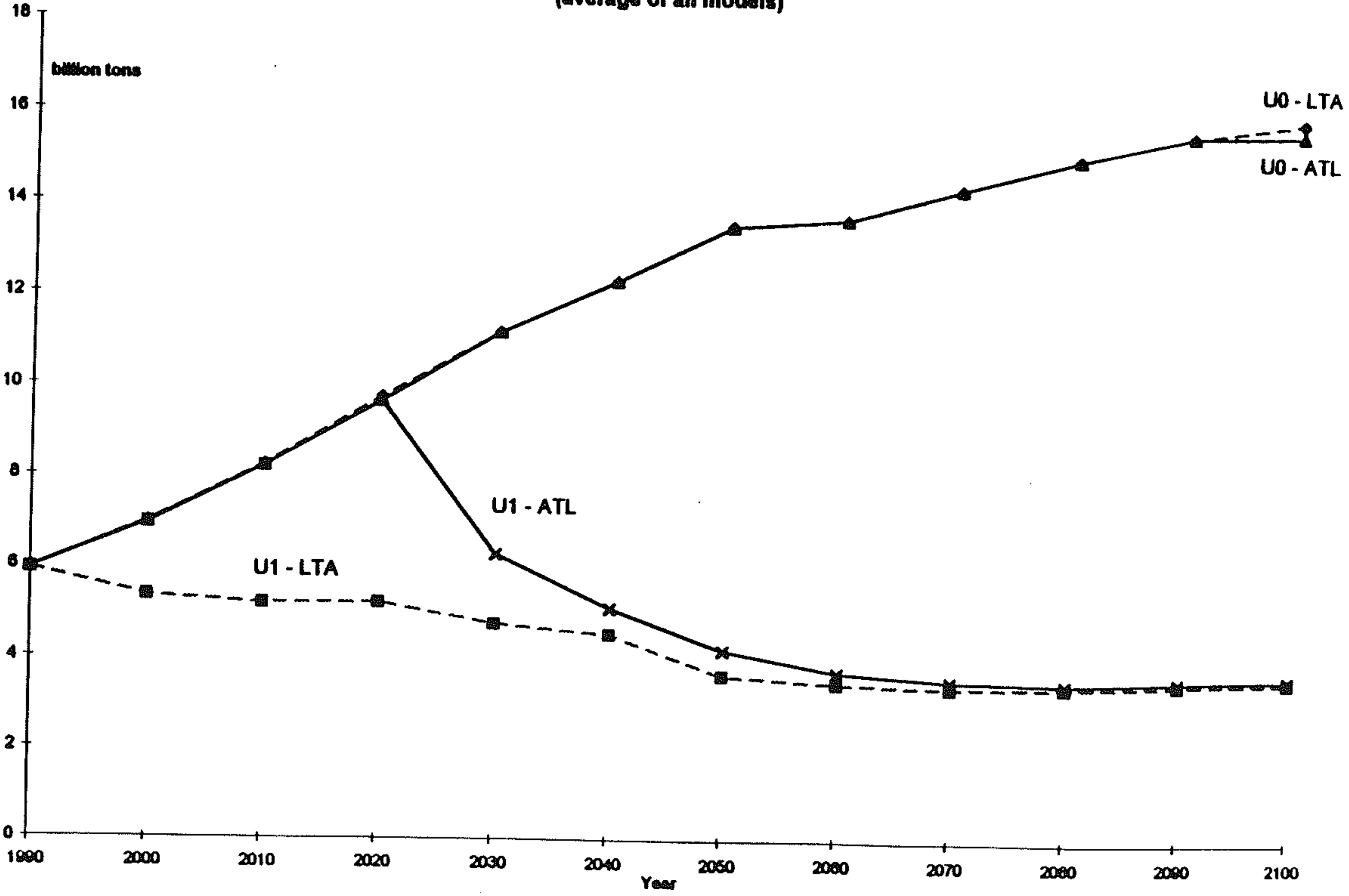

Figure 7. Carbon Emissions
(all models, U0-ATL)

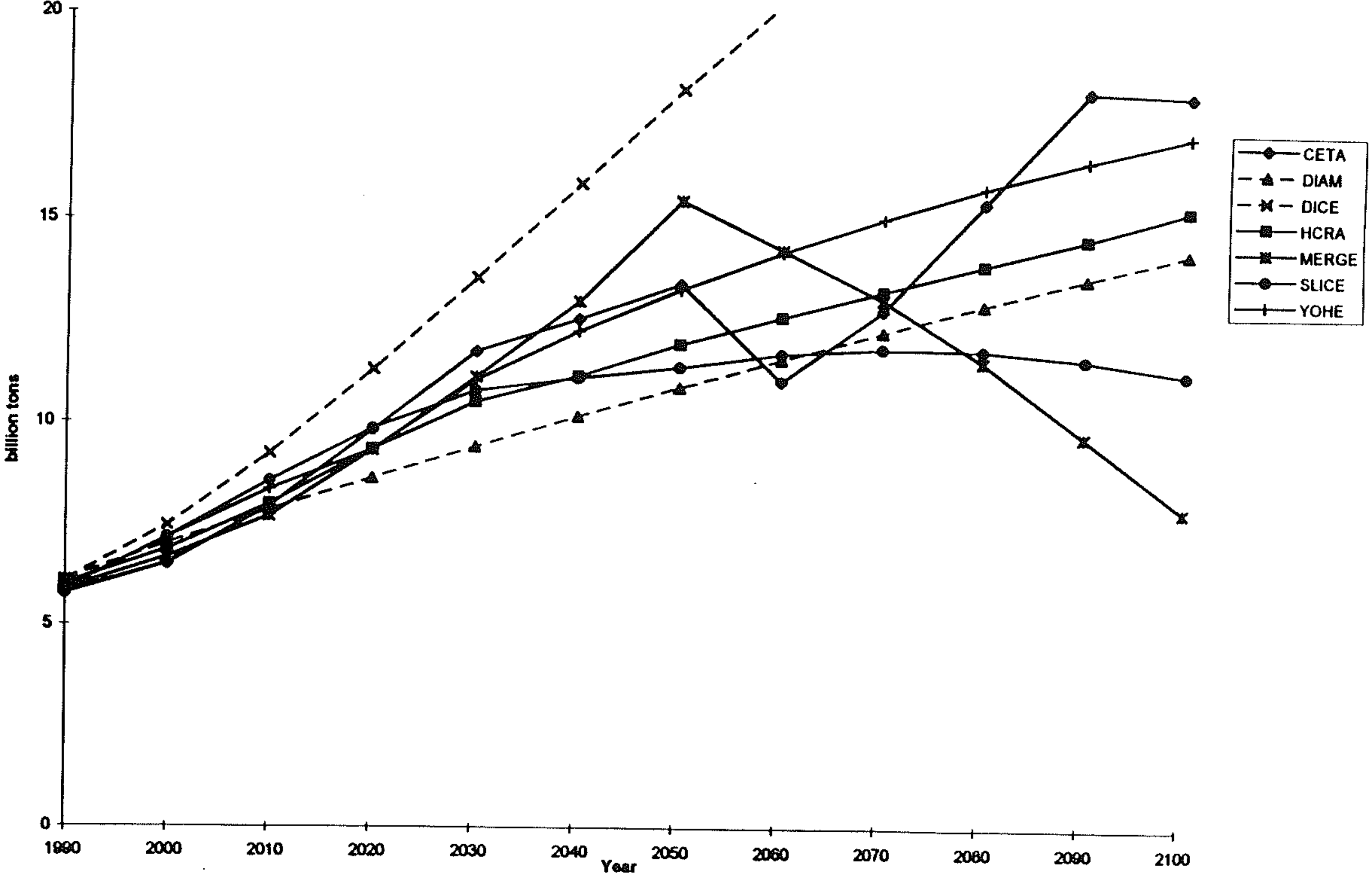

Figure 8. Carbon Emissions
(all models, U1-ATL)

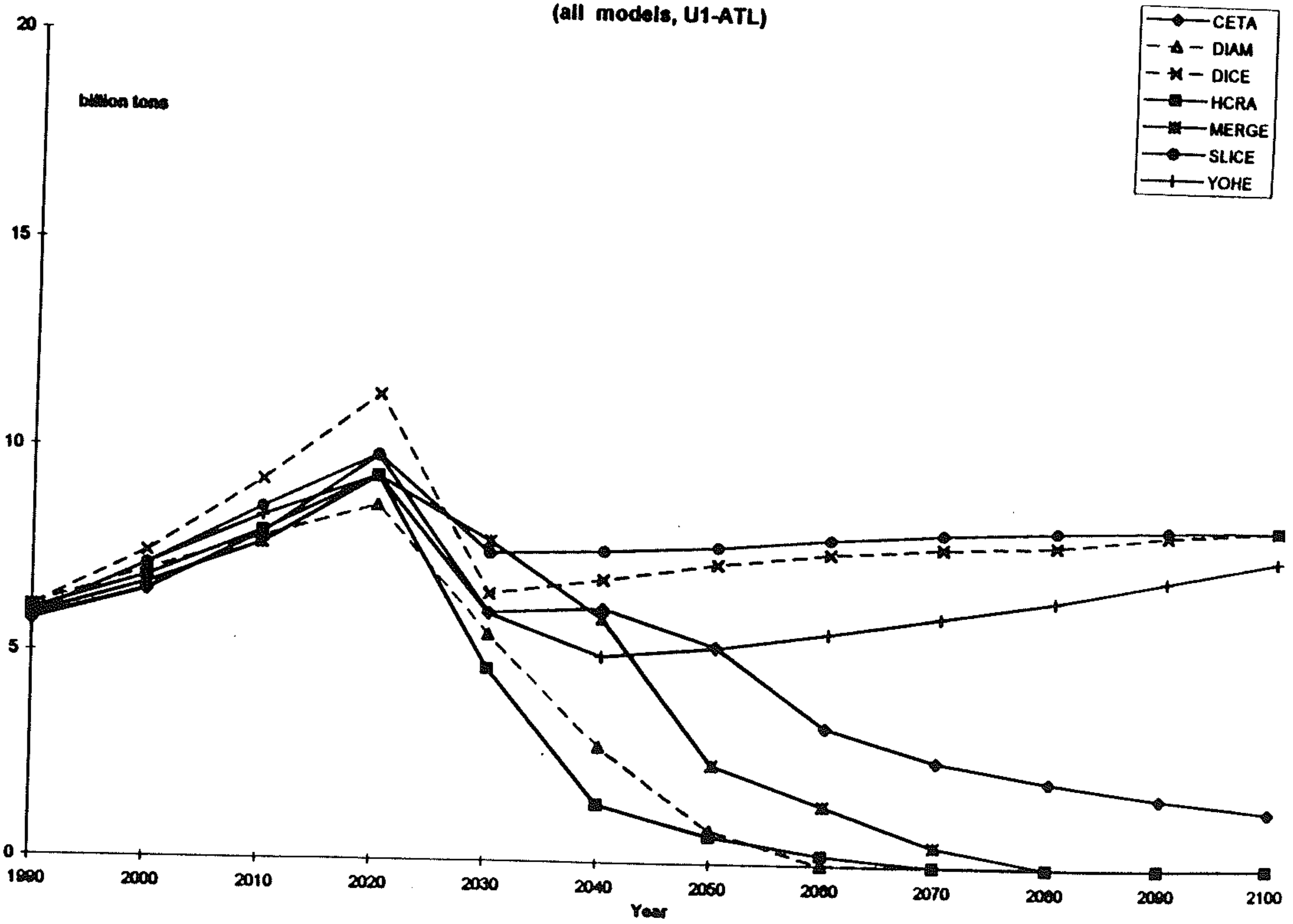

Figure 9. Value of Carbon Emission Rights
(all models, U0-ATL)

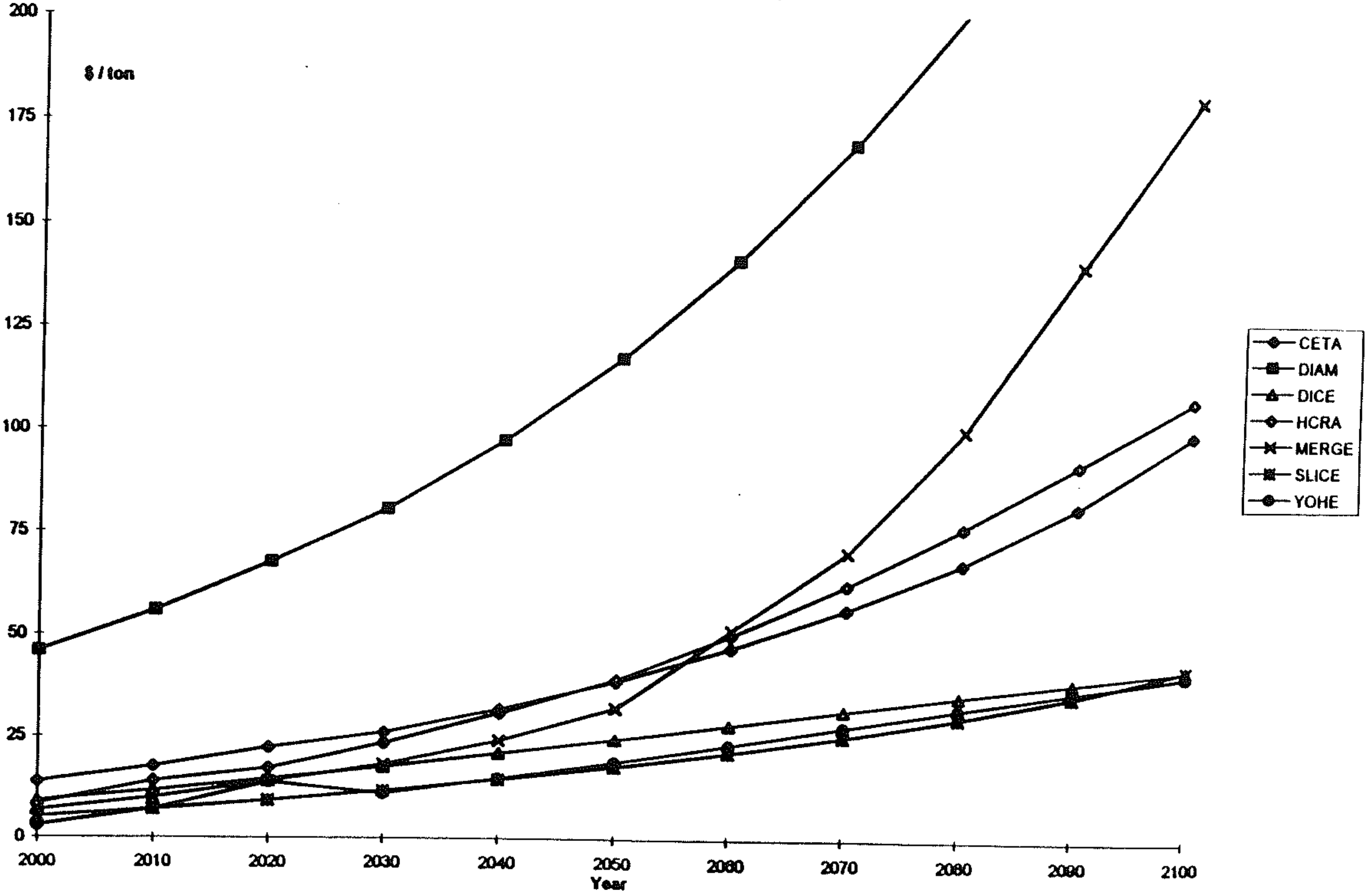

**Figure 10. Value of Carbon Emission Rights
(all models, U1-ATL)**

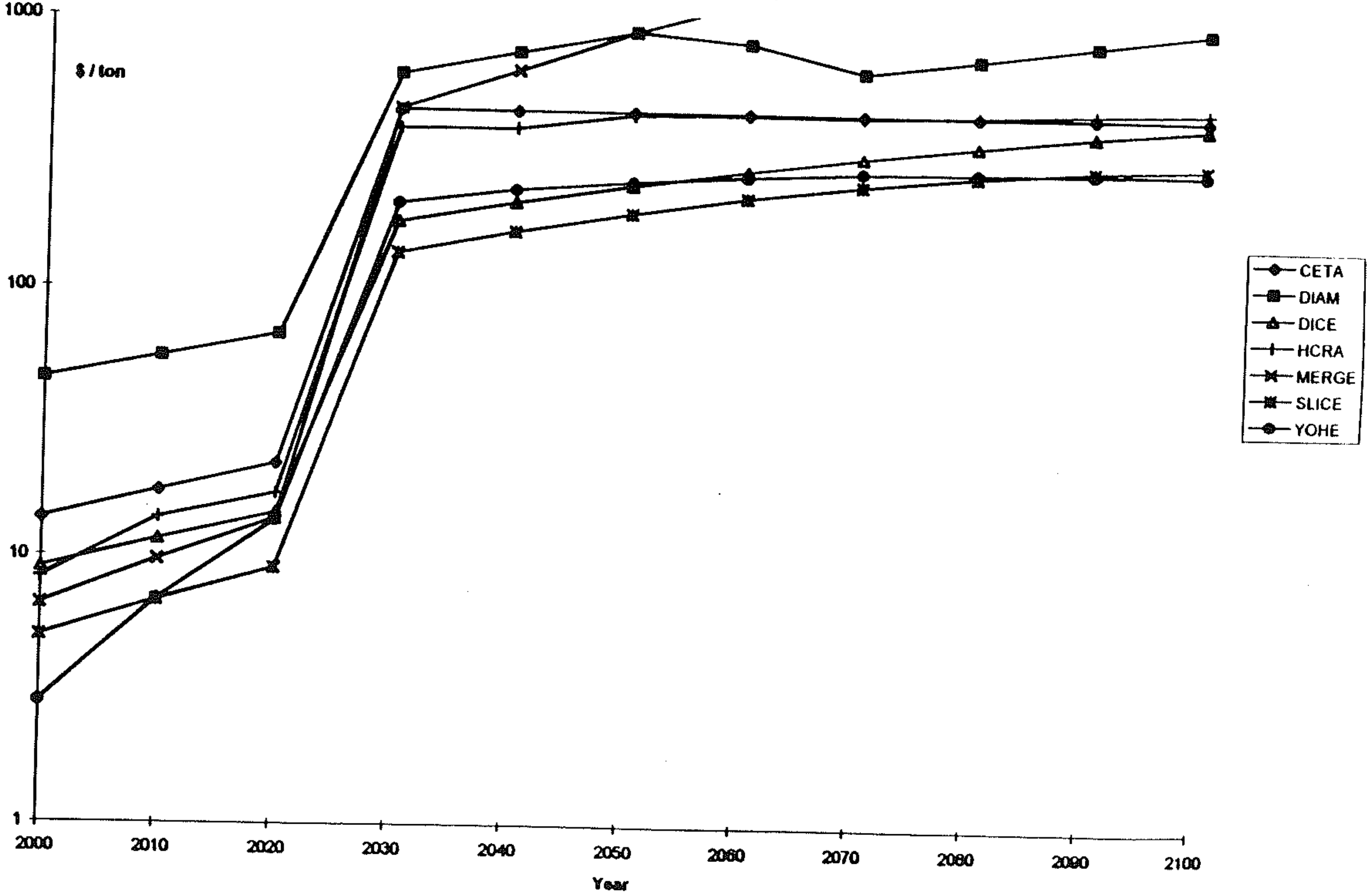

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Figure 11. Carbon Emissions in 2020

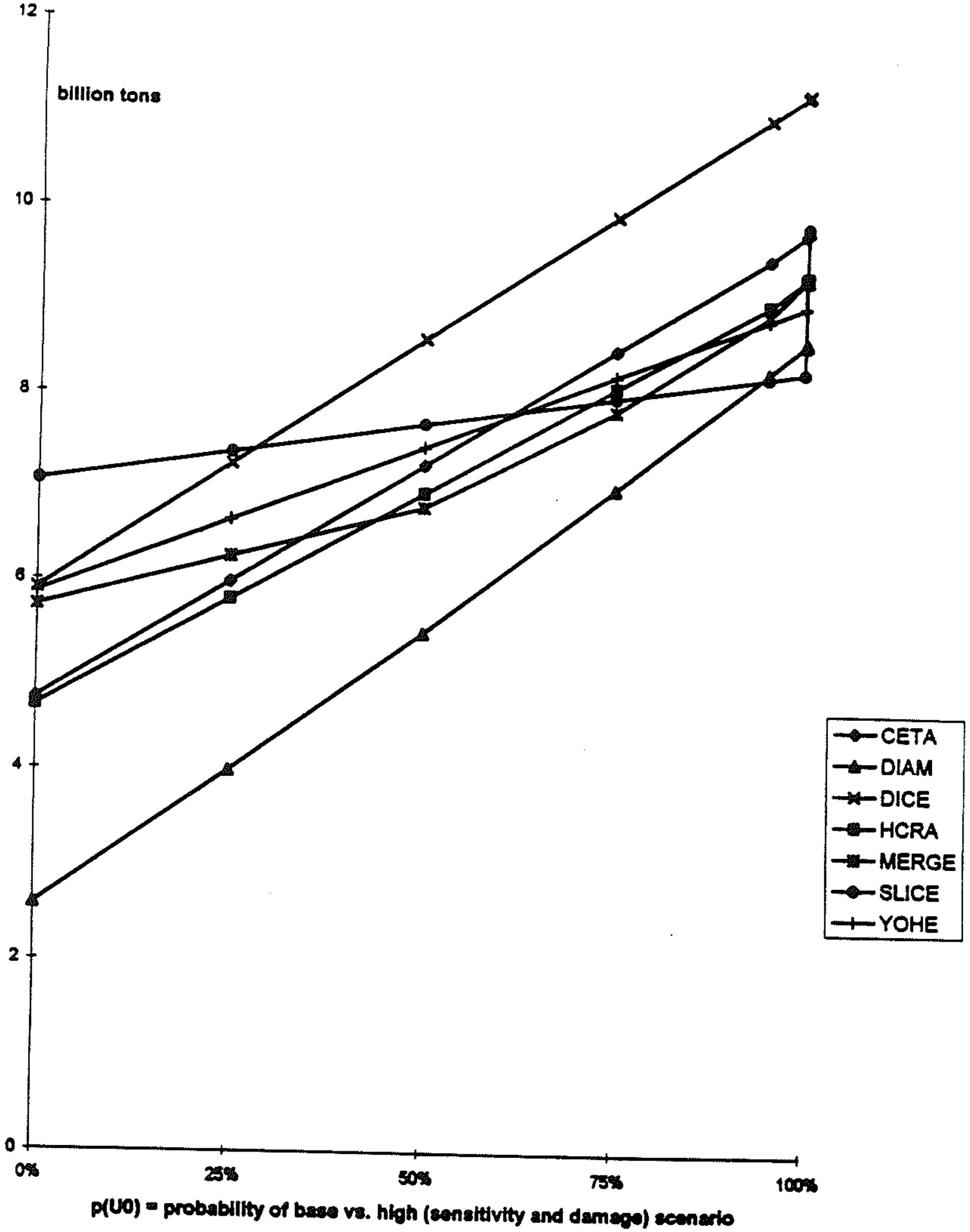
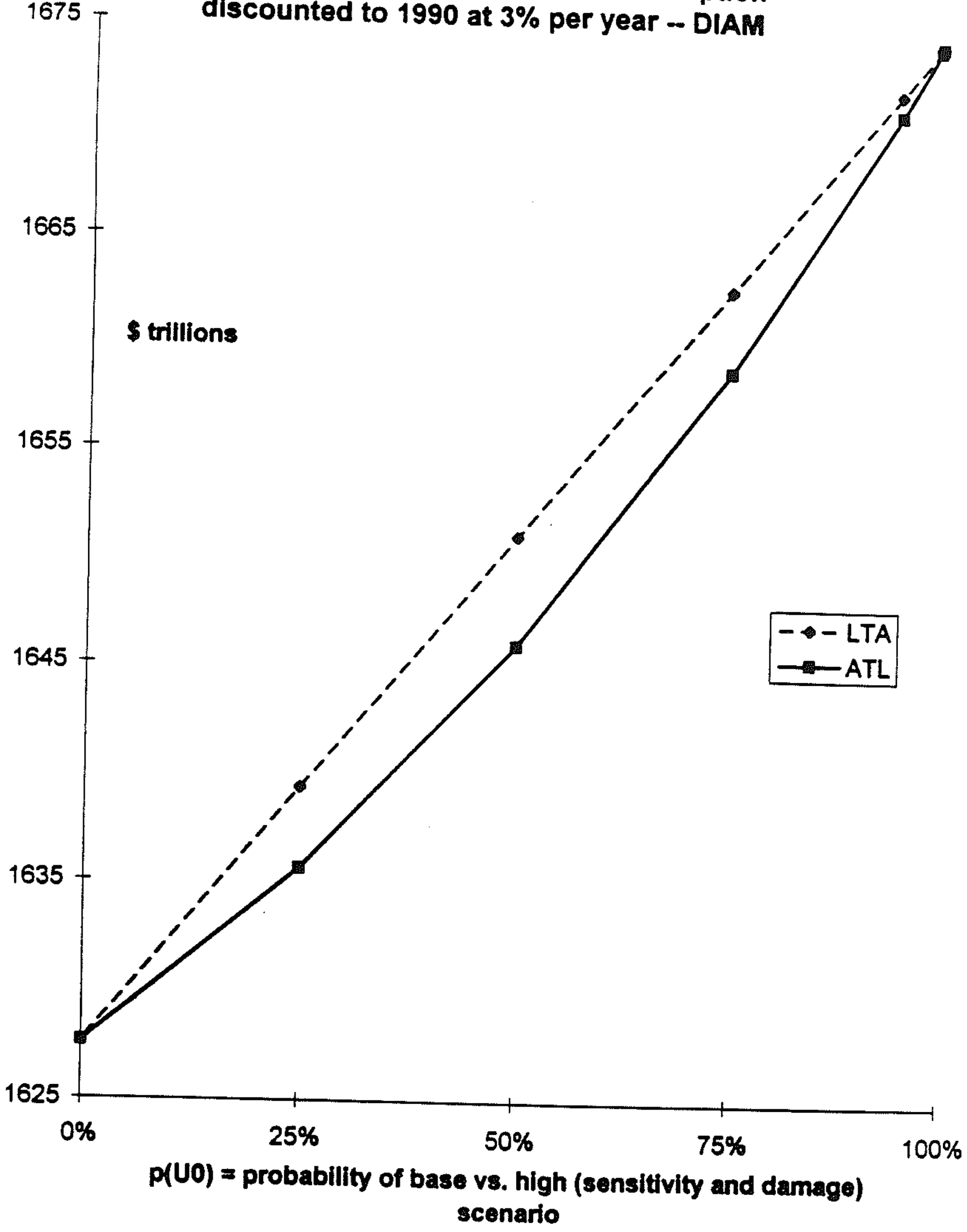


Figure 12. Expected value of consumption discounted to 1990 at 3% per year -- DIAM



EMF-14: Analysis for Decisions Under Uncertainty -- Data tables

Organized by model, variable, then LTA U0..U3, ATL U0,U1

CETA:

CO2 Emissions

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	5.760	6.510	7.930	9.850	11.770	12.570	13.450	11.060	12.810	15.470	18.200	18.150
LTA U1	5.760	3.840	4.420	4.740	3.570	2.470	2.020	1.650	1.350	1.100	0.900	0.740
LTA U2	5.760	6.250	7.540	9.260	10.880	11.240	10.440	4.550	3.900	3.380	2.940	2.590
LTA U3	5.760	5.520	6.220	7.030	6.980	6.170	5.230	4.460	3.830	2.300	1.880	1.530
ATL U0	5.760	6.500	7.920	9.830	11.770	12.570	13.440	11.060	12.810	15.460	18.190	18.090
ATL U1	5.760	6.500	7.920	9.830	6.050	6.190	5.300	3.350	2.560	2.090	1.710	1.390
ATL U2	5.760	6.490	7.910	9.820	10.860	11.310	10.860	6.010	5.100	4.350	3.740	3.240
ATL U3	5.760	6.450	7.840	9.690	7.940	7.390	5.250	4.130	3.560	2.080	1.700	1.380
ATL U0-50	5.760	6.490	7.910	9.820	11.710	12.470	13.180	11.030	12.800	15.460	18.180	18.010
ATL U1-50	5.760	6.490	7.910	9.820	11.710	12.470	13.180	4.760	3.890	3.180	2.600	2.120
ATL U2-50	5.760	6.490	7.910	9.820	11.710	12.480	13.230	8.050	6.760	5.710	4.850	4.150
ATL U3-50	5.760	6.450	7.850	9.720	11.570	12.260	12.780	5.700	4.840	4.140	2.550	2.090

Carbon Concentrations

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	359.390	378.500	397.620	421.930	452.240	487.930	523.350	559.640	581.590	612.050	652.460	701.510
LTA U1	359.390	378.500	385.120	395.670	406.700	411.470	411.780	411.180	409.800	407.870	405.600	403.140
LTA U2	359.390	378.500	396.420	419.150	447.200	479.570	510.090	534.320	529.870	527.290	524.420	521.310
LTA U3	359.390	378.500	393.000	410.290	429.490	446.640	458.880	466.650	471.380	473.980	470.300	466.620

Temperature Change

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	0.000	0.170	0.410	0.630	0.850	1.080	1.330	1.600	1.870	2.130	2.380	2.640
LTA U1	0.000	0.320	0.710	1.040	1.350	1.630	1.880	2.090	2.260	2.400	2.510	2.600
LTA U2	0.000	0.320	0.710	1.080	1.460	1.860	2.280	2.720	3.140	3.480	3.750	3.970
LTA U3	0.000	0.170	0.410	0.620	0.820	1.020	1.210	1.390	1.580	1.710	1.830	1.940

	Value of Carbon Emission Rights											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	10.100	12.980	16.560	20.940	26.150	32.000	38.870	47.200	56.690	67.940	82.000	100.030
LTA U1	219.360	281.790	358.050	447.340	465.000	465.000	465.000	465.000	465.000	465.000	465.000	465.000
LTA U2	27.270	35.520	45.800	58.470	73.610	90.930	111.320	136.290	165.810	201.170	245.140	465.000
LTA U3	80.530	103.410	131.860	166.890	208.690	257.260	311.330	378.460	456.330	465.000	465.000	299.930
ATL U0	10.710	13.790	17.610	22.290	26.150	32.000	38.860	47.200	56.700	67.950	82.020	465.000
ATL U1	10.710	13.790	17.610	22.290	465.000	465.000	465.000	465.000	465.000	465.000	465.000	100.050
												465.000
DIAM:												
	CO2 Emissions											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	6.097	6.994	7.844	8.655	9.433	10.181	10.903	11.602	12.281	12.946	13.600	14.244
LTA U1	6.097	5.297	4.084	2.589	1.119	0.100	0.000	0.000	0.000	0.000	0.000	0.000
ATL U0	6.097	6.990	7.834	8.639	9.420	10.171	10.895	11.596	12.277	12.942	13.597	14.242
ATL U1	6.097	6.990	7.834	8.639	5.517	2.810	0.815	0.000	0.000	0.000	0.000	0.000
	Carbon Concentrations											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	354.000	372.933	393.665	415.889	439.349	463.825	489.128	515.099	541.604	568.535	595.809	623.361
LTA U1	354.000	369.707	380.329	384.952	383.571	377.573	369.930	362.711	356.071	349.964	344.348	339.182
	Value of Carbon Emission Rights											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	0.000	45.431	55.105	66.772	80.809	97.649	117.782	141.748	170.118	203.469	242.323	287.054
LTA U1	0.000	238.930	337.851	479.925	630.309	761.663	562.432	594.768	668.966	756.943	860.926	983.602
ATL U0	0.000	45.915	55.812	67.805	80.809	97.649	117.782	141.748	170.118	203.469	242.323	287.054
ATL U1	0.000	45.915	55.812	67.805	630.309	761.664	918.703	842.200	668.966	756.943	860.936	983.602

DICE:												
	CO2 Emissions											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	6.088	7.458	9.256	11.335	13.583	15.904	18.205	20.391	22.366	24.035	25.318	28.158
LTA U1	6.088	4.750	5.338	5.904	6.410	8.840	7.197	7.490	7.732	7.934	8.113	8.280
ATL U0	6.088	7.448	9.239	11.311	13.583	15.904	18.205	20.392	22.369	24.032	25.308	26.162
ATL U1	6.088	7.448	9.239	11.311	6.523	6.887	7.305	7.595	7.768	7.863	8.154	8.316
	Carbon Concentrations											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0(N)	736.400	775.709	820.510	873.082	934.584	1005.354	1085.082	1172.893	1267.380	1366.633	1468.302	1569.713
LTA U1(N)	736.400	775.709	803.179	832.114	862.273	893.156	924.221	954.983	985.057	1014.170	1042.156	1068.952
LTA U0	353.000	371.843	393.319	418.520	448.001	481.926	520.144	562.237	607.530	655.108	703.844	752.456
LTA U1	353.000	371.843	385.011	398.881	413.338	428.142	443.034	457.780	472.196	486.152	499.567	512.412
	Temperature Change											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0(N)	0.430	0.522	0.665	0.844	1.051	1.283	1.537	1.809	2.092	2.384	2.677	2.967
LTA U1(N)	0.430	0.583	0.783	0.994	1.214	1.442	1.675	1.911	2.148	2.383	2.615	2.842
LTA U0	0.000	0.092	0.235	0.414	0.621	0.853	1.107	1.379	1.662	1.954	2.247	2.537
LTA U1	0.000	0.153	0.353	0.564	0.784	1.012	1.245	1.481	1.718	1.953	2.185	2.412
	Value of Carbon Emission Rights											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	0.000	8.810	11.300	14.250	17.540	21.020	24.630	28.280	31.920	35.510	39.010	42.430
LTA U1	0.000	93.380	118.530	148.540	182.210	218.560	256.770	296.190	332.800	375.550	414.140	451.070
ATL U0	0.000	9.020	11.570	14.580	17.540	21.020	24.630	28.280	31.920	35.510	39.010	42.430
ATL U1	0.000	9.020	11.570	14.580	179.330	212.800	248.640	285.950	323.900	361.860	399.420	435.520

HCRA:											
	CO2 Emissions										
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	6.000	6.850	8.000	9.370	10.520	11.170	11.970	12.630	13.280	13.920	14.570	15.290
LTA U1	6.000	5.010	4.490	4.660	3.950	2.930	1.900	0.690	0.000	0.000	0.000	0.000
LTA U2	6.000	6.600	7.520	8.720	9.540	9.870	10.290	10.460	10.510	10.390	10.250	10.050
LTA U3	6.000	6.070	6.480	7.240	7.340	6.980	6.640	5.900	4.940	3.760	2.480	0.980
ATL U0	6.000	6.840	7.990	9.350	10.520	11.170	11.960	12.630	13.280	13.920	14.570	15.290
ATL U1	6.000	6.840	7.990	9.350	4.680	1.410	0.660	0.240	0.000	0.000	0.000	0.000
	CO2 Concentrations											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	353.000	370.660	390.520	413.510	439.140	465.690	492.830	520.570	548.810	577.500	606.720	636.680
LTA U1	353.000	366.600	375.420	384.260	391.420	394.750	394.620	390.840	383.980	378.120	373.300	369.210
LTA U2	353.000	370.110	388.460	409.490	432.410	455.300	477.840	499.820	520.800	540.250	558.210	574.720
LTA U3	353.000	368.950	384.100	400.740	417.490	432.210	444.750	454.510	460.790	463.110	461.380	455.360
ATL U0	353.000	370.650	390.470	413.400	439.010	465.600	492.740	520.490	548.740	577.430	606.650	636.610
ATL U1	353.000	370.650	390.470	413.400	426.050	420.290	412.580	404.830	397.320	391.050	385.790	381.260
	Temperature Change											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	0.000	0.190	0.350	0.510	0.680	0.850	1.020	1.190	1.350	1.510	1.660	1.810
LTA U1	0.000	0.350	0.600	0.780	0.930	1.030	1.100	1.120	1.110	1.060	1.010	0.970
LTA U2	0.000	0.360	0.660	0.930	1.200	1.460	1.710	1.950	2.170	2.380	2.580	2.750
LTA U3	0.000	0.180	0.320	0.450	0.570	0.690	0.790	0.870	0.930	0.970	0.990	0.980
ATL U0	0.000	0.190	0.350	0.510	0.680	0.850	1.020	1.190	1.350	1.510	1.660	1.810
ATL U1	0.000	0.370	0.670	0.950	1.210	1.340	1.370	1.350	1.310	1.250	1.190	1.130
	Value of Carbon Emission Rights											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	0.000	7.960	13.370	16.520	23.370	31.110	39.260	50.270	62.630	76.780	92.330	108.440
LTA U1	0.000	142.030	193.350	225.860	301.030	352.510	419.760	473.030	459.710	469.310	483.150	497.460
LTA U2	0.000	22.230	35.610	42.410	59.330	77.150	96.070	120.180	148.370	180.330	212.970	247.800
LTA U3	0.000	55.910	86.990	105.580	148.350	187.230	230.650	282.440	335.240	393.100	449.650	513.020
ATL U0	0.000	8.300	13.950	17.240	23.410	30.980	39.350	50.260	62.610	76.820	92.340	108.450
ATL U1	0.000	8.300	13.950	17.240	397.750	402.090	455.070	460.640	459.710	469.310	483.150	497.460

MERGE:												
	CO2 Emissions											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	5.864	6.664	7.692	9.342	11.137	12.999	15.487	14.274	13.061	11.534	9.693	7.853
LTA U1	5.864	5.830	5.730	5.723	4.962	4.043	0.770	0.462	0.154	0.000	0.000	0.000
ATL UO	5.864	6.663	7.686	9.332	11.136	13.005	15.493	14.281	13.071	11.544	9.702	7.861
ATL U1	5.864	6.663	7.686	9.332	7.805	5.949	2.404	1.442	0.481	0.000	0.000	0.000
	CO2 Concentrations											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	353.000	372.171	393.257	417.934	447.442	481.757	521.911	561.110	592.365	616.448	633.040	642.373
LTA U1	353.000	370.466	386.095	400.379	412.219	420.124	419.489	412.693	406.341	400.282	394.907	390.301
ATL U0	353.000	372.164	393.243	417.902	447.412	481.770	521.980	561.231	592.534	616.664	633.286	642.636
ATL U1	353.000	372.164	393.243	417.902	440.609	454.751	457.575	452.382	445.181	436.751	428.907	422.289
	Temperature Change											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	0.000	0.167	0.351	0.551	0.773	1.017	1.284	1.567	1.848	2.112	2.351	2.561
LTA U1	0.000	0.330	0.678	1.028	1.373	1.701	1.986	2.206	2.364	2.480	2.567	2.635
ATL U0	0.000	0.167	0.351	0.551	0.772	1.017	1.284	1.567	1.849	2.113	2.353	2.563
ATL U1	0.000	0.167	0.351	0.551	0.947	1.500	1.975	2.351	2.631	2.836	2.983	3.090
	Value of Carbon Emission Rights											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	0.000	6.351	9.288	13.183	18.239	24.276	32.462	51.601	70.741	100.617	141.228	181.84
LTA U1	0.000	134.564	206.766	303.922	430.889	582.026	790.314	874.188	958.062	1387.115	2161.346	2935.577
ATL U0	0.000	6.616	9.726	13.904	18.221	24.248	32.426	51.548	70.670	100.529	141.125	181.720
ATL U1	0.000	6.616	9.726	13.904	471.340	653.286	918.924	1202.618	1486.312	1858.730	2319.873	2781.015

SLICE:												
	Carbon Emissions											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	5.864	7.146	8.571	9.905	10.798	11.112	11.389	11.726	11.868	11.821	11.602	11.237
LTA U1	5.864	6.150	6.293	7.063	7.520	7.619	7.750	7.980	8.143	8.251	8.315	8.351
LTA U2	5.864	7.027	8.299	9.562	10.398	10.678	10.928	11.241	11.371	11.327	11.127	10.796
LTA U3	5.864	6.475	7.072	8.028	8.627	8.795	8.975	9.243	9.406	9.472	9.458	9.381
ATL U0	5.864	7.141	8.559	9.859	10.798	11.112	11.389	11.726	11.868	11.821	11.602	11.237
ATL U1	5.864	7.141	8.559	9.859	7.505	7.584	7.710	7.937	8.101	8.209	8.274	8.310
	Carbon Concentrations											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	351.162	368.488	389.439	414.276	442.319	471.559	499.602	526.403	552.307	576.614	598.708	618.098
LTA U1	351.162	368.488	385.499	401.662	419.520	437.698	454.752	470.904	486.620	501.672	515.895	529.190
LTA U2	351.162	368.484	388.960	412.757	439.563	467.441	494.106	519.536	544.085	567.104	588.031	606.426
LTA U3	351.162	368.336	386.480	405.458	426.607	448.350	468.938	488.518	507.523	525.582	542.398	557.758
	Temperature Change											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	0.000	0.115	0.247	0.398	0.570	0.759	0.958	1.151	1.336	1.511	1.674	1.822
LTA U1	0.000	0.156	0.334	0.524	0.716	0.915	1.118	1.317	1.510	1.696	1.875	2.044
LTA U2	0.000	0.156	0.334	0.535	0.761	1.009	1.273	1.540	1.802	2.057	2.300	2.528
LTA U3	0.000	0.115	0.246	0.388	0.536	0.691	0.849	1.004	1.150	1.289	1.420	1.541
	Value of Carbon Emission Rights											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	0.000	5.025	6.874	9.104	11.706	14.598	17.812	21.430	25.509	30.198	35.746	42.514
LTA U1	0.000	61.270	82.251	106.754	134.395	163.467	193.316	223.295	251.616	278.428	295.558	306.390
LTA U2	0.000	8.590	11.710	15.475	19.864	24.712	30.057	35.997	42.532	49.757	57.844	67.025
LTA U3	0.000	36.704	49.563	64.584	81.565	99.571	118.225	137.161	155.407	171.984	185.735	195.223
ATL U0	0.000	3.024	6.873	9.103	11.705	14.598	17.810	21.428	25.508	30.197	35.744	42.512
ATL U1	0.000	5.024	6.873	9.103	137.407	166.524	196.441	226.432	254.711	279.468	298.583	309.482

YOHE:												
	CO2 Emissions											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	5.864	7.251	8.519	9.833	11.065	12.195	13.243	14.175	15.024	15.774	16.459	17.074
LTA U1	5.864	6.609	6.027	5.866	5.796	5.771	5.917	6.164	6.513	6.897	7.312	7.718
ATL UO	5.864	7.141	8.345	9.343	11.056	12.269	13.305	14.239	15.074	15.823	16.495	17.108
ATL U1	5.864	7.141	8.345	9.343	6.027	5.027	5.258	5.649	6.069	6.504	7.034	7.551
	Value of Carbon Emission Rights											
	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
LTA U0	0.000	1.740	4.180	8.070	11.460	15.070	19.210	23.460	28.010	32.430	36.840	40.920
LTA U1	0.000	24.500	58.960	120.730	163.200	198.130	226.810	247.240	263.570	275.660	286.400	295.840
ATL U0	0.000	2.860	6.920	13.710	11.080	14.840	18.920	23.300	27.800	32.360	36.760	40.950
ATL U1	0.000	2.860	6.920	13.710	210.490	238.440	256.980	272.090	284.500	287.580	290.800	293.470

DRAFT

APPENDIX C

The Berlin Mandate: The Design of Cost-Effective Mitigation Strategies

by Richard Richels[1], Jae Edmonds[2], Howard Gruenspecht[3] and Tom Wigley[4]

with contributions from Henry Jacoby[5], Alan Manne[6], Stephen Peck[7], Tom Teisberg[8], Marshal Wise[9] and Zili Yang[10]

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DRAFT

Abstract

The Berlin Mandate calls for strengthening developed country commitments for limiting greenhouse gas emissions. This paper addresses a key issue in the current analysis and assessment phase -- the costs of proposals to limit CO2 emissions. Employing four widely-used energy-economy models, we explore the direct and indirect effects of alternative proposals on the global economy. We also examine the implications for atmospheric CO2 concentrations.

We begin by examining an AOSIS-like proposal in which OECD countries agree to reduce CO2 emissions by 20% below 1990 levels by a specified date. We find that implementing such a proposal could be quite costly. Not surprisingly, OECD countries would be hardest hit. Their costs could be as high as several percent of GDP. The analysis also shows that because of trade effects, non-OECD countries would likely incur costs even when reductions are confined to the OECD. An economic slowdown in the OECD would affect the full range of developing country exports, and hence their economic growth. This would likely be the case for both oil-importing and oil-exporting developing countries.

We then explore alternatives that are apt to be quite similar in terms of environmental benefits, but allow for flexibility in where and when emission reductions are made. We find that costs could be substantially reduced through international cooperation and the optimal timing of emission reductions. Indeed, such flexibility can reduce costs by more than 80%, potentially saving the international community *trillions* of dollars in mitigation costs. We find that reliance on more flexible alternatives reduces costs more effectively than adopting weaker, but still inflexible, commitments.

1. Introduction

The Berlin Mandate calls upon the Parties to the United Nations Framework Convention on Climate Change to strengthen developed country commitments to reduce greenhouse gas emissions.[11] A number of proposals have been put forward. These range from slowing the current growth in emissions to sharp reductions below present levels. The choice is a difficult one. Acting too slowly risks irreversible environmental damages. Acting too aggressively risks imposing large, and perhaps unnecessary costs on the global economy. As noted by the Intergovernmental Panel on Climate Change (IPCC), the challenge is to develop a prudent hedging strategy in the face of climate-related uncertainties.[12]

The Framework Convention is the mechanism established by the international community for implementing precautionary measures. It recognizes that a sensible hedging strategy should be flexible, with ample opportunities for learning and mid-course corrections. Periodic reviews are required "in light of the best available scientific information on climate change and its impacts, as well as relevant technical, social and economic information." Based on these reviews, appropriate measures would be taken, including the adoption of new commitments.

Upon entering into force in 1994, the Convention established an initial (but non-binding) aim for developed countries to return emissions to their 1990 levels by 2000. At the first meeting of the Conference of the Parties (COP-1) in Berlin in April of 1995, it was determined that existing commitments under the Convention were inadequate. Further commitments for developed countries are to be negotiated, and prepared for approval at COP-3 in 1997.

While calling for new commitments, the Berlin Mandate does not specify what these commitments should be. Rather it seeks further analysis and assessment to guide and inform the decision making process. This paper addresses a key issue in the analysis and assessment phase -- the costs of proposals to limit CO2 emissions. Rather than rely on a single model, the analysis is based on independent runs of four widely-used energy-economy models.[13] In each instance, we explore both the direct and indirect effects on the global economy.

We also examine the impact of alternative proposals on atmospheric concentrations. The ultimate objective of the Framework Convention is "the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[14] Although the issue of what constitutes an appropriate limit has yet to be resolved, it is instructive to explore the implications that alternative emission pathways have for future concentrations.

We pay particular attention to the design of cost-effective mitigation strategies. The Framework Convention states that "policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible costs." Adopting least-cost mitigation strategies will free up valuable resources for further addressing the threat of climate change or for meeting other societal needs. We explore two ways of promoting this objective. In the first, emission reductions take place *where* it is cheapest to do so. In the second, they take place *when* it is cheapest to do so.

A number of studies have suggested that the cost of emission reduction can be substantially reduced through international cooperation.[15] From a global perspective, it would be economically wasteful to incur high marginal abatement costs in one country when low-cost alternatives are available elsewhere in the world. We discuss ways to ensure that emission reductions are made where it is cheapest to do so, and explore the potential gains.

The timing of emission reductions can also influence costs. What is important in meeting a concentration target is cumulative – not year-by-year – emissions.[16] A particular concentration target can be met through a variety of emission time paths. Several studies have suggested that emission time paths that provide flexibility in making the transition away from fossil fuels will be less costly.[17] We examine the implications for the design of cost-effective mitigation strategies under the Berlin Mandate.

Mitigation costs are, of course, only part of the story. The more difficult question is the appropriate level of emissions abatement. This requires consideration of both costs *and* benefits. The present analysis is confined to the cost-side of the ledger. That is, we focus on the costs of emissions reduction. Policy makers will also want to know what they are buying in terms of reducing the undesirable consequences of global climate change. Such an analysis is beyond the scope of the present effort.

2. The models

The analysis employs four energy-economy models: CETA[18], EPPA[19], MERGE[20], MiniCAM[21]. These models reflect the recent trend towards hybrid modeling tools which incorporate features from both bottom-up and top-down approaches to energy modeling. On the supply-side, each model employs a bottom-up representation of the energy system. Energy technologies are described in process model detail (e.g., availability dates, heat rates, carbon emission coefficients, etc.). The technology vector includes both existing sources and new options that are likely to become available. Cost and performance constraints are adjusted for regional differences. A more top-down perspective is taken towards the balance of the economy. This is done using macroeconomic production functions that provide for substitution between capital, labor, and energy inputs.

The models provide a consistent way to examine alternative strategies for limiting CO2 emissions and to examine the impacts of higher energy prices on economic output. They can be used, for example, to estimate the increase in fossil fuel prices required to induce consumers to reduce emissions. They also can be used to analyze the possibility of significant regional differences in marginal abatement costs that would lead to opportunities for cost savings through international cooperation.

The models employ a general equilibrium formulation of the global energy and economic system. This allows us to examine the impacts of actions taken in one region on the economies of another. This is particularly important in the case of the Berlin Mandate. Constraints imposed on developed countries may have unexpected consequences for developing countries. For example, the international price of oil will be affected by the imposition of carbon constraints on oil importing countries.

While general equilibrium models are useful in tracing the long-term implications of a carbon constraint, they may ignore important short-term effects. This is because they assume full employment of the economy and instantaneous adjustment to policy shocks. The lack of attention to adjustment costs, means that these models may *understate* the short-run cost of economic shocks, particularly if these are large and unexpected.

On the other hand, some have argued that the exogenous specification of technology change tends to *overstate* the cost of a carbon constraint. This is an important issue in the energy policy debate -- one that is deserving of considerably more attention than it has received to date. It should be noted, however, that the direction of any bias is still unclear. An acceleration of energy related technical progress may be accompanied by a slowdown in labor and capital productivity improvements throughout the economy. To receive proper consideration, the issue of endogenous change must be examined on an economy-wide basis.[22]

Although similar in many respects, the models differ in important ways. For example, EPPA is a recursive rather than an intertemporal optimization model. EPPA and MERGE employ a "putty-clay" rather than a "putty-putty" approach to the vintaging of capital stocks (i.e., they explicitly recognize that one type of capital cannot be "transformed" into another, once it is put into place). And all models differ in regional disaggragation: CETA (2 regions), EPPA (12 regions), MERGE (5 regions) and MiniCAM (9 regions).[23]

The models also differ with respect to key inputs, e.g., population, per capita productivity trends, the fossil-fuel resource base, the cost and availability of long-term supply options, etc. Rather than try to impose a common set of driving assumptions, the choice of inputs was left to the discretion of the modeling teams. It was felt that, with a diverse set of energy futures, we would be better able to assess the robustness of our results.

3. Future emissions

We begin with an examination of how fossil fuel emissions are projected to grow in the absence of policy intervention. The costs of a carbon constraint are quite sensitive to the emissions baseline. The baseline describes how emissions will grow under existing policies. The higher the emissions baseline, the more carbon must be removed from the energy system to meet a particular target, and the higher become the costs.

Figure 1 compares baseline projections for our four models.[24] Note that in each instance emissions are projected to grow in the absence of policy intervention. This is the case for the OECD and for the world as a whole. This is consistent with the overwhelming majority of analyses recently reviewed by the IPCC.[25] Of the dozens of studies surveyed, all but a few showed a rising emissions baseline.

In reviewing these emission projections, several points are worth noting. First, although the annual growth rates are substantial – between 1.5 percent and 2 percent -- they represent a marked slowing in the historical trend. Indeed, global emissions grew at an annual rate of approximately 3.5 percent between 1950 and 1990. In part, the slowdown is due to a projected decline in global economic growth. Since 1950, gross world product grew at an average annual rate of 2.9 percent. The projected growth rate for the next half century or so is closer to 2.5 percent. Also at work is the gradual decoupling between energy and GDP growth and a decoupling between CO2 emissions and energy use.

The differences in emission baselines should come as no surprise given the uncertainty over the period studied and thus the freedom the modelers had in the choice of input assumptions. Although it would be impractical to sort out all of the reasons for the differences, several factors have been identified as being particularly important when modeling future emissions.[26] High up on the list is economic growth. Those models with higher GDP growth rates tend to project higher emissions. Conversely, the more optimistic one is about the prospects for reducing energy intensity or the availability of low-cost carbon-free substitutes, the lower the CO2 growth rate.

Although the models differ on the cost and availability of supply and demand side alternatives, it should be noted that each includes some "no regrets" emission reduction options. These are alternatives that would be worth adopting apart from climate considerations. A growing emissions baseline does not imply the absence of economically competitive alternatives to fossil fuels. It only means that such options are in insufficient supply to arrest the growth in carbon emissions.

The focus of the Berlin mandate is on developed country emissions. Negotiators will be interested in how a particular proposal changes the emissions baseline. We start by examining a case in which OECD countries return emissions to 1990 levels by the year 2000, reduce them by an additional 20% by 2010, and hold them at that level thereafter. This is similar in many respects to the proposal put forward by the Alliance of Small Island States (AOSIS).[27] For the present analysis, we place no constraints on non-OECD emissions.

Figure 2 shows the implications for global emissions. An AOSIS-like proposal may slow the growth in global emissions, but it is unlikely to stabilize them at anywhere near present levels. This is because non-OECD countries currently account for over half of the global total and their share is expected to grow. The implications for climate policy are clear. Stabilization of global emissions will eventually require the participation of developing countries.

4. The costs of alternative commitments

We next turn to the issue of costs. In recent years, a number of studies have highlighted the potential role of international cooperation and flexible timing in reducing the costs of a carbon constraint.[28] To explore the implications for the Berlin Mandate, we first estimate the costs of adopting the AOSIS-like proposal described above. We then examine three variants. Each results in the same cumulative emissions, but there are significant differences in the geographical location and timing of the emission reductions.

Before proceeding, one caveat is in order. We use trade in emission rights to examine the potential gains from international cooperation. By allowing such trade, we ensure that, at a given point in time, emission reductions are made where it is cheapest to do so. It should be noted that this is but one of a number of mechanisms that could be used to facilitate international cooperation. For example, various forms of bilateral joint implementation could accomplish the same objective. Hence, trade in emission rights is intended only as a proxy for any of a number of cooperative mechanisms.

With the above caveat in mind, we now describe our four cases:

- Case 1 (no interregional or intertemporal efficiency) -- Each OECD region is required to meet its annual emissions constraint independently. There is no trade in emission rights between the OECD and other regions.[29]

- Case 1a (interregional efficiency) -- The constraint is still on year-by-year emissions, but trade in emission rights is now permitted between the OECD and other regions. Non-OECD countries are allowed to emit in each period up to the level of their emissions in Case 1. If they reduce their emissions below this level, they may benefit from the sale of the emission rights generated.

- Case 1b (intertemporal efficiency) -- Rather than a set of year-by-year emission limits, the constraint on emissions from each OECD region is expressed as an upper limit on its cumulative emissions. This allows for higher emissions in years where the cost of emissions abatement is highest. "Payback" must occur by 2050. There is no trade in emission rights between the OECD and non-OECD regions.

- Case 1c (interregional and intertemporal efficiency) -- The constraint is now on cumulative emissions at the global level. Both interregional and intertemporal trading is permitted. Emission rights are based on Case 1. As a result, reductions take place both where and when it is cheapest to do so.

Figure 3 shows costs for Case 1 discounted to 1990 at 5% per year. The constraint on carbon-emitting activities leads to a reallocation of resources, away from the pattern that is preferred in the absence of this limit and into potentially costly conservation activities and fuel substitution. Relative prices change as well. These forced adjustments lead to a reduction in economic performance, as measured by GDP or some other indicator depending on the model. The tighter the constraint the greater the effect.

Note that, because of trade effects, many non-OECD countries will incur costs even when reductions are confined to the OECD. Restrictions on carbon emissions lead to lower OECD demand for oil, which results in lower revenue for the oil-exporting countries. In addition, an economic slowdown in the OECD countries affects the full range of developing country exports, and thus their growth. For many oil-importing developing countries these broader trade effects outweigh the gain from lower world oil prices. Three of the four models shown account for at least some of these effects (MiniCAM is the exception) and show a spillover of OECD loses onto non-OECD countries.

Not surprisingly, the models differ as to the magnitude of the economic impacts. This is to be expected given the large differences in emission baselines. EPPA, with the highest baseline, shows the highest costs. MiniCAM, with the lowest baseline, shows the lowest costs.

A second factor contributing to the large spread among models is the speed with which the capital stock is allowed to adjust to higher energy prices. As noted earlier, two of the models, EPPA and MERGE employ a so-called putty clay formulation. They attempt to track the economic lifetime of existing plant and equipment. As a result, these models show less responsiveness of energy demand to price changes in the short run than over the long run. Alternatively, models which assume greater malleability of capital (CETA and MiniCAM) produce lower cost estimates.

Potential gains from interregional efficiency. The models are in more agreement on the relative costs of the various alternatives (Figure 4). Note that the potential benefits from economic efficiency are substantial. In Case 1, each OECD region is required to act independently to reduce its emissions. There is no opportunity to take advantage of low-cost emission reduction options elsewhere in the world. From the perspective of global economic efficiency, this makes little sense. Clearly, it is inefficient to incur high marginal domestic abatement costs when low-cost alternatives exist in other countries. In Case 1a, we allow OECD countries to take advantage of the lower cost alternatives. We do this by permitting trade in carbon emission rights. Note that cooperation of this type can cut the costs of a carbon constraint by well over one-half.

Figure 5 shows the impact on non-OECD countries. International cooperation not only reduces costs within the OECD, it may also result in substantial wealth transfers. Indeed, for three of our models, the revenue received from the sale of emission rights more than offsets the trade-related losses to non-OECD countries. Alternatively, one could devise a burden sharing scheme which imposes zero net costs on non-OECD countries.[30] Such a scheme would compensate non-OECD countries for losses accruing through international trade, but results in no additional wealth transfers. In this instance, costs to the OECD would be equivalent to global costs.

Potential gains from intertemporal efficiency. We next turn to the issue of timing (Case 1b). When given the choice, each model shifts some emission reductions into the future. That is, it chooses to emit more in the early years with payback coming later on (see Figure 6a). This behavior can best be understood in terms of an optimal allocation problem. A constraint on cumulative emissions defines a carbon budget. That is, it specifies a total amount of carbon to be emitted over a fixed period of time. For Case 1b, each

OECD region's carbon budget is defined as the sum of its permissible emissions between 2000 and 2050 (as specified in Case 1). The issue is how best to allocate the carbon budget over this period.

There are several factors that argue for using more of the available budget in the early years.[31] Deferring emission reductions provides valuable time to reoptimize the capital stock. Energy producing and energy using investments are typically long-lived (e.g., power plants, houses, transport). They were put into place with a particular set of expectations about the future. Abrupt changes are apt to be expensive. This is particularly the case when it comes to premature retirement of existing plant and equipment. Time is needed for the capital stock to adapt.

The optimal timing of emission reductions is also influenced by the prospects for new supply and conservation technologies. 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 draw more heavily on the carbon budget 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 fossil fuels.

Finally, with the economy yielding a positive return on capital, future reductions can be made with a smaller commitment of today's resources. For example, suppose that the net real return on capital is 5% per year and it costs $100 to remove a ton of carbon -- regardless of the year in which the reduction is made. If we were to remove a ton today, it would cost $100. Alternatively, we could invest $31 today to have the resources to remove a ton in 2020.

Before leaving the timing issue, several additional caveats are in order. First, it should be noted that the two emission paths of Figure 6 result in different levels of atmospheric concentrations (prior to 2050). They may therefore differ in terms of environmental impacts. Given that the concentration paths lie so close together, however, the differential impacts on temperature and sea level are likely to be negligible.[32]

Second, the above considerations (capital stock turn over, R&D and discounting) argue for shifting some emission reductions into the future. They cannot, however, be used as an excuse for deferring these reductions indefinitely. The carbon budget is finite. There is an upper limit on the amount to be emitted between now and 2050 which continued deferral would soon exceed. The issue is one of optimal timing.

Finally, note that the amount of deferral depends on the size of the carbon budget. In this instance, there is insufficient flexibility to defer emission reductions altogether in the early years. The optimal emissions path lies between Case 1 and business as usual.

Returning to Figure 4, we see that the most efficient strategy is one which combines international cooperation with flexible timing (Case 1c).[33] In this instance, costs are reduced by more than 80%. Figure 7 provides some insight into why the savings are so large. It shows OECD GDP losses averaged across the four models. In Case 1, GDP losses grow to 2.4% over the next quarter century -- roughly $400 billion in today's economy. In Case 1b, GDP losses grow more slowly. Although annual losses exceed those of Case 1 toward the end of the time horizon, they are considerably lower early on. As a result, cumulative losses are smaller. If OECD countries are able to take advantage of low-cost emission reduction options elsewhere in the world, losses can be held to under 1% of GDP.

The costs of less stringent carbon constraints. One way to reduce costs would be to design more cost-effective strategies. A second way would be to make the constraint less stringent. We now consider two additional variants on Case 1. In Case 2, we delay the date by which OECD countries must achieve the 20% reduction by 10 years. In Case 3, we put off the 20% reduction altogether. That is, OECD countries continue to hold emissions at 1990 levels.

From Figure 8, note that a substantial fraction of the costs of a 20% reduction would be incurred simply by extending the existing target. That is, much of the costs result from reducing emissions from the business-as-usual path to 1990 levels. Between 40% and 70% of the costs are associated with the decision to stabilize emissions at 1990 levels.

Figure 9 compares OECD GDP losses for the three cases. In Case 1, annual losses rise to 2.4% of GDP by 2020. Postponing the 20% cut by 10 years results in lower GDP losses during the initial two decades of the next century. But losses are similar thereafter. For Case 3, GDP losses are lower for the entire period. On average, lowering the target cuts GDP losses by nearly one-half.

5. Some final comments

Estimating mitigation costs is a daunting task. It is difficult enough to envisage the evolution of the energy-economic system over the next decade. Projections involving a half century or more must be treated with considerable caution. Nevertheless, we believe that exercises like the present one contain useful information. The value, however, lies not in the specific numbers, but in the insights for policy making. With this in mind, we attempt to summarize what we have learned.

- Implementing an AOSIS-type proposal may require substantial CO2 reductions for OECD countries. With a growing emissions baseline, more and more carbon must be removed from the energy system to maintain an absolute target. Such reductions could be quite costly -- perhaps, as much as several percent of GDP to OECD countries.

- Because of trade effects, the non-OECD countries likely will incur costs even when emissions reductions are confined to the OECD. Restrictions on carbon emissions lead to lower demand for oil, which results in lower revenue for oil-exporting countries. In addition, an economic slowdown in the OECD countries affects the full range of developing country exports, and thus their growth. For many oil-importing developing countries, these broader trade effects outweigh the gain from lower world oil prices.

- One way to reduce mitigation costs would be to design cost-effective constraints. Indeed, the present analysis suggests that the potential gains from international cooperation (interregional efficiency) and flexible timing (intertemporal efficiency) are huge. Taken together, they can reduce costs by more than 80 percent. The key is to allow emission reductions to take place both *where* and *when* it is cheapest to do so.

- A second way to reduce mitigation costs would be to adopt less stringent constraints. For example, rather than a 20 percent cutback, the OECD could agree to hold emissions at 1990 levels. The analysis suggests that the reduction in overall mitigation costs would be between 30 and 60 percent. The savings, however, must be weighed against the impacts of the incremental emissions through larger changes in climate.

- The following steps could substantially reduce the costs of implementing a carbon constraint under the Berlin Mandate: 1) allow developed countries to purchase low-cost abatement options in developing countries, 2) allow time for the economic turn over of existing plant and equipment, 3) invest in the development of economically attractive substitutes for carbon-intensive fuels, and 4) ensure that cost-effective options are adopted to the greatest extent possible.

- Our results are consistent with other studies which suggest that carbon emissions will continue to grow in the absence of policy intervention. Proposals which focus exclusively on developed countries may slow the growth in global emissions, but they will not stabilize them at anywhere near present levels. Nor will they stabilize atmospheric concentrations, the ultimate goal of the Framework Convention. To do so, would eventually require developing country participation.

The present paper identifies enormous savings from international cooperation and flexible timing. Realizing this potential, however, may be another matter. For example, how do we divide up the savings from international cooperation? Or, how do we ensure that parties maintain a credible path toward fulfilling commitments? Considerable ingenuity will be required, but given the stakes, even partial success is likely to be well worth the effort.

Fortunately, some of the necessary concepts are already being tested. For example, efforts to incorporate international cooperation can build upon the experience gained from national and international joint implementation initiatives. With regard to flexible timing, a limit might be placed on a country's cumulative emissions. Subject to this constraint, the country could lay out its own projected emissions time path and prepare a formal plan that builds on existing experience with National Action Plans under the Framework Convention. Periodic reviews could then track adherence to the commitment. Technology development efforts, with suitable performance milestones, also could be an integral part of both the path definition and review processes.

Negotiators must consider a myriad of competing ideas and interests inherent in shaping a global policy. One of their greatest challenges will be to meet the injunction of Article 3 of the Framework Convention: "policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible costs." Our success in confronting the challenge of climate change may depend directly on their success in doing so.

The larger question, of course, is what constitutes an appropriate set of emission constraints. This requires consideration of both benefits and costs. The present analysis has been confined to the cost side of the ledger. That is, we examine the costs of reducing CO2 emissions. Policy makers will also want to know what they are buying, in terms of reducing the undesirable consequences of global warming. Such an analysis is beyond the scope of the present effort.

Notes

[1] Electric Power Research Institute

[2] Pacific Northwest Laboratory

[3] US Department of Energy

[4] University Corporation for Atmospheric Research

[5] Massachusetts Institute of Technology

[6] Stanford University

[7] Electric Power Research Institute

[8] Teisberg and Associates

[9] Pacific Northwest Laboratory

[10] Massachusetts Institute of Technology

[11] For the text of the Berlin Mandate, see United Nations Climate Change Bulletin, Issue 7, 2nd Quarter 1995, published by the interim secretariat for the UN Climate Change, Convention, Geneva. For the text of the Framework Convention, see Intergovernmental Negotiating Committee for A Framework Convention on Climate Change, Fifth Session, Second Part, New York, 30 April-9 May 1992

[12] See Intergovernmental Panel on Climate Change (IPCC), Report of Working Group III, Chapter 1, forthcoming, Cambridge University Press.

[13] The four models comprise the Subgroup on the Regional Distribution of Costs and Benefits of Climate Change Policy Proposals. The Subgroup is open to models participating in Stanford University's Energy Modeling Forum (EMF) Study on "Integrated Assessment of Climate Change."

[14] See Intergovernmental Negotiating Committee for A Framework Convention on Climate Change, Fifth Session, Second Part, New York, 30 April-9 May 1992.

[15] See Intergovernmental Panel on Climate Change (IPCC), Report of Working Group III, Chapter 9, forthcoming, Cambridge University Press.

[16] See Intergovernmental Panel on Climate Change (IPCC). *Climate Change 1994*, Cambridge University Press, 1994. Also see, Wigley, T., Richels, R. and Edmonds, J. "Economic and Environmental Choices in the Stabilization of Atmospheric CO2 Concentrations," *Nature*, Vol. 379, 18 January, 1996.

[17] See Intergovernmental Panel on Climate Change (IPCC), Report of Working Group III, Chapters 9 & 10, forthcoming, Cambridge University Press.

[18] See Peck, S. and Teisberg, T. "International CO2 Emissions Targets and Timetables: Analysis Using CETA-M", Working Paper, 1995.

[19] See Z. Yang, et. al, "The MIT Emissions Projection and Policy Assessment (EPPA) Model", Draft report, MIT Joint Program on the Science and Policy of Global Change, February 1996.

[20] See Manne, A. and Richels, R. "The Berlin Mandate: the Costs of Meeting Post-2000 Targets and Timetables", Stanford University, Stanford , CA, forthcoming in *Energy Policy*, 1995.

[21] See Edmonds et al

[22] See Hogan, W. and Jorgenson, D. "Productivity Trends and the Costs of Reducing CO2 Emissions"' *Energy Journal* 12 No. 1, 1991.

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[23] For a detailed model comparison, see EMF-14.

[24] These projections are intended as examples of how emissions might evolve under existing policies. They should not be interpreted as each analysis team's "best guess" of future emissions.

[25] See Intergovernmental Panel on Climate Change (IPCC). *Climate Change 1994*, Cambridge University Press, 1994.

[26] See Manne, A. and Richels, R. "The Costs of Stabilizing Greenhouse Gas Emissions: A Probabilistic Analysis based on Expert Judgments," *The Energy Journal* 15(1), 1994.

[27] The AOSIS proposal calls for Annex 1 countries to reduce emissions by 20% by 2005.

[28] See notes 15 and 16.

[29] There is some trade in emission rights within the OECD, however. This is the consequence of aggregating single countries into larger regions.

[30] With an international market in carbon emission rights, global abatement costs are independent of the burden sharing scheme. This allows us to separate the difficult issues of efficiency and equity. For the theoretical considerations underlying this proposition, see Manne, A. "Greenhouse Gas Abatement - toward Pareto Optimality in Integrated Assessments", in Education in a Research University, edited by Kenneth J. Arrow, Richard W. Cottle, B. Curtis Eaves and Ingram Olkin, Stanford University Press, Stanford CA, 1996.

[31] For a more detailed discussion of the timing issue, see Wigley et al, note 16.

[32] For the analysis, we use the carbon cycle model of Wigley. See Wigley, T.M. "Balancing the Carbon Budget: the Implications for Projections of Future Carbon Dioxide Concentration Changes," *Tellus*, 45B, 1993.

[33] EPPA is a recursive rather than an intertemporal optimization model. Several alternative emission paths were explored for Cases 1b and 1c. The results reported here are for the lowest-cost of the paths tested, and the results are not strictly comparable with those from the other models.

Figure 1. Carbon Emissions under Business As Usual

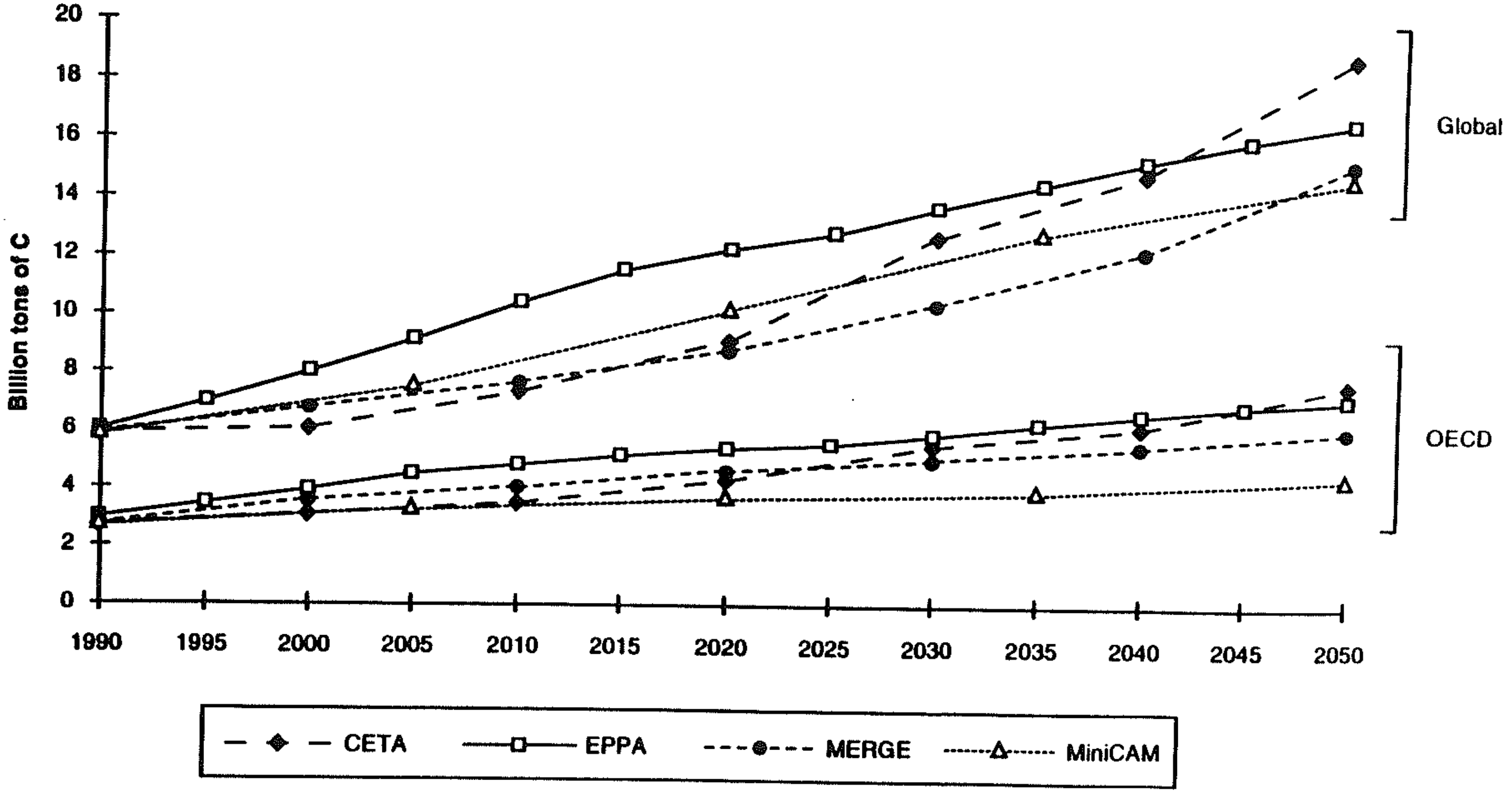


Figure 2. Global Emissions under Business as Usual and with a 20% Cut in OECD Emissions (based on average of model results)

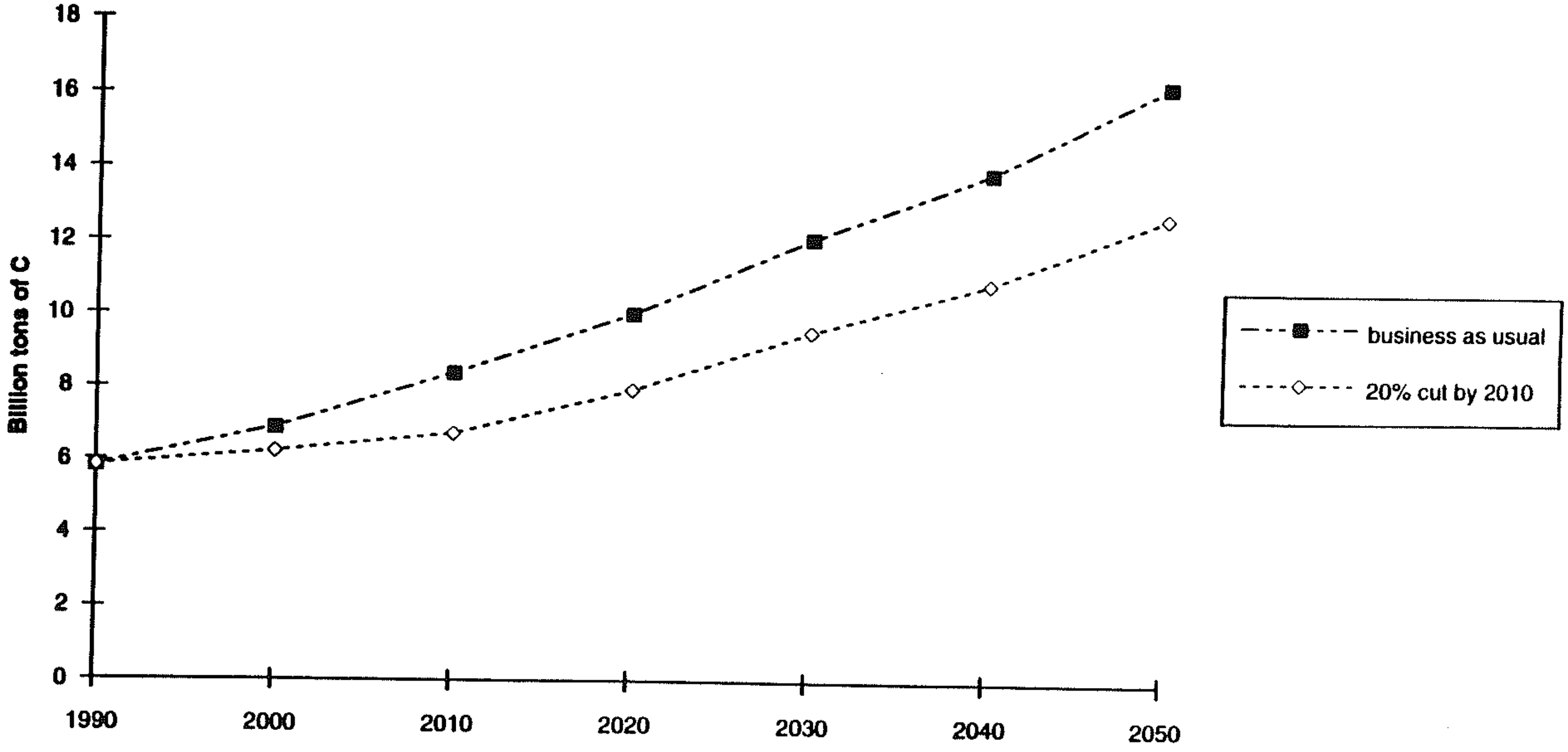


Figure 3. Costs of 20% Cut in OECD Emissions by 2010 -- Case 1
(costs through 2050 discounted to 1990 at 5%)

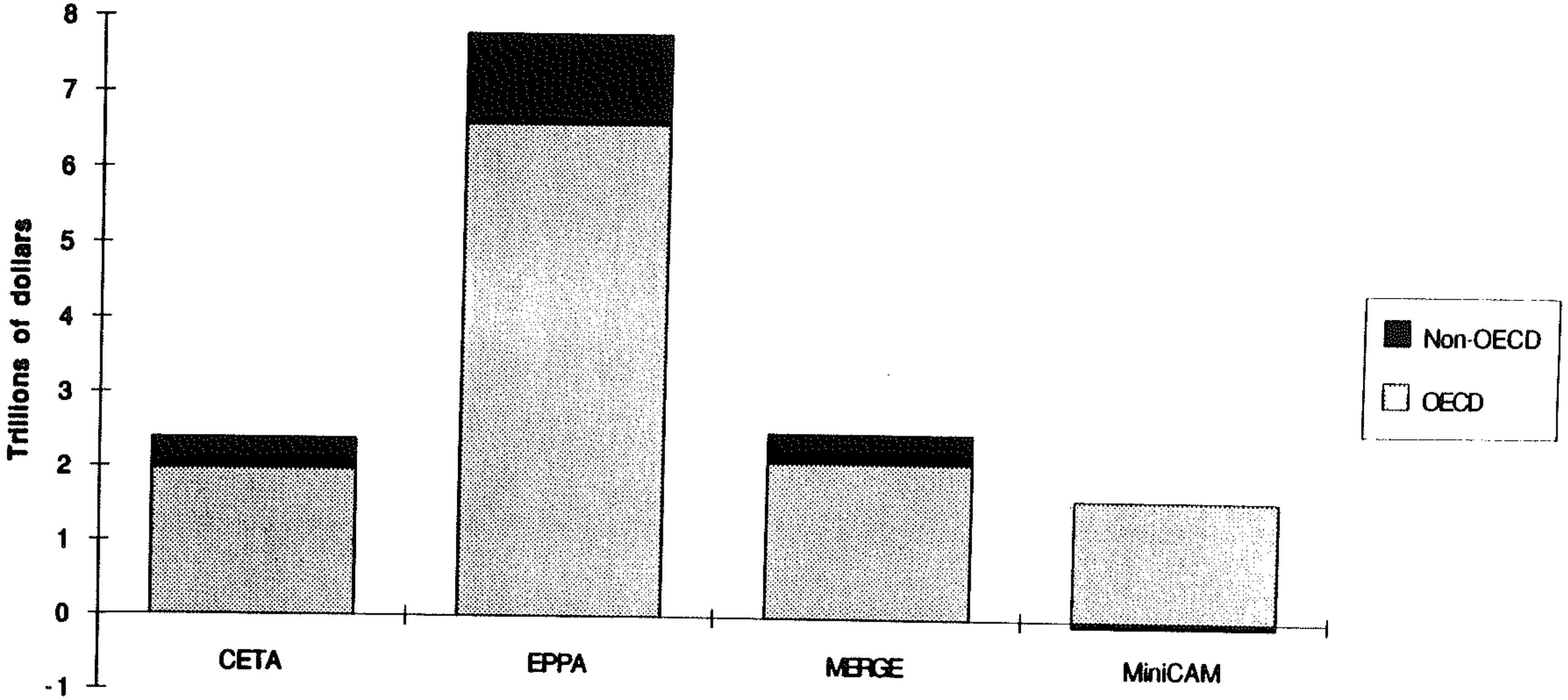
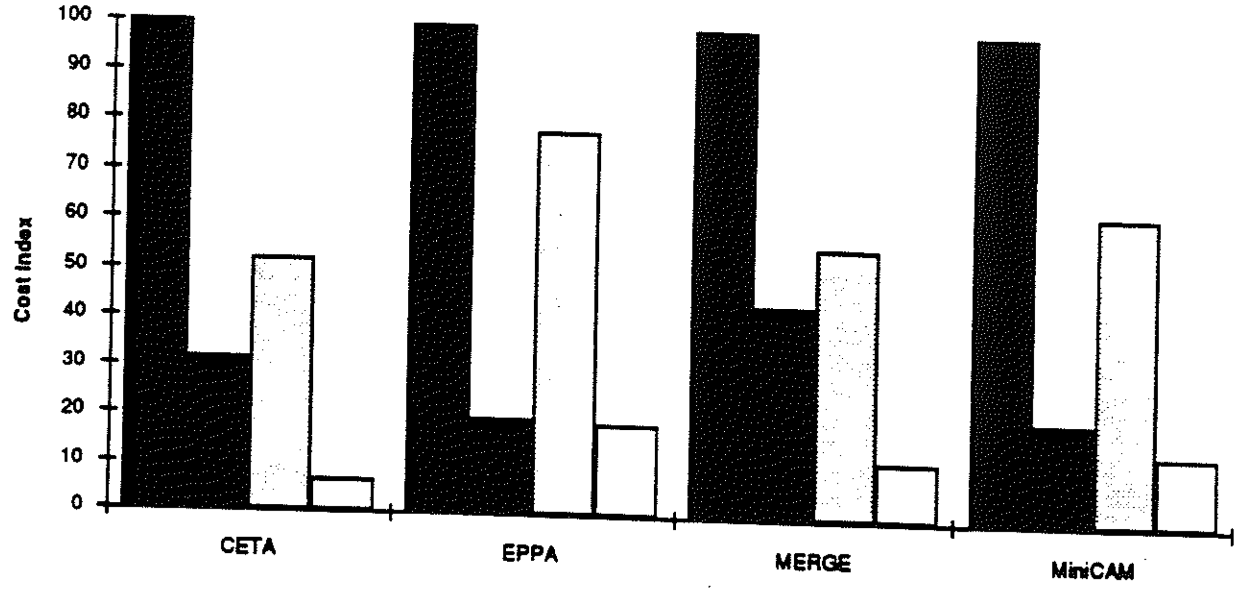
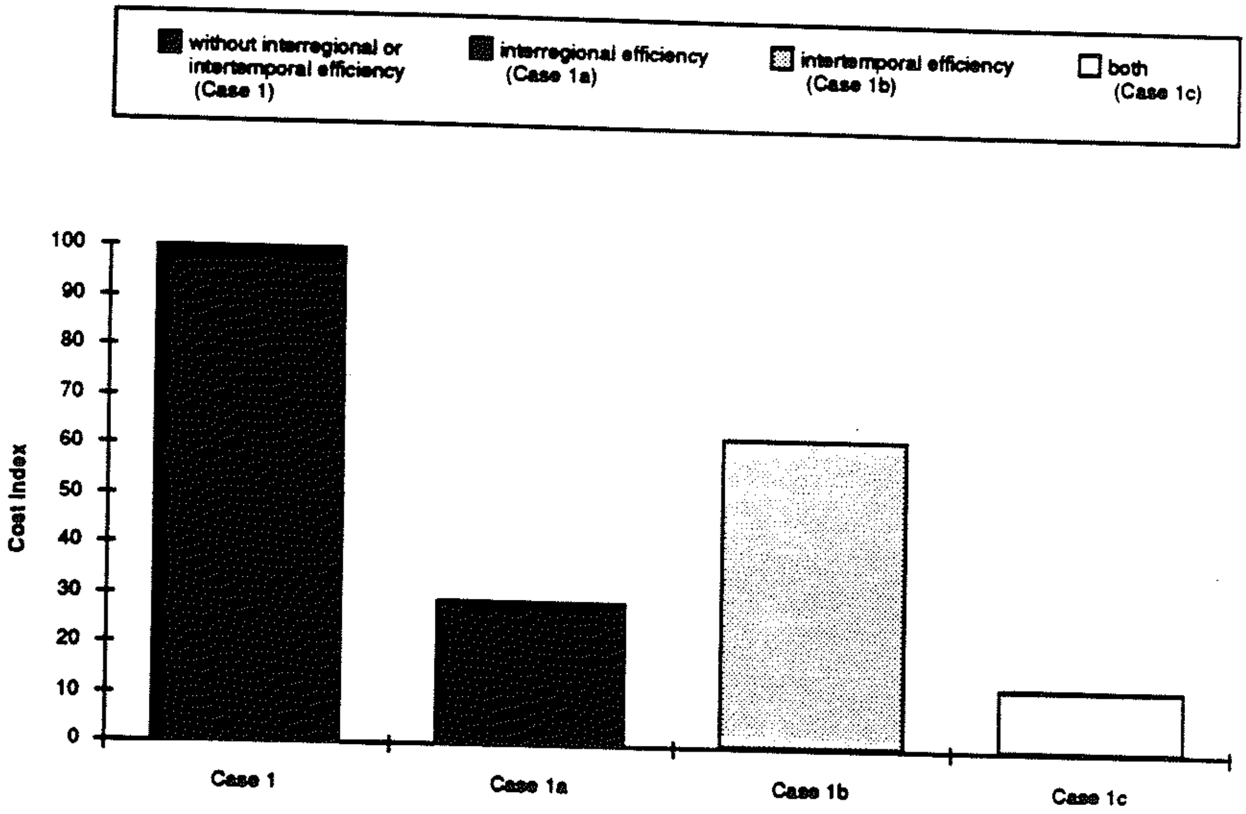


Figure 4. Global Costs under Four Alternative Cases



a) Case 1 = 100



b) Average of model results

Figure 5. Regional Costs under Four Alternative Cases (costs through 2050 discounted to 1990 at 5%)

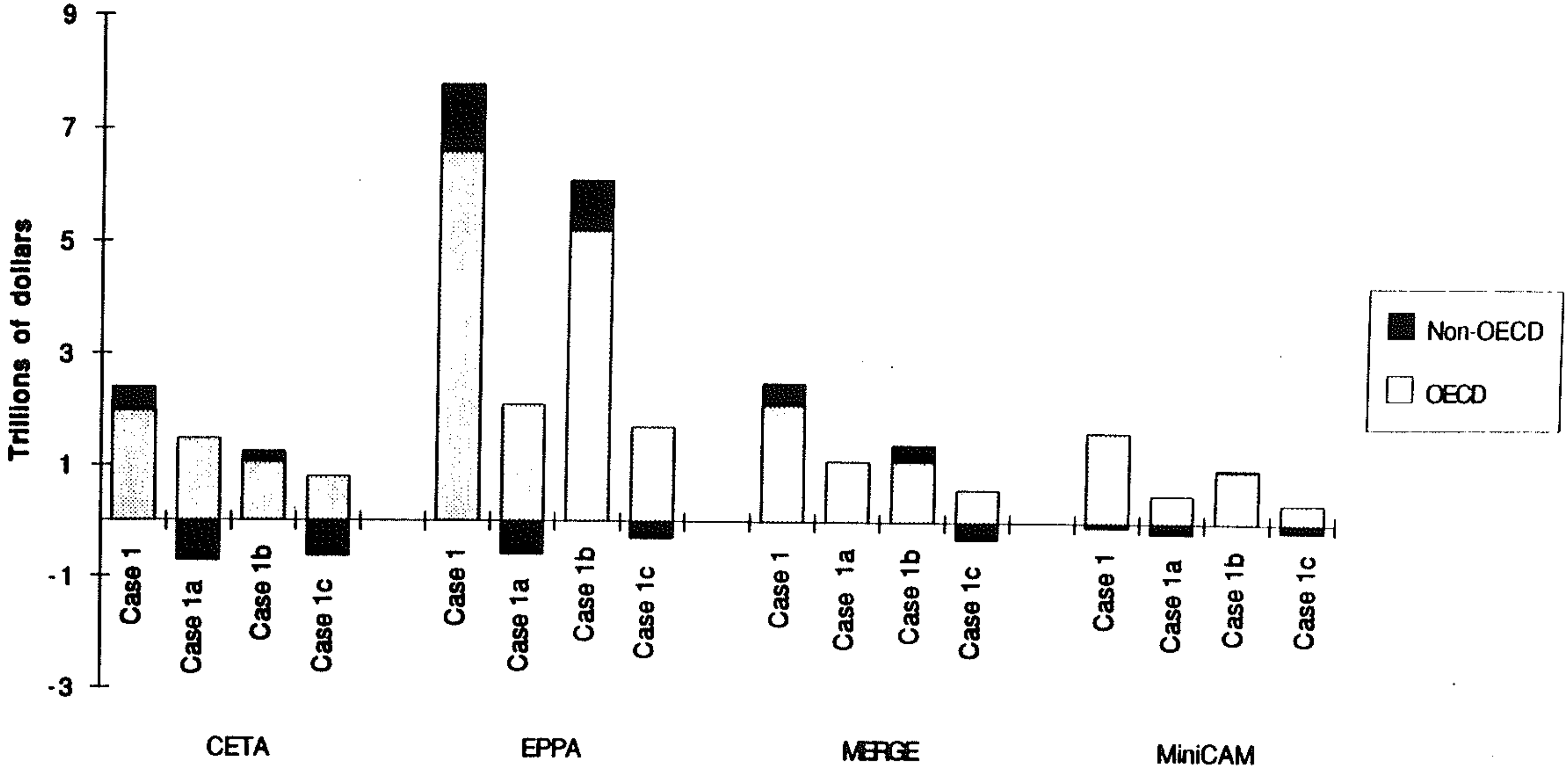
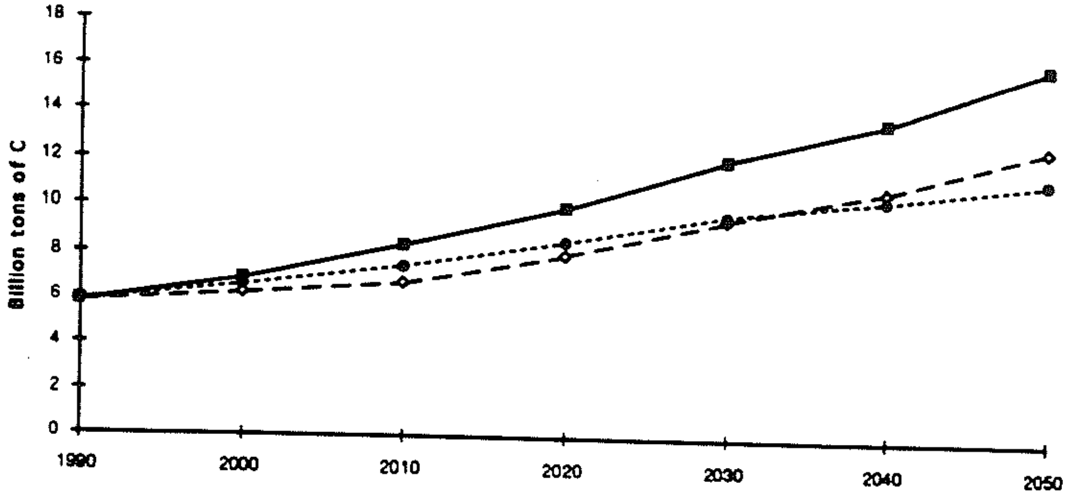
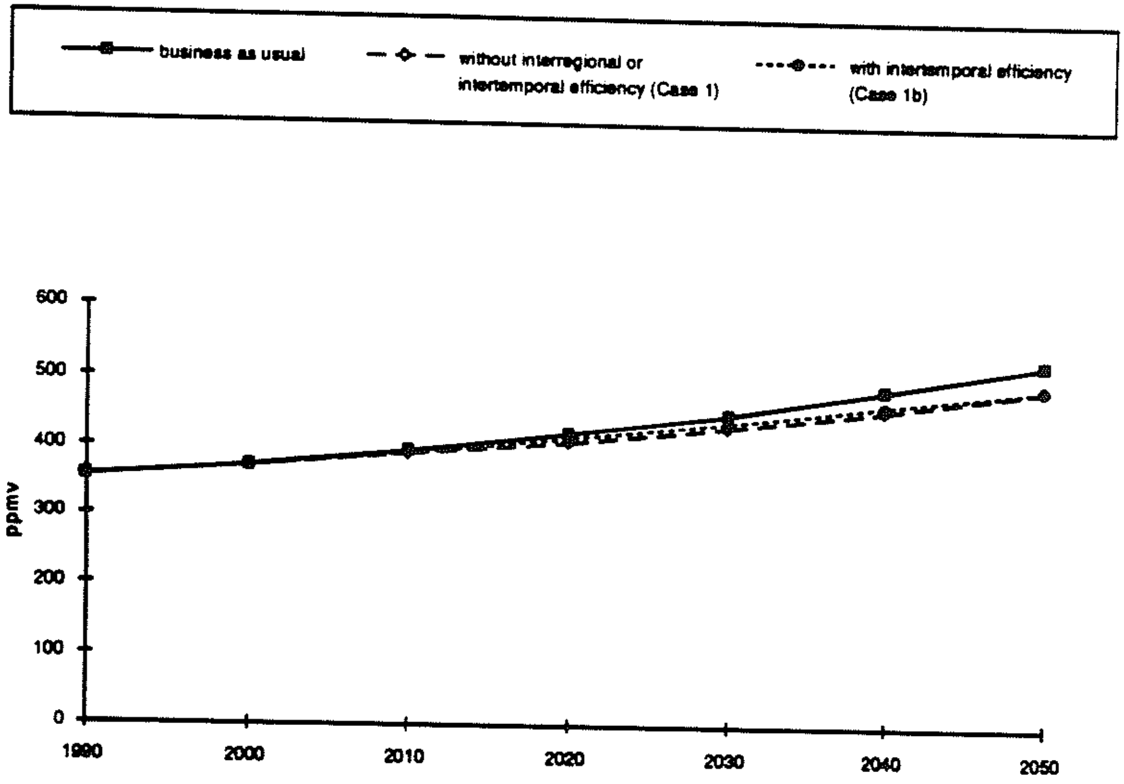


Figure 6. Global Emissions and CO2 Concentrations with and without Intertemporal Efficiency (based on average of model results)



a) Global emissions



b) CO_2 Concentrations

Figure 7. OECD GDP Losses under Alternative Assumptions about Economic Efficiency (based on average of model results)

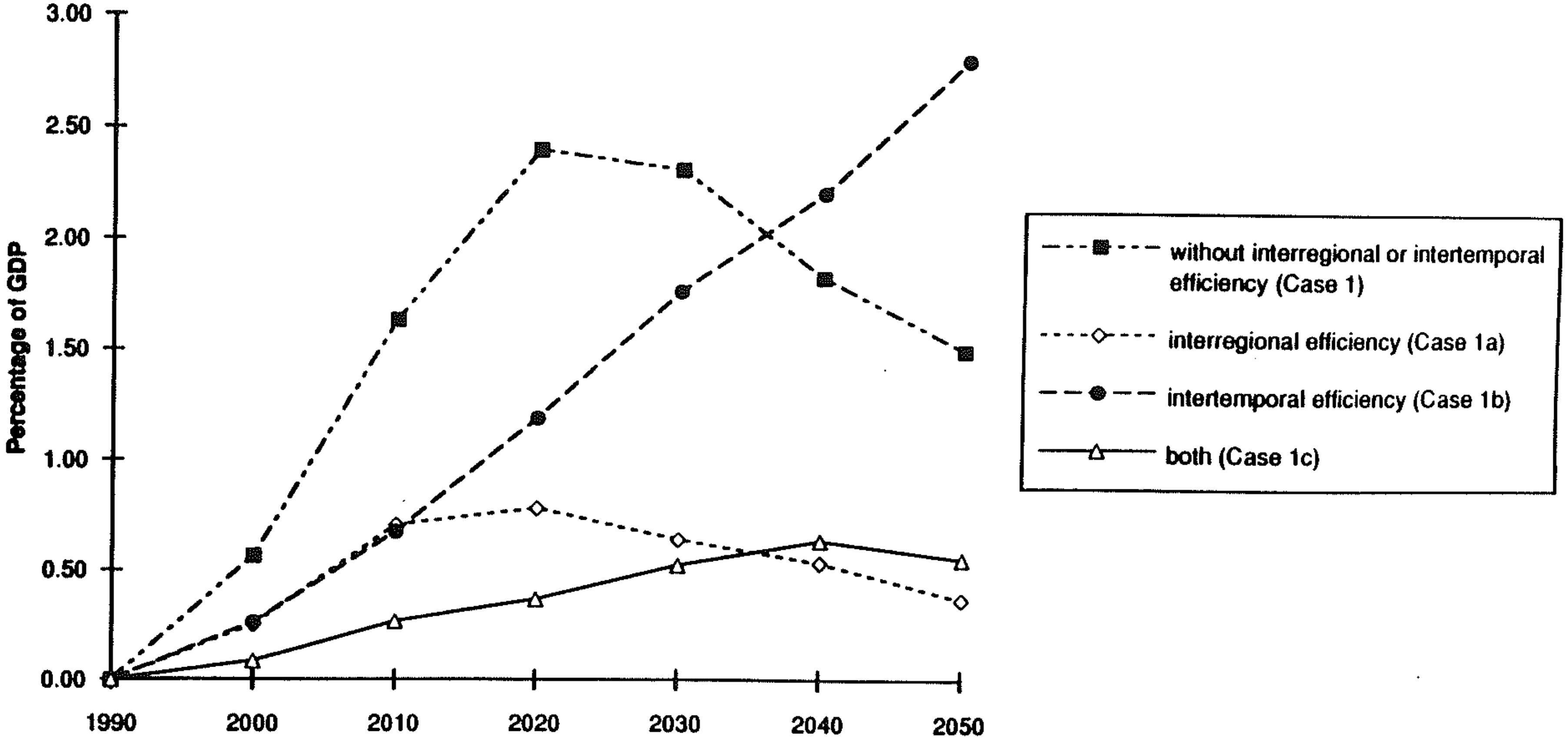
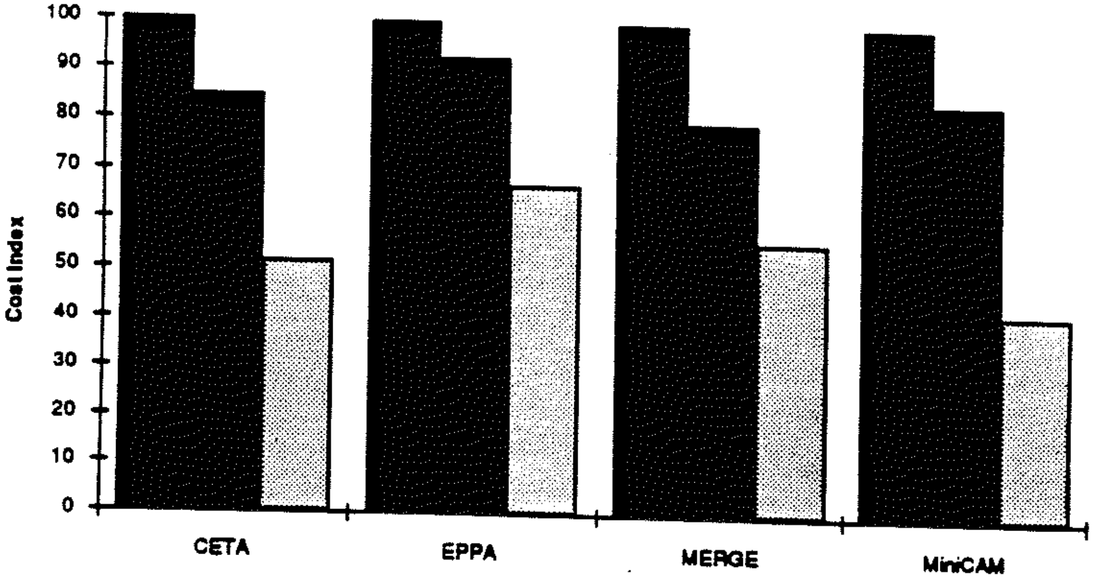
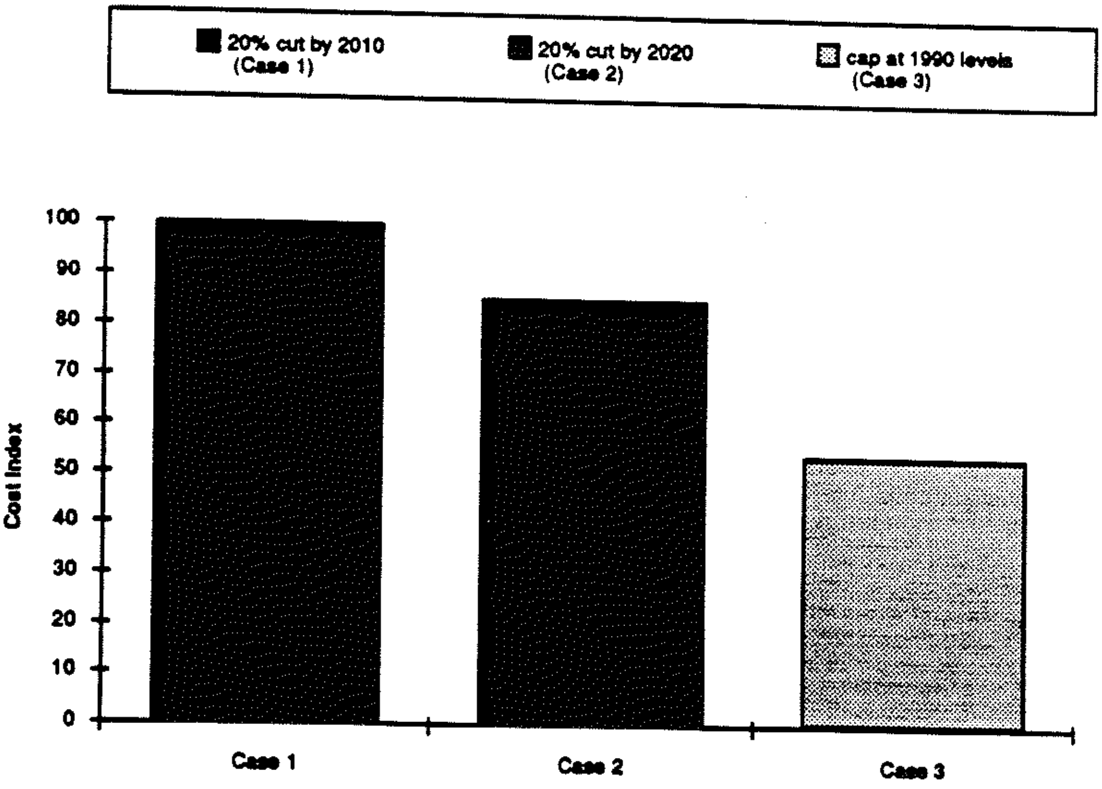


Figure 8. Costs of Alternative Sets of Targets and Timetables



a) Case 1 = 100



b) Average of model results

Figure 9. OECD GDP Losses under Alternative Targets and Timetables
(based on average of model results)