# Integrative Assessment of Mitigation, Impacts, and Adaptation to Climate Change

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(Editors)

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# Introduction

The collective effort reported in this volume presents an assessment of the current state of integrated assessments. Numerous models and less formalized approaches analyze anthropogenic sources of greenhouse gas emissions, their concentrations in the atmosphere, the resulting climate forcing, impacts of the induced climate change on the economy and other human activities, as well as possible mitigation and adaptation strategies. Studies that include all or several of these salient aspects of the climate change problematique are known as integrated assessments. The number of such studies is increasing, highlighting the need for consistent and comprehensive analytic frameworks, model verification, and comparison. The studies are further complicated by the need to incorporate the scientific, economic, technological, and social dimensions of climate change in the integrated assessments. There is a pressing need for comparative analyses of these emerging studies. The Intergovernmental Panel on Climate Change (IPCC), representing the analysts who perform the assessments and the political system which commissions them, together with the International Institute for Applied Systems Analysis (IIASA), organized the first international workshop to focus on the comparative assessment of mitigation of climate change and on its potential impacts and adaptation strategies (1–2 September 1992). One of the key findings of this workshop was the need for integrated assessment. Subsequently, IPCC included integrated assessment in its Working Group III that deals with economic questions and cross-cutting issues. One year after the first workshop IIASA convened a second workshop (13–15 October 1993), specifically to review the current practice of integrated assessments, directions for improvement and further research, and implications for climate change policies. This volume presents the proceedings of the 1993 workshop. The proceedings of the 1992 workshop were also published at IIASA as a collaborative paper (CP-93-2).

Considerable methodological hurdles face the construction of integrated models and assessments. Among the problems are processes occurring on different time and space scales, selection of appropriate discount rates and rates of technological change, representation of behavioral and structural change, as well as tradeoffs between realism and model transparency and tractability. The participants of the workshop agreed to intensify efforts to verify and test models by sensitivity and uncertainty analyses, model intercomparisons based on standard reference runs, reproduction of historical records, and open debate on reasonable values for key variables and coefficients. These efforts will be enhanced by the next Energy Modeling Forum (EMF), this time jointly organized by Stanford University and IIASA, and devoted exclusively to a comparison of integrated assessment frameworks.

Some 100 scientists, representing different disciplines from more than 20 countries, participated in the workshop. The three-day workshop was divided into six sessions covering issues such as the role of science, integrated assessment, impacts and benefits, mitigation and adaptation, intergenerational assessments, and the role of technology. Each session started with three to four invited papers and contributions by invited panel discussants and was followed by general discussion. This volume includes the original papers presented at the workshop. The four parts of these proceedings reflect the written contributions and the discussions of the six workshop sessions. They are preceded by an introductory paper to this volume that summarizes both the proceedings and findings as well as discussions of the workshop.

The workshop was jointly organized by the four editors of this volume who share the responsibility for both the scientific content and the financial support. The editors are listed in alphabetical order because of their joint contributions to the organization of the workshop. Ferenc Toth made the largest contribution toward the production of this volume and thus deserves most of the scientific credit. The workshop was financially supported by the Central Research Institute of Electric Power Industry, the Electric Power Research Institute, the International Institute for Applied Systems Analysis, the National Science Foundation, the United States Department of Energy, and Yale University.

The workshop organizers would like to extend their thanks to the participants and contributors who provided the essential intellectual substance during the sessions and discussions, the authors of papers presented in this collaborative volume, and the institutions that provided financial support to bring such a distinguished group of scientists together for a second time on this important research topic. The organizers are deeply indebted to Ewa Delpos, Eva Hizsnyik, Anka James, Valerie Jones, Lieselotte Roggenland, and Patricia Wagner for their valuable help and assistance in the organization of the workshop and preparation of this volume.

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# Overview

# Practice and Progress in Integrated Assessments of Climate Change: A Review

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## Abstract

An increasing number of models investigate biophysical processes of climate and most relevant processes of the economy in an integrated framework. These models analyze the full cycle of anthropogenic emissions of greenhouse gases, their concentrations in the atmosphere, the resulting climate forcing, and finally the impacts of the induced climatic change on the economy as well as other human activities. For economists and social scientists, the great advantage of this approach is that it provides a comprehensive framework for assessing the possible economic losses due to climate change (damage function) and for estimating the costs to slow or delay climate change (cost function). By creating the same metric for cost and benefit assessments, integrated models are expected to contribute to developing economically efficient climate policies.

This paper is intended to provide an overview of the state-of-the-art integrated socioeconomic-biophysical assessments of climate change as presented at the IIASA workshop in October 1993. The paper seeks to tally the major improvements facilitated by integrated assessments in understanding the global warming problem and the crucial unresolved problems they currently face. Selected issues in economics, technological studies, and political sciences that are pertinent to understanding and managing climate change are also addressed. Reviewing the various studies included in this volume, one might conclude that, as a result of a healthy diversity in practice, integrated assessments show significant progress in structuring the economic issues of climate change and providing the first broad insights into policy options. But, as some of the simple and traditional cases seem to be solved, more complex and difficult contingencies come to the fore. This suggests a long way to go to develop skills that will be required to address the numerous open issues.

# 1. Introduction

Very few problems that seem to require scientifically based policy decisions generate debates with such extreme spread of opinions as can be witnessed in the case of global climate change. Representatives of one extreme emphasize that uncurbed emissions of greenhouse gases (GHGs) would increase the global mean temperature of the Earth within a few decades to an unprecedented level in the history of modern civilization. They fear that this change would entail a series of climate-induced catastrophes. Their recommendation is to reduce GHGs, especially carbon dioxide ($CO_2$) emissions immediately and drastically, largely irrespective of the costs that societies would need to pay in the form of retarded development. Members of the opposite camp emphasize that humanity is likely to adapt to modest and gradual changes in climate without any difficulty. They retain that there is little knowledge and even less evidence about climatic disasters. This group cautions against rushed, overambitious, and therefore costly emissions reductions; they emphasize the importance of preparing markets and technologies for future action as well as scientific research to support them. Prospects for integrating these and many other concerns into a consistent decision analytical framework do not look very promising.

Yet the need for integration is clearly there. Economic analyses related to various aspects of global climate change have received increasing attention over the past few years. The wide range of issues of global warming has solicited a large variety of studies that seek to clarify specific aspects of the problem. A workshop organized by IIASA in September 1992 (Kaya *et al.*, 1993) reviewed the then state-of-the-art and recommended several research directions to improve concepts, methods, and data vital for improving the policy relevance of the results.

Probably the most important recommendation of the 1992 workshop was that assessments of impacts and damages from climate change and estimates of the economic costs of slowing or preventing climate change should be integrated into a single analytical framework. The major objective of the 1993 workshop was to review the practice of these integration efforts and to evaluate their progress with a view to climate policy.

This paper is intended to provide an overview of the state-of-the-art integrated socioeconomic-biophysical assessments of climate change as presented at the IIASA workshop in October 1993 and as documented in this volume. In addition, this overview hopes to provide guidance to the collection of papers that follows by drawing attention to important complementary efforts that might usefully enhance each other and to interesting parallel efforts that seek alternative approaches to unravel the same problem.

Following this short introduction (Section 1) about the background of the workshop, Section 2 presents a précis of the major improvements facilitated by integrated assessments in understanding the global warming problem and the cardinal unresolved problems they currently face. Section 3 pertains to the papers from climate research and economics included in Part 1 of the volume and summarizes recent advances in key study areas contributing to integrated assessments. Section 4 is devoted to the fast expanding family of integrated assessments and observes both common elements and diverse approaches in these efforts based on the collection of papers in Part 2. Deeper analyses of specific problems based on partially integrated frameworks, feasibility studies of normative scenarios, and in-depth investigations of distinctive problems of major regions are necessary given the large number of open issues on both the cost and the damage side. The potential contribution of these studies to integrated assessments is addressed in Section 5 and draws on papers in Part 3 of the book.

The real difficulties of integrated modeling are demonstrated in Section 6 by briefly discussing issues in economics, technological studies, and political sciences that are largely unresolved in their own disciplinary fields (see the three groups of papers in Part 4 of the book) but are gravely needed for the integrated climate-economy research. Finally, Section 7 attempts to summarize the most important achievements and identifies the major missing pieces in integrated climate-economy analyses.

## 2. Overview

Over the past few years, the number of models integrating the biophysical processes of climate and the most relevant processes of the economy has grown exponentially. These models analyze the full cycle of anthropogenic emissions of GHGs, their concentrations in the atmosphere, the resulting climate forcing, and finally the impacts of the induced climatic change on the economy as well as other human activities. For economists and social scientists, the great advantage of this approach is that it provides a comprehensive framework for assessing the possible economic losses due to climate change (damage function) and for estimating the costs to slow or delay climate change (cost function). By creating the same metric for cost and benefit assessments, integrated models are expected to contribute to developing economically efficient climate policies.

Perhaps the most surprising outcome from the review of integrated assessments at this workshop was that they do not produce surprising results. Both damage assessments and cost estimates are roughly in the range where they had been in the case of individual studies. Thus, outcomes of the integrated cost-benefit frameworks justify only modest outlays to delay or slow climate change. There appears to be a reasonable degree of consensus that a smooth, *gradual increase* in the *mean temperature* is likely to leave the *economy* largely unaffected. Problems start as we look behind each component of this statement.

First, *temperature averages* do not matter much, rather it is extremes that count: extremes in time (the frequency of extreme weather events), extremes in space (in sensitive regions small changes might induce drastic impacts), or simply a different variance of temperature (same average but very different distribution). Moreover, our fixation on temperature as the prime indicator may have been often misleading if not even a serious mistake. It is rather plausible to depict scenarios with very little change in temperature, but with a major change in cloudedness, for example, where the final outcome is a drastically different climate. Current models have major difficulties to treat and give appropriate weight to the climate-related extremes in formulating their policy conclusions.

Second, even a slowly increasing number of ambitious efforts to estimate *economic damages* fail to come up with more than 1 to 2 to 4% of GDP. However, we have very little data about non-market, ecosystem impacts, the natural adaptive capacity of these systems, the possibilities to manage them and increase their adaptive capacity, the cost of those management options, and finally the net damage that we should ultimately quantify in monetary terms. Principal improvements in monetary evaluation of ecosystem services will be necessary to improve what is now the missing piece in damage/benefits assessments.

Third, if real impacts arise from the *extreme tails* of the distribution of possible future climates, how do we capture that risk in terms of the cost-benefit framework and how do we recognize them when they will occur in practice. Relatively small fluctuations in climate have caused major disasters in a number of vulnerable regions in the recent past, but would it be justified to include these cases in a climate damage register on a 100% basis when numerous other factors have contributed to engender these vulnerable regions in the first place? Furthermore, how can we model discontinuities and bifurcations in both natural and socioeconomic systems that are involved in the climate-economy interactions. Consolidating these three issues in a decision analytic framework is likely to be the next major challenge for integrating modelers.

Despite the facts that we have a substantial body of analyses on the costs of control for various GHG (mainly energy-related $CO_2$) emissions and that there is a growing number of investigations into the economically quantifiable damages, adding the climate system component to build an integrated framework is no mean task. Our ignorance is vast at every single step in this process as we go from emissions to concentrations to climate forcing to changes in temperature and other climatic attributes over to impact assessments and damage estimates. Moreover, recent results in science that have been presented at the workshop, do not provide much assistance to reduce those uncertainties. On the contrary, they may even add to the uncertainty of integrated models. The new ice core analyses, for example, suggest that climatic variability with periods of rapid change was more the norm than the exception in the Earth's geological history and the relative stability of the past 10,000 years may have been an unusual event in the midst of those fluctuations. At this point, the policy implications are rather ambiguous if we include the possibility of an abrupt climate change in our analytical framework.

One helpful strategy for integrated assessment may be to employ a "critical load" concept. This concept initiated a major breakthrough in managing the acid deposition problem. With a view to the numerous non-linearities in the climate system and their possibly chaotic combined outcome, a similar approach might provide useful insights into our options for climate policy. Integrated assessments can readily analyze the implications of given limits for atmospheric GHG concentrations and produce useful cost estimates and ideas for policy design. Yet, this approach has its problems too. The question is whether in the climate issue a scientific basis can be found for defining thresholds or rates of change which the system should not exceed. The apparent lack of correlation between GHG concentration and temperature over several decades, as well as the inconsistency over the last decade between the new satellite-based global temperature records (which show little or no warming) and traditional surface measurements (which warm a lot) indicate that currently any proposed "critical load" indicator of climate change could easily be challenged.

Reviewing the various studies presented at the workshop and included in this volume, one might conclude that, as a result of a healthy diversity in practice, integrated assessments show significant progress in structuring the economic issues of climate change and providing the first broad insights into policy options. But, as some of the simple and traditional cases seem to be solved, more complex and difficult contingencies come to the fore. This suggests a long way to go to develop skills that will be required to address the numerous open issues listed above.

## 3. Changing Climate and Changing Perceptions

Emergence of modern geography in the 17th century coincided with the establishment of geographical determinism as the mainstream theoretical framework. According to this theory, human development and economic activity are determined by the geographical environment. The first representative of this line of thought was Bernhard Varenius (1622-1650) in the Netherlands. He was followed by the majority of philosophers and geographers in the 18th and 19th century, most notably Montesquieu, Holbach, and to some extent von Humboldt.

An interesting thread of the school of geographical determinism devoted special attention to climate-related factors. Montesquieu maintained that even ethical rules, the type of state and government organization, and legal codes are determined by geographical factors like climate, soil, and the geographical area available to people. He developed this theory to the level where he determined the most suitable religion and state form for each climatic zone. H.T. Buckle followed this line of thought and stated that economic development and the distribution of wealth is exclusively determined by laws of physics and nature. V. Cousin derived the historical role of nations/countries and their relative position in the hierarchy of nations from geographical and geological factors. The general discernment of all these scientists was that the temperate climate in the Northern hemisphere provides the most favorable environmental conditions for human development.

The climax of climate determinism is the ouvre of Elseworth Huntington. Regrettably, his racist thinking and social Darwinism gravely contributed to the reluctance of geographers to revisit the issue of climate and development for decades. Nordhaus (this volume) presents an amusing, but also counseling review of Huntington's analysis as a preamble to his assessment of the economic importance of climate at the end of the 20th century. He finds relatively low level of correlation between climate and contemporary economic activity. Even for economic sectors and specific areas that are perceived to be sensitive to changes in climatic attributes, the climate effects tend to be overwhelmed by other variables. We witnessed the collapse of several major ocean fisheries in the last two decades in the virtual absence of climate change. Similarly, the potential threat of climate-induced changes in the spread of water-born diseases or in habitat abundance of insect vectors of diseases is apparent. Yet health status of populations around the world seems to be primarily determined by the financial and institutional development of public hygiene and medical health care systems. Nonetheless, the question of possible health impacts of climate change remains open and very important for further research.

Turning toward the future, Nordhaus briefly presents DICE, the Dynamic Integrated model of Climate and the Economy that was developed to account for both costs and benefits of GHG mitigation in a comprehensive albeit simple framework. This framework is an extended version of an optimal growth model in which both impacts of possible climate change and resources devoted to prevent it affect the long-term integrated welfare of mankind. Welfare in this model is maximized when marginal costs and marginal benefits of GHG abatement are equal.

One interesting application of the DICE model (see Nordhaus, 1994, chapter 8) and other integrated studies (Kolstad; Peck and Teisberg; Lempert *et al.*; all this volume) are assessments of the policy implications of learning about the climate system, the fate of anthropogenic emissions, and about the extent of potential damage from changing climate. If past learning performance has any evocative value to guide our expectations about the speed and policy relevance of future learning then the historical review by Nierenberg (this volume) provides a mixed set of indications.

Probably the most significant policy-relevant new information over the past decade was the reduction in the assumed residence time of $CO_2$ in the atmosphere from about 1000 years to as short as 50-150 years. This implies that the potential efficiency of short-term carbon mitigation policies is much higher because recent additions to the atmospheric carbon stock play a larger relative role if $CO_2$ in the atmosphere lasts 50 years than if its decay would take 1000 years. Consequently, the pressure for initiating drastic emissions reduction measures in the near term is much smaller because one can afford to wait and learn without committing major irreversible perturbations of the atmospheric system.

It seems that the time will be very much required because learning about many aspects of the biogeochemical cycles and the climate system have been impressive over the past ten years, especially theoretically, but this does not help policy modelers much to reduce uncertainty ranges in their models. Increase in global mean temperature for a $2\times CO_2$ equivalent concentration of GHGs is still in the same interval of 1.5 to 4.5 °C as it was 10-15 years ago. Fitting Global Circulation Model (GCM) results to the historical climate records and explaining the possible role of aerosols is still largely unresolved.

So are the questions about the missing carbon sink (1 to 2 Gt per year), the relative radiative importance of clouds and CFC (believed to be important GHGs before and attributed a very low net warming effect recently).

An exceedingly important and equally perplexing recent advancement in our learning about the climate system originates in paleoclimatology and suggests that the potential of abrupt changes in the global climate system is far from unprecedented. As presented by Schotterer (this volume), recent results from ice core analyses suggest that the global climate system was rather unstable in various geological periods and that major climatic changes occurred in very short periods of a few decades in the complete absence of anthropogenic influence. This raises serious doubts about the predictability (and modelability) of the climate system in the first place. A more important question is how this would affect our strategy for mitigating emissions or preparing ourselves to adapt to perhaps rapid changes. Precaution-oriented might fear a possibly low threshold in atmospheric GHG concentrations and climatic forcing passing of which might activate uncontrollable biogeochemical processes that drove abrupt climate changes in the geological past. Others might take a more fatalistic position and argue that current anthropogenic emissions of GHGs account only for a small perturbation compared to the magnitude of natural forces underlying those abrupt changes.

Whether as a result of gradual or abrupt change, an anthropogenically induced increase in atmospheric carbon concentration would simply imply the restoration of the chemical composition of the atmosphere that characterized earlier warm periods. So summarizes his previous findings Budyko (this volume). He estimates that increasing bioproductivity due to increasing atmospheric $CO_2$ fertilization could make a major contribution to solve the socioeconomic problems associated with feeding a rapidly increasing global population. This is in sharp contrast to most agricultural climate impact assessments that predominately report yield losses and disruptions of agricultural production in many regions as a result of GHG-induced global warming (see, for example, Rosenzweig and Parry, 1994).

A combined influence of anthropogenic factors and natural forces in the region of the Caspian Sea over several decades is nicely documented by Golitsyn (this volume). Large-scale diversions of water for irrigation projects and changes in the regional climate over the sea and in the watershed (e.g., changes in average wind speed over the sea) produced fluctuations in the sea level that are unprecedented elsewhere. Although estimates of the extent of global warming-induced sea level-rise have been repeatedly modified downwards over the past decade (now estimated to be around 30 cm for

$2\times CO_2$ climate), the recent abrupt sea level rise of more than 2 meters in 15 years of the Caspian might offer useful lessons for those who wish to study socioeconomic impacts of abrupt changes in sea level.

In sum, there are both encouraging and depressing messages for integrated modeling from the various studies of the climate system and climate-society interactions. Our knowledge about the climate systems improves, but this does not necessarily entail better understanding or reduced uncertainty ranges in the integrated models. This suggests that currently one important application of integrated assessments is to sort out long-term consequences of short-term strategies. This would help to avoid losses from both overaction and no-action in view of better information 5-10-15 years from now. Climate policies formulated today do not constitute once-for-all commitments. It is possible to modify strategy in view of new information. The crucial question is what is the best "assist policy" to prepare for efficient action on a wide range of plausible new information expected to become available during the next decade or two.

## 4. Integrated Models and Assessments

The term 'integrated modeling' has different connotations even for the various groups that contribute to the scientific analysis of the global warming problem. Meteorologists refer to integrated models when they investigate interactions between atmospheric, terrestrial, and oceanic systems, including possible feed-back mechanisms (e.g., release of methane from melting permafrost regions as a consequence of increasing temperature). Natural scientists allude to the need to integrate vegetation and other ecosystem models with pedological and hydrological models in order to pursue a more realistic assessment of climate-induced changes in natural vegetation systems.

In this paper, and throughout the collection that follows, the terms 'integrated model' and 'integrated assessment' refer to a set of formal models or studies without modeling support that are combined into a consistent framework to address one or more issues in the problem of global climate change. Figure 1 shows one possible arrangement of the key building blocks in such integrated assessments. I will call 'fully integrated assessments' studies that cover the entire cycle, that is, they provide the possibility to determine base-line GHG emission scenarios and to calculate the costs associated with any perturbation (mainly GHG abatement) from that base-line; include an albeit simplified atmospheric and climate component; produce or utilize some kind of biophysical impact assessment; and finally accomplish a monetary

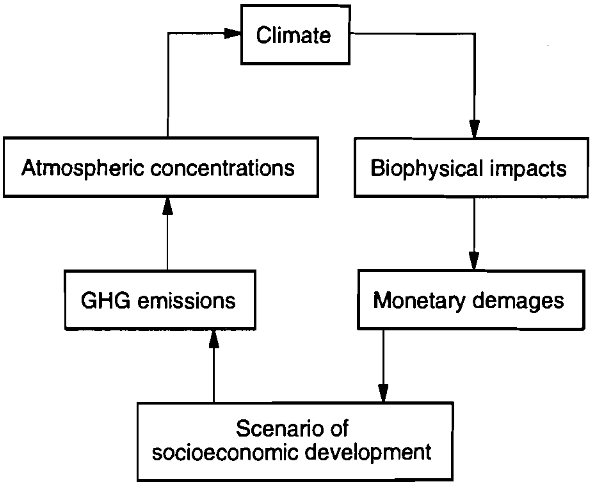


**Figure 1.** Integrated assessments of climate–economy interactions.

assessment of the directly measurable economic and the indirectly imputed non-market damages. Many studies encompass just a few steps in this succession to study more specific issues of the climate-economy interactions; I call them partially integrated assessments/models.

The level of integration varies significantly across different studies. Some models integrate equations describing economic and atmospheric processes into a single system. Other projects rely on various forms of hard and soft linking to transmit data between individual modules.

Another term frequently used in studies of global climate change is 'comprehensiveness'. This term refers to the degree at which models include sources and sinks of all GHGs or, looking beyond the climate issues, models contain other air pollutants that cause other global-scale problems (CFCs), continental-scale problems (acidification), or local air quality deterioration (visibility degradation due to heavy hydrocarbons). While these studies are very important to help manage the complete syndrome rather than just specific problems that are part of it, our major focus here will be on integrated studies of climate-economy relationships as defined above.

Given the immense uncertainties characterizing each step in the integrated assessment framework presented in Figure 1, some modelers approach the problem by making these uncertainties the central issue and formulate models that consider uncertainties in their design. The first two models adopting the probabilistic formulation are ICAM-1, the Integrated Climate

Assessment Model (Dowlatabadi, this volume; Dowlatabadi and Morgan, 1993) and PAGE, a comprehensive model for Policy Analysis of the Greenhouse Effect (Hope *et al.*, this volume).

In the midst of perpetual debates on most issues of the climate change problem, one refreshing exception is the consensus on our ignorance about the biophysical impacts on unmanaged ecosystems and the difficulties of monetizing non-market damages. One possibility to include ecosystemic effects in the damage function is the "multiplier approach" in which aggregated damage assessments from various economic sectors are multiplied by some estimated constant to adjust for assumed damages outside the national accounts. MERGE, a Model for Evaluating Regional and Global Effects of GHG reduction policies (Manne *et al.*, this volume) implements a different approach. Ecological losses are evaluated in terms of willingness-to-pay (WTP) to estimate how high they would need to be in order to reach a break-even level (together with the market-related damages derived from a quadratic damage function) to justify a proposed policy. The WTP-based model of damage assessment is embedded in an integrated framework that includes the Global 2200 model, an extended applied general equilibrium version of Global 2100 (Manne and Richels, 1992) to provide the GHG emission scenarios and abatement cost calculations; a reduced-form carbon cycle model developed by Maier-Reimer and Hasselmann (1987) to compute future $CO_2$ atmospheric concentrations; and the IPCC'90 equations to derive values of radiative forcing, potential temperature, and actual temperature.

Recent concerns about the possibility of abrupt climate change raise the question of possible thresholds in the climate system beyond which anthropogenic forcing might trigger unforeseeable changes. We do not know where those thresholds are but some consider this as additional evidence to undertake immediate drastic actions to reduce GHG emissions. Therefore, it seems to be important to compare the costs of early vs. delayed actions with what would they buy in terms of long-term concentrations and temperature changes with a view to the possibility of abrupt climatic change.

Hammit *et al.* (1992) developed a two-stage decision model to explore the effects of uncertainty about the damages of climate change on how ambitious near-term GHG abatement strategy should be. They analyze two near-term (10 years) abatement policies: a moderate one with moderate emissions reduction involving energy conservation alone and an aggressive strategy involving both energy conservation and switching to non-fossil fuels. Their model also includes the learning element: they assume resolution of uncertainty by the second decision point.

Recently, the authors extended their analysis (Lempert *et al.*, this volume) to include the case of the potential impact of abrupt climate changes on the relative merits of the moderate and aggressive abatement policies. This required changes in the treatment of individual GHGs in their model. The conclusion from the modified model is that although abrupt changes tend to increase the long-term costs of responding to climate change, they do not significantly affect the validity of earlier conclusions drawn from the smooth climate change case that is: the cost difference is insensitive to the selection between moderate vs. aggressive abatement policies in the near-term.

Another critical problem in the climate risk issue and its management is the irreversibility characterizing both anthropogenic emissions of most GHGs and investments to abate those emissions. The irreversibility problem is perplexed by the fact that we have learned a lot over the past two decades and we expect to learn a lot more over the next two about both the biogeophysical and the socioeconomic aspects of climate change. Therefore, it may be worth waiting a little longer for better information before committing substantial irreversible investments in capital assets and infrastructure with long life times. Incidentally, one important piece of information learned relatively recently is related to the irreversibility problem per se. If the $CO_2$ lifetime in the atmosphere is between 50 and 100 years then its emission irreversibility is getting very close to that of committing fixed assets that are important in emissions or abatement.

Lempert *et al.* (this volume) model the learning process by exogenously specified dates of when uncertainties are resolved. Kolstad's model (this volume) includes a dynamic learning process. His study is based on an extended version of the DICE model and covers two basic processes considered irreversible over a reasonable time horizon: emissions (because $CO_2$ remains in the atmosphere for a long period) and mitigation investments (which are practically lost if they turn out to be unnecessary after they had been committed). His results provide interesting insights into how relative time-paths of the learning process and major emission reduction commitments might influence the magnitude of economic losses from over-action vs. inaction. Kolstad's results are consistent with those of Peck and Teisberg (1994) to the extent that even modest learning rates tend to reduce the expected value of perfect information, which is defined as the difference between the net present value of expected consumption less damage if emission control can be completely based on the state of nature and the same figure under uncertainty and non-state-dependent controls. Moreover, rapid learning biases current $CO_2$ control levels downward, but does not eliminate the desirability of some control.

The next major issue in the management of global environmental risks like climate change is how to engage all nations, or at least a critical group contributing the bulk of GHG emissions, in a world-wide emission control scheme. Nations are likely to investigate their own cost-benefit ratios carefully before engaging into expensive commitments, although the ultimate decision will probably be motivated by other factors as well. Some politicians seem to have a ready answer to the "who bears the costs" question by counseling that "the rich (countries) must pay". In a new two-region version of CETA, Peck and Teisberg (this volume) analyze the rich world (OECD) vs. poor world (ROW) dilemma under three GHG control strategies possibly adopted by OECD: emission controls to offset own warming damages, emission controls to balance global damages, and side-payments from OECD to ROW to participate in a globally optimal emissions control policy. In contrast to Nordhaus' original version and to Kolstad (this volume), Peck and Teisberg adopt a cubic damage function in their analysis. While damages associated with a 3 °C global warming amount to 2% of the global/regional output, they increase to 16% for a 6 °C warming. Not surprisingly, there are dramatic differences in carbon tax and carbon emission paths as well as in the welfare implications of various strategies. This stresses the importance of devising global control strategies that can achieve the greatest reductions at the minimum costs.

Most economic studies of climate policy focus on $CO_2$ and give limited, if any, attention to other GHGs. Although $CO_2$ is and continues to be the single most important GHG, contributions of other trace gases to increase the aggregated global warming potential are sufficiently significant to justify their more equitable treatment in climate policy analysis. Moreover, the costs and possibilities of abating different GHGs may widely vary among countries thus it is important to the value of abating one GHG relative to another. Maddison (this volume) presents an optimal control model that calculates a set of shadow prices for the most important GHGs under the constraint of holding the present value of damages constant. His results suggest that it will be worthwhile to include these non-$CO_2$ GHGs in whatever control schemes will actually be designed and implemented in the coming decades.

The very first attempt to integrate pieces of the global climate puzzle into a single framework was IMAGE 1, the Integrated Model to Assess the Greenhouse Effect (Rotmans, 1990). Further development of this model has been interwoven with another European integrated modeling effort, the ESCAPE-MAGICC project. A new stage of this development process has recently been reached by completing IMAGE 2.0 (Alcamo *et al.*, this volume). Interestingly, the current version of IMAGE 2.0 still belongs to the partially integrated category in my classification scheme because there is neither the possibility of calculating the costs of emission control measures nor approaches to assess economically measurable implications of the computed biophysical climate impacts.

This version of IMAGE includes three modules: Energy-Industry, Terrestrial Environment, and Atmosphere-Ocean. The model has global coverage and a time horizon to the year 2100, with a calibration period of 1970 to 1990. Spatial resolution varies across modules from large global geopolitical regions in the socioeconomic model down to a 0.5 degree latitude by 0.5 degree longitude resolution in the vegetation model.

Modeling the socioeconomic system is basically reduced to calculating atmospheric pollutant emissions from two main sources. The first sector is energy consumption in which demand for thermal and electric energy is calculated by combining a projected activity level with specific 'elasticity' functions in industry, transportation, residential sector, commercial sector, and other sectors. The second sector covers industrial production and the generation of process-related industrial emissions (energy-related emissions are treated in the first sector model.) Here again, specific emission parameters are combined with projected future industrial activity levels.

The terrestrial environment module covers both socioeconomic processes that lead to GHG emissions and natural processes that operate between sources and sinks of GHGs. The primary driving force here is the demand for agricultural products. Demand is calculated from dietary, welfare, trade, and technological parameters. The computed demand for agricultural land is then combined with land suitability data in each region to determine changes in global land cover. This in turn serves as an input to the terrestrial carbon model that estimates sources, sinks, and reservoirs of carbon in the terrestrial biosphere and to a land use emissions model that computes land use related emissions of non-$CO_2$ GHGs and other trace gases.

Emissions computed in the socioeconomic and terrestrial environment modules are combined to drive the climate module. Based on the changing composition of the atmosphere, zonal atmospheric temperature and precipitation is calculated for a series of 10 degree latitudinal bands. In order to increase the accuracy of these calculations, an oceanic climate and ocean biochemistry model are also included.

The kind of simulation models to which IMAGE 2.0 also belongs, permits experimentation with a very broad range of scenarios. This might be both a curse and a blessing. On the one hand, it is great to have a tool that permits one to explore implications of non-conventional or extreme future scenarios like the population of the globe becoming vegetarian or the global energy demand fulfilled from biomass energy. Yet, there is little empirical base to re-estimate model parameters for cases that are very different from the original estimation period. Returning all the affected parameters in a consistent way is no mean task, if at all possible.

As mentioned above, the second major line of research building on the original IMAGE 1 model has developed toward generating regional-scale climate scenarios. Recent results with ESCAPE, the Evaluation of Strategies to address Climate change by Adapting to and Preventing Emissions and current work on the new global climate module and the improved regional scenario generating module that will lead to a new integrated model MAGICC (Model for the Assessment of Greenhouse gas Induced Climate Change) is reported by Hulme and Raper (this volume). The scope of the integration in this line of research is limited to generating climate scenarios and does not include either biophysical or economic impact assessments. A great advantage is, however, that the design allows other research groups to incorporate MAGICC into their own integrated assessment frameworks.

The primary regional focus for the ESCAPE-MAGICC models is Europe and the North Atlantic. A similar effort is underway in the most dynamic region of the world economy, the Asia/Pacific region where the bulk of the global population and a significant and fast growing fraction of the global economy is concentrated. The objective of AIM (Asian-Pacific Integrated Model) is to establish base-line demographic, economic and GHG emissions scenarios, to explore the costs of GHG control, and to assess potential impacts of climate change in this important region (Kainuma *et al.*, this volume). The results can also be useful to compare them with results from other models for this very important region.

## 5. Cost and Benefit Studies

Uncertainties are profound in each step of our analysis as we go from emissions to radiative forcing to predicted climate change to impact assessment. Uncertainties tend to accumulate in the integrated assessments producing results where uncertainty ranges around markedly different scenarios have substantial overlap. These results have limited practical value as they are difficult to interpret from a policy perspective.

One response to these difficulties might be that analysts limit the scope of their work to the most essential components of the integrated framework.

Probably the best recent example of this kind of analysis is that of Richels and Edmonds (this volume).

The concept of critical load turned over the acid rain debate and served as a useful tool to guide policies to abate emissions contributing to the acid deposition problem. Similarly, the global warming debate could be considerably simplified if we had a target established for atmospheric concentrations of GHGs beyond which induced climate change would reach intolerable scales. Even in the absence of such well-established targets, analyses of the relationships between hypothetical concentration limits, the amount and temporal path of emissions, and the associated costs of control provide useful information, especially for near-term climate policy. These analyses help identify critical points in the decision process, e.g., "point of no return" in emissions when delayed action cannot keep peak concentrations within a given target, no matter how ambitious it is.

Richels and Edmonds (this volume) combine two global energy models and a reduced form carbon cycle model in their assessment. The energy models are the Edmonds-Reilly-Barns (ERB) partial equilibrium model and the Global 2100 dynamic nonlinear optimization model. Alternative emission paths for achieving any prespecified level of atmospheric concentrations are calculated by the impulse-response function of Maier-Reimer and Hasselmann (1987). Although the level of integration in this case is rather low (emissions, concentrations, costs), the Richels-Edmonds analysis provides interesting details about the costs of various near-term policies and their long-term impacts on concentrations.

A different kind of target is set and its feasibility explored by an integrated assessment study conducted under the auspices of Greenpeace International (Boyle, this volume). Given the fact that any amount of anthropogenic GHG emission interferes with the global biogeochemical cycles, these emissions must be terminated completely if one adopts the precautionary principle strictly. The bulk of the GHG emissions originate from fossil fuel combustion, therefore, the most significant step is to phase out their use and to restructure the global energy system to fossil-free fuels. The Greenpeace study combines the global energy end-use model LEAP (Long-range Energy Alternative Planning system), the ASF (Atmospheric Stabilization Framework) model that includes the Edmonds-Reilly global energy-economy model, and STUGE (Sea-level and Temperature change Under the Greenhouse Effect) climate model for exploring the feasibility of such dramatic restructuring. Although it is not straightforward determining to what extent prices in the FFES analysis follow from exogenous assumptions and circumstantial evidence quoted from efficiency-improvement studies as opposed to explicitly modeled price mechanisms, the results are worth comparing to other those of other GHG abatement cost studies.

Another course to reduce GHG emissions is presented by Bashmakov (this volume). This method has been widely practiced over the past few years in the region of Eastern Europe and the Former Soviet Union (EEFSU). As a result of the painful processes of economic restructuring and transition, economic activity and associated energy use has declined dramatically in the EEFSU region. By relating GDP losses to the decline in GHG emissions in Russia, Bashmakov points out that economic crisis is an extremely expensive "mitigation strategy". With a view to future emissions, he raises the need to credit these drastic involuntary reductions over several years in future global abatement agreements. This coincides with the concept of cumulative emissions discussed by Richels and Edmonds in their target-cost study (see above). The good news is that for the 25-year period between 1991 and 2015 Russia will practically stabilize its emissions at the 1990 level based on the cumulative emissions concept.

The less good news is, however, that it is to a large extent difficult guesswork to determine future scenarios of Russian economic development, energy use, and energy exports. The common practice is still to combine selected assumptions about the deepest point of the economic recession, the time when this will be reached, and the rate of structural change and recovery thereafter. No doubt, it is troublesome to calculate and compare costs of future abatement strategies when even the baseline is difficult to establish. Kononov (this volume) presents a set of such scenarios that provide an interesting supplement to the analysis by Bashmakov.

Next to the EEFSU region, another country of great importance in the global climate issue is China. As a result of nation-wide modest economic reforms and large-scale liberalization in some regions, the country joined the group of fast growing Asian economies. In the period of 1985-92, GDP grew at an annual average rate of 7.6% and total GDP (taken at purchasing power parity) by 1992 was only about 15% below that of Japan. Given the size and the momentum of the Chinese economy, the evolution of its contribution to GHG emissions and of the concern over possible effects of climate change will make a major difference in the global climate policy. The analysis by Xia and Wei (this volume) might also be useful for global modelers to check their assumptions and input parameters about China.

Climate change affects the electric utilities is several ways. First and probably most important, any emissions control policy that might be adopted in the near- or medium-term future will drastically affect the primary fuel input structure. This may raise substantial costs due to the conversion or early retirement of fossil fuel power plants. The second is related to the implications of changing climatic conditions for hydropower (and in the future, solar- and windpower) generating facilities and to the direct physical impact on the electricity supply infrastructure. The third impact comes from the demand side: changing climate is bound to change the level and temporal distribution of electricity demand, especially for space heating and cooling. Nishinomiya and Nishimura (this volume) present an in-depth study of these impacts on the electric utilities in Japan. The analysis provides useful insights but it also draws the attention to the need to step beyond the "dumb engineer" approach when climates of 2050 are superimposed on today's energy delivery technologies and energy use patterns associated with lifestyles of the late 20th century.

# 6. Selected Issues in Integrated Assessments

Integrated assessments of climate change draw on inputs from many scientific disciplines. Integrating (sub)models, analytical tools or simple parameters with such a diversity of origins is a challenging job. Difficulties of integration increase when modelers need to adopt concepts or methods that are insufficiently understood or fiercely debated within their own disciplines. Three such issues are addressed below from economics, technological studies, and political science.

## 6.1. Discounting

The effective discount rate is one of the most sensitive parameters in integrated climate-economy assessments. The appropriate technique and the choice of the "correct" discount rate is the subject of a major debate. The central issue is whether the special characteristics of the global warming problem like the very long time horizons, the possibility of irreversible changes, the threat of potential climate catastrophes and others would justify an exceptional treatment among the many issues on the current public policy agenda. Setting the discount rate to ethically pleasing low levels would not only be economically ungrounded, but it would also make the cost and benefit calculations related to the various abatement and adaptation strategies incompatible and thus incomparable with a long list of other environmental and social policy issues that also demand immediate attention and action.

More than a decade ago, a study by Resources for the Future produced a standard setting study on the discounting issue (Lind, 1982). These results have been subsequently revised in light of new theoretical research and empirical evidence. Lind (this volume) revisits the discounting problem in the context of global warming. This contribution marks a turning point in the discounting debate as he seems to abandon the consumption equivalent technique for both conceptual and practical reasons.

The discounting problem is at the heart of any intertemporal decisions. Consequently, it also plays a central role in models of economic growth. Alan Manne (this volume) points out that setting an arbitrary discount rate without destructing the consistency of the overall modeling framework would imply unrealistically high investment rates until the accelerated capital accumulation would drive down the marginal productivity of capital to a level consistent with the plugged-in discount rate. This implies that the lower discount rate would not necessarily result in lower carbon emissions, but may produce other undesirable environmental impacts.

One important assumption behind Manne's simple model is a single immortal agent who controls all decisions about production and consumption, as well as savings and investments. Eternity is, of course, an unrealistic assumption for an individual, but it provides a meaningful representation of long-lived organizations. In contrast, Schelling (this volume) presents arguments of why the concept of time preference is irrelevant in the context of such long-term issues like global warming. His reasoning is based on the concerns of a benevolent individual and may not necessarily coincide with the assignments of a guardian of long-term public interest like, for example, a trust fund manager.

With a view to the importance of the discounting problem in integrated cost-benefit assessments of climate change, it would be useful to know to what extent are the sometimes excessively different optimal policy outcomes due to differences in concepts, techniques, and effective rates of discounting adopted in individual studies. The present author (this volume) has made the first attempt at such a comparison covering some of the best known and most often cited models. The most important conclusion is that these models differ in so many aspects that it will take a more systematic, in-depth study to isolate the relative contribution of the discount rate to the differences in model outcomes.

## 6.2. Technological change

While the discounting debate is largely dominated by the conflict between ethically motivated and economic rationality based arguments, adequate treatment of technological change and development in integrated climate-economy models is hampered by difficulties in the modeling technique. Bottom-up engineering economic studies present a rich variety of cost-effective, low-emission, environmentally benign technologies in the present and for future. This abundance is then reduced in most integrated studies to a few parameters like the AEEI, the rate of autonomous energy efficiency improvement or the dates of availability and the costs of some carbon-free back-stop technologies. Very little is implemented about the development, introduction, deployment, and market penetration of technologies at such time scales in these models. The treatment of technologies that might play a role in adapting to climate change leaves even more to be desired.

The importance of the appropriate portrayal of technological development in integrated assessments is probably greater than that of discounting. In addition to the atmospheric stock of GHGs and the emission potential embodied in the capital stock, timely development and large-scale deployment of carbon-free technologies is the third most important inertia in the climate-economy system. We have witnessed revolutionary technological progress transferring a number of manufacturing and service sectors over the past few decades. Ausubel (this volume) presents a collection of technological development trajectories that should make integrated modelers think seriously about the limitations of their models as far as technological potentials are concerned. Here again, it seems to be valid that it is easy to tell the truth but it is difficult to make people believe it.

Grubb (this volume) reviews the technological development of the energy sector in response to external forcing in the past and develops a model that incorporates lessons from this review. Specifically, he demonstrates that capturing induced technological development in optimal control models of global warming might significantly change the optimal emission trajectories and the associated costs. An important policy conclusion is that if energy markets function properly and technological development is possible to induce by market forces then giving the markets an initial sign about the possible carbon constraint might be the best and least expensive strategy of controlling emissions.

The importance of the market signal is reconfirmed by the results from a simple model developed by Hourcade and Chapuis (this volume). The authors use this model to address a series of problems important for policy formulation: the possibility of climatic catastrophes, the difference between the results from a cost/benefit and a minimum surprise approach, and the issue of a short-term no-regret policy. Their most interesting results indicate how suitable innovation policies might reduce the relative price of carbon abatement technologies substantially over the long term.

It is equally important to make clear distinction between substitution with a given technology and technological change. Technologies come in clusters often focused around one complex product very high in the commodity hierarchy. These clusters drive processes of transformation and cannot be captured by simply assuming rates of efficiency improvements of 2% here and 1.5% there. The problem is the difficulty of incorporating them into our economic models. Watanabe (this volume) develops a strategy deducted from a comprehensive R&D program that explicitly acknowledges this clustering effect.

### 6.3. Joint implementation

In the late 1980s, a great deal of enthusiasm about global environmental issues was observed in several more developed countries (MDCs). This partly originated in response to the first alarming reports on possible consequences of climate change (20-30 m sea-level rise, melting of the ice sheets, and other climate catastrophes) and to the call for sustainable development. Some countries announced plans to drastically reduce GHG emissions after they had already decided to phase out nuclear energy and after they had been left with limited additional hydropower capacity. Once the costs of even modest emissions reductions and the infeasibility of more ambitious ones were recognized, enthusiasm turned toward abatement potentials in the less developed countries (LDCs). Given the global character of GHG-induced climate change, it does not really matter in which region of the world emissions are reduced. Moreover, the costs to reduce emissions are perceived to be substantially lower in LDCs than in MDCs.

It follows from the above that the pathway has been well prepared for the argument drafted in the UN Framework Convention of Climate Change (FCCC) that advocates cost-effective mitigation measures and promotes joint implementation as one possible way to achieve it. Yet the idea is plagued with abundant politically motivated reservation. The economics are not fully clear either. Aaheim (this volume) addresses the most important economic concerns in joint implementation. The issues include the possibility of diverging preferences between the investing and receiving countries, the changing terms of trade as a result of resource transfer under joint implementation, the impact on long-term prospects of economic growth, and the uncertain prospects concerning the opportunities and costs of future emissions reductions in LDCs a few decades later when they might also be committed to control their own emissions.

Aaheim's analysis is usefully supplemented by Parikh (this volume) who lists several issues of joint implementation that might be ambiguous from an LDC perspective. The greatest danger according to Parikh (and also addressed by Aaheim) is that MDCs harvest the cheapest abatement options in the short term leaving the more expensive ones for the host LDCs when they will also need to reduce emissions. These concerns, however, are based on a static cost function that ignores technological development. Investigations to identify low-cost efficiency improvement opportunities keep finding additional openings even after several rounds of implementation. Similarly, low-cost GHG abatement opportunities will become available in LDCs over time and this is likely to keep marginal costs low.

Nonetheless, cost differences between MDCs and LDCs exist as it is apparent from UNEP's national GHG abatement costing study (Halsnaes *et al.*, this volume). This indicates the possibility of efficiency gains and availability of potential savings from international cooperation in GHG control. However, the study also demonstrates a major problem. These cost curves are based on reductions relative to a base line and establishing the base line in most LDCs is at least as difficult as in the economies in transition (ETs). Moreover, cost calculations of this sort are subject to easy manipulation: the cheapest abatement strategy is to set an unrealistically high baseline. It is very difficult to verify even current GHG emissions inventories for LDCs and it is practically impossible to validate future emission scenarios.

Tradable emission permits have been proposed by several experts. Several modeling studies have included the permit trade market in their energy-economy models to assess the potential trading volume and expected prices of these markets. It is generally agreed that these markets will take time to pick up momentum in practice. However, joint implementation seems to create additional problems without solving any of the difficulties potentially restricting the permit market.

## 7. Summary and Conclusions

An often-quoted spoof of the roots of our climate policy dilemma was first proposed by *The Economist* (1989):

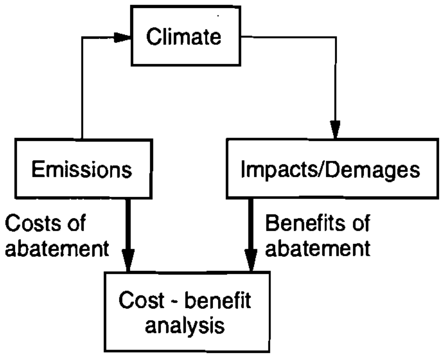


**Figure 2.** Major components of integrated cost–benefit assessments.

> How full is a bucket of indeterminate size, with unknown capacity and a questionable number of leaks, that is being refilled at an unknown rate that you cannot easily see?

At the end of our tour across integrated assessments of climate-economy interactions we realize that this enigmatic bucket is only part of the problem. Even if we had a reliable deterministic model to portray it, this would not warrant apparent consensus on how to optimally control it. This is because uncertainties plague the costs and implementation possibilities of changing the various inflows in the bucket on the one hand, and because little is know about the effects of changing water level in the bucket on the other.

To make this discussion explicit, let us consider a simplified version of Figure 1 featuring the most important components of integrated cost-benefit assessments (Figure 2). Anthropogenic emissions of GHGs induce changes in global and regional climates which in turn have both ecological and economic repercussions, part of which can be alleviated by adaptation, and part that might be beneficial. The economically efficient policy would be based on balancing the marginal net damages (benefits) with the marginal costs of controlling emissions. Let us briefly consider some of the major difficulties associated with each component.

## 7.1. Emissions and the costs of control

An age-old problem in efforts to project future emission paths of GHGs and the costs of control is associated with the single most important GHG, $CO_2$. There is an apparent gap between top-down macroeconomic-energy models and bottom-up microeconomic-engineering models in their cost estimates of carbon emissions control. An emerging understanding is that analytical approaches and modeling techniques applied by both bottom-up and top-down studies contain shortcomings that follow from their necessarily idealistic representation of reality. The gap can be substantially reduced by accounting for the modeling limitations and the reality is likely to be found somewhere in between. However, it is interesting to observe that in the context of the broader climate policy debate, those preoccupied with the precautionary principle advocate bottom-up models and emphasize cheap or even negative costs of abatement. In contrast, those who stress scientific uncertainties about the anthropogenic influence on climate and consider adaptation to possible changes both feasible and financially affordable, they endorse top-down models and warn about the possible high costs of emissions control.

A desirable and plausible extension of top-down models is to include more energy technology details and technology dynamics to support both base line projections and costs of control calculations. Extensions of the bottom-up models in any direction seem to be more problematic. For example, several macroeconomic models demonstrate that recycling tax revenues may half the actual costs of abatement. Another flaw in some energy models is related to secondary market responses which are also difficult to overcome in the bottom-up studies. Supply-side responses are not always appropriately covered especially in models without a full-fledged resource-energy-economy representation. Specifically, a carbon or energy tax leads to reduced demand only if the base price of energy does not change. However, it is likely to drop and this may at least partially counterbalance the tax effect.

While macroeconomic models tend to overestimate costs of GHG control to the extent that they do not account for market imperfections, bottom-up models often underestimate these costs by not including information, transaction, and other costs. The difficulties of producing consistent cost estimates is illustrated by the treatment of new building standards in Denmark in the UNEP costing study. Here, new standards for building insulation and resulting energy savings are included in the cost curve as negative cost (savings) because one cannot build a house otherwise. But this means that energy savings are accounted for but the higher costs of construction are not. This is inconsistent and clearly underestimates costs. A possible alternative would be to include the energy savings in the base case (as it is going to happen anyway) which would push the cost-curve upwards and reduce the size of the free lunch. International comparability of emission reduction cost curves is even more difficult due to the major differences in assumptions about possible efficiency improvements and how much of these are included already in the base line.

## 7.2. Climate

Moving over to the climate box, one major deficiency here is the "GMT problem", that is the primary focus on changes in global mean temperature. There is increasing evidence from the body of integrated assessments presented here that meaningful impact and damage assessments would require regional- and local-scale seasonal and extremes distributions of an array of climate attributes. Global mean temperature may be misleading even as a first-order proxy. Consider the case of China: some studies project a 10% increase in agricultural output based on temperature-based computations. However, the main factor that will affect Chinese agriculture is water rather than temperature. Chinese impact assessment forecast a reduced agricultural production potential by at least 5%. This also indicates the importance of scale to the analysis: simple broad-scale assumptions about how far north the productive zones can be extended in China, versus more detailed assumptions about changing evaporation potentials and precipitation levels at a regional scale.

The list of research tasks to obtain vital information for integrated assessments is rather long. Perhaps the most often mentioned and most needed data are the carbon cycle and the missing carbon problem. This is the main source of uncertainty in the relationship between emissions and concentrations. Model outcomes differ depending on these assumptions, but the basic story is the same: 600-800 ppm in the year 2100 for the IPCC central case emissions. Atmospheric uncertainties are sometimes coupled with the lack of driving scenarios. Practically no reliable long-term sulfate and other aerosol emissions scenarios exist. A study on the impact of aerosols related to coal combustion in China produced a substantial negative forcing on the order of 8 $Wm^{-2}$.

## 7.3. Impacts and damages

Looking at the damage side next, there are two major unknowns, as is apparent from the review of integrated assessments. In MDCs, impacts and losses are mainly related to the use of leisure time, to environmental goods and services, and the value of ecosystems. In LDCs, a substantial fraction of population is employed in climate-sensitive sectors. Knowledge about these impact domains is virtually zero. What we know is that climate impacts will be manifested in the midst of other social, economic, and environmental changes that may alleviate or aggravate the composite outcome. In the world food study by Rosenzweig and Parry (1994), for example, the difference between the low and medium population projections makes almost as big a difference as climate change itself with respect to world food supply, hunger, etc.

## 7.4. Integrated models and assessments

If the building blocks are so shabby, is it worthwhile to build integrated models at all? The answer is clearly yes, despite the present weaknesses of the models. The reason is that modeling forces us to reveal our assumptions and changing those assumptions shows how important they are with respect to the outcome. The clear danger in integrated assessments is that the more detailed and the more specific they get, the more unreliable the modeling results will be. The uncertainty should be given bigger weight in determining the level of detail in the model and how one structures the model. Moreover, uncertainty analysis in large-scale modeling is getting increasingly difficult due to the modular structures and the diversity of linkages. Uncertainty indicators are likely to be possible for the overall uncertainty of aggregate indicators and their temporal paths computed by the linked models.

A related debate concerns the appropriate level of aggregation vs. disaggregation in integrated models and their (sub)modules. The trend seems to be moving toward greater and greater disaggregation, assuming that it is always better. At least the economist involved in integrated assessments should remind others about the performance of small econometric models which are often superior.

At the current stage of the learning curve, the best strategy for integrated modelers is to maintain and extend the healthy diversity of modeling approaches. Hybrid models may ease the aggregation dilemma by adopting regionally detailed models to bring in region-specific information for areas where they are important (forests, land use, etc), but maintain the ability to run at a fairly high level of aggregation. A similar encouragement concerns the differences between simulation and optimization models. They simply provide different kinds of information. Simulation models are typically richer in detail and more flexible in simplifying assumptions. Optimization models are more explicit and are therefore more useful in identifying the trade-offs between various policy options. However, simplification is often motivated by the constraints of current optimization tools and techniques.

My review of current integrated assessments indicates the emerging need for a systematic and critical appraisal. An important component of such a venture would be model verification. At least three approaches should be taken. The first is to check against historical records. Some models do this over a past period of 20-30 years while their projections tend to reach out 50–200 years into the future. Would the reproduction of longer historical periods be a meaningful criterion for model evaluation? If yes, why is it not done? Clearly, the past is not always a relevant guide to future development tracks and in some cases it is very difficult to reconstruct (e.g., land use and land cover transformation over the last 100 years globally). Some components of the model can be easily tested, others are impossible to do meaningfully (e.g., 4 of our 5 current energy systems have not been around 50-100 years ago). The second aspect of verification concerns the adoption of models and codes from others. This should be done for conceptual verification of endogenous and exogenous assumptions: are they compatible (what are theoretical assumptions underlying the model structure); it also involves assumptions about exogenous model parameters; and finally affects computer codes if applicable. The third component of verification is related to model intercomparisons. They might be informative but limited because most models end up within a reasonable uncertainty band. Here a better organized basis for more systematic model comparison studies is needed.

## 7.5. Policy analysis

The policy messages that can be derived from current integrated assessments seem to converge toward a common understanding - consensus would probably be too strong a word here. This is related to the stringency and urgency of abatement actions. The present review portrayed independent modeling studies that investigate the impacts of a ten-year delay in action and come roughly to the same conclusion: it may not be optimal but the costs of delay are relatively modest. The only exception is the case when action today would lead to avoiding a catastrophic climate change and ten years later would be too late. The question is how to formulate this risk-benefit case in a meaningful, quantitative way?

A related concern is the cost of control. An often heard anxiety is that the longer we wait the more expensive will be the abatement. Independent modeling results show that this is not the case and that the cost difference issue is not the important part anyway. Rather, the crucial question is the resolution of uncertainties. The Lempert *et al.* study, for example, explicitly points out that the cost difference between the ambitious and less ambitious abatement policies will not change much if we learn later that the climate sensitivity is higher (say 4°C rather than 2.5° C).

These results seem to be robust even if we consider the possibility of abrupt climate change. Here, the implicit assumption is that the conditional probability of more rapid climate change increases. That is, we face a higher conditional probability of a catastrophic climate change beyond an unknown threshold. Yet, this does not seem to affect the choice of near-term policies at the global level. However, we need to consider the local and regional climate change as well. Here it is really important to assess impacts. Historical case studies may be a useful starting point: the case of the Caspian Sea level presented by Golitsyn (this volume), or Lake Victoria where a 2-meter lake level change occurred in a two-year period, or the classic example of the Sahel region where abrupt change in precipitation on the order of 30–40% occurred during the 1960s and the region belongs to a much drier regime now. Social and economic impacts of these abrupt local changes are more tangible and more significant than those derived from slow and gradual climate change scenarios.

Perhaps the most common misunderstanding in the "delay or not delay action" debate stems from the false interpretation of the underlying models. Delaying action by ten years in intertemporal energy economy models does not mean business-as-usual continued for ten years. Non-myopic models will anticipate the imposition of a carbon constraint in the future and start adding new technologies that are necessary for an optimal preparation for the carbon constraint to be imposed. Therefore, it is important to distinguish between instantaneous adaptation to the carbon constraint today and planning for a possibly fast adjustment in 10, 20, or 30 years.

A more general aspect of the same misunderstanding is that results of integrated assessments, especially those looking for an efficient control path in an optimization framework, are interpreted as projections of future paths for 50-200 years. This is simply not correct. The decision problem is about the action today and not about action over the next 100 years. However, a practical concern should also be addressed more thoroughly in the context of this debate. Namely, industrial development and technology deployment will not wait. Large quantities of industrial capacities and infrastructure will be deployed in the LDCs and in the ETs where deep structural changes over the next decade fashion energy-economy relationships for the long term.

Despite the numerous open issues in both the contributing scientific disciplines and in the techniques of synthesis, integrated assessments provide useful insights in the complex issue of global climate change. Considering the impressive development in a short period and the large number of current efforts underway, one might expect that the emerging results will be more relevant and more reliable for policy makers involved in various national and international processes of managing the climate change problem.

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# Part 1
# The Science and Economics of Climate Change

# The Ghosts of Climates Past and the Specters of Climates Future

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## Abstract

This paper analyzes the view of historians about the role of climate in economic development and the relationship between climate and economic growth today. It emphasizes alternative views about adaptation as the key to projecting the impact of future climate changes on human societies.

## 1. Introduction

Those concerned with promoting economic growth and development have a long agenda of concerns including inadequate public and private capital, poor training and education, or counterproductive attitudes, ideologies, and practices. To this already heavy burden, it is feared that we are adding another list of potential problems in the form of harming our natural environment through a multitude of interventions – injecting into the atmosphere trace gases like the greenhouse gases or ozone-depleting chemicals, engineering massive land-use changes such as deforestation, depleting multitudes of species in their natural habitats even as we create transgenic ones in the laboratory, and accumulating sufficient nuclear weapons to destroy human civilizations. As natural or social scientists, we need to understand the human sources of these global changes, the potential damage they cause to natural and economic systems, and the most efficient ways of alleviating or removing the dangers. Just as towns in times past decided on the management of their grazing or water resources, so must we today and in the future learn to use wisely and protect economically our common geophysical and biological resources. This task of understanding and controlling interventions on a global scale can be called managing the global commons.

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The issue I address in this contribution is the threat of greenhouse warming. Many scientific bodies, along with a growing chorus of environmental groups and governments, are calling for severe curbs on the emissions of greenhouse gases. In response, governments have recently approved a framework treaty on climate change to monitor trends and national efforts, and this treaty formed the centerpiece of the Earth Summit held in Rio in June 1992.[1]

Natural scientists have pondered the question of greenhouse warming for a century. Only recently have economists began to tackle the issue, studying the impacts of climate change, the costs of slowing climate change, and alternative approaches for implementing policies. Moreover, most of the studies of the impacts of climate change as well as the potential approaches to slowing climate change have focussed on the high-income countries, especially the United States and Europe. The developing countries have been the subject of only a minuscule part of the research effort on global warming even though many scientists fear that the major impacts would arise in poorer countries.

The purpose of this contribution is to place the issue of climate change in the context of the debates on economic development. Given the meager data on which to base any economic analysis, the approach is at this stage impressionistic. I begin with a review of views about the role of climate in economic and social development from an earlier age. I then present a nontechnical survey of current knowledge about greenhouse warming. The final sections then discuss current knowledge about the impact of global warming on economic activity.

## 2. The Ghosts of Climates Past

From the age of Aristotle until early in this century, most philosophers and scientists reflecting on the progress of nations assumed that climate was among the chief determinants of the differences among nations. This approach was summarized by the controversial Yale geographer, Ellsworth Huntington (1915, p. 411), who argued:

> The climate of many countries seems to be one of the great reasons why idleness, dishonesty, immorality, stupidity, and weakness of will prevail.

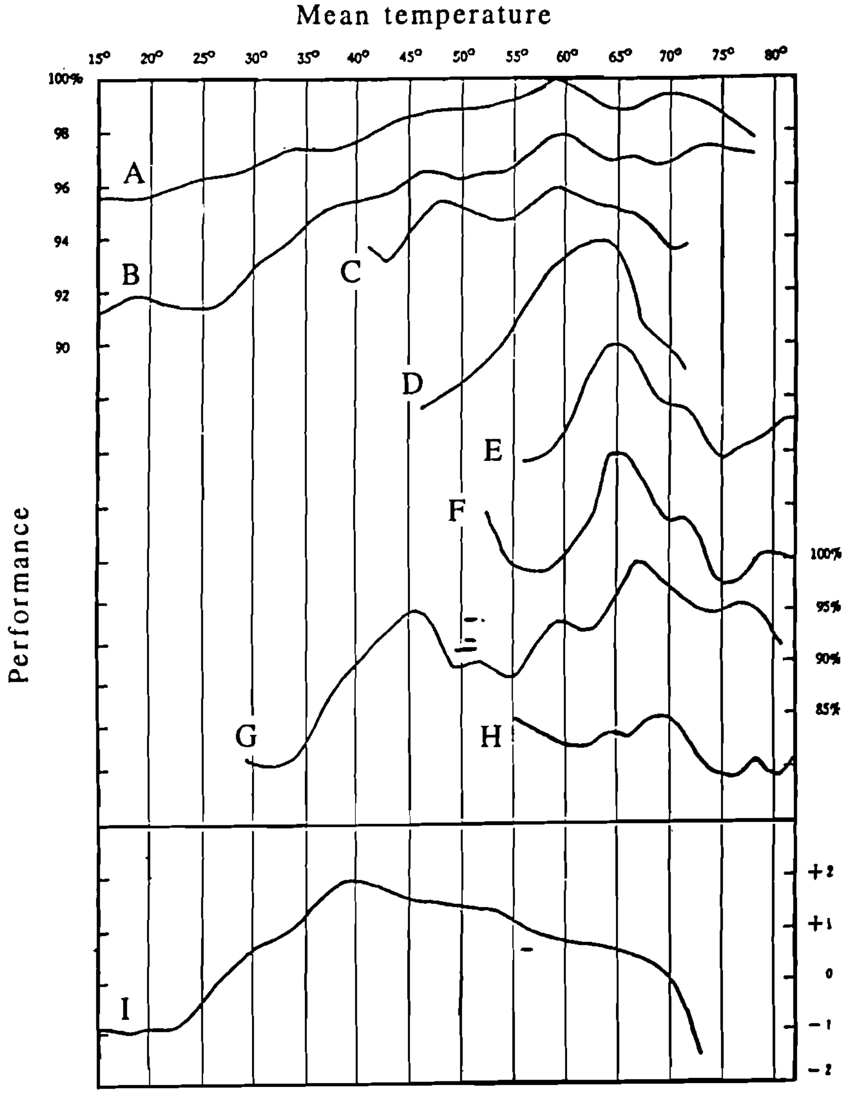
[1] Formally known as the United Nations Conference on Environment and Development (UNCED), the Earth Summit was the culmination of an effort to reach international agreements on climate, forest, biodiversity and biotechnology, as well as to develop principles for environmentally sound economic development.

Sometime around the middle of this century, climate virtually disappeared from the economic-development literature – or, more accurately, it was eclipsed by other factors, such as investment, trade policies, education, and other "modern" factors. In the last few years, however, climate has reemerged as a new concern – as the centerpiece of international environmental issues in the form of the threat of global warming. Whereas in an earlier era, geographers analyzed the influence of "temperature, humidity, wind movements, storminess, variability, and sunlight" on health and economic activity (Huntington, 1915, p. 6.), today geographers and environmentalists worry about the impacts of droughts, sea-level rise, species depletion, ecosystem health and diversity, and forest migration.

Many writers of earlier periods pointed to the obvious fact that climate had economic impacts on human civilizations, but the most influential scholar of the modern era was Ellsworth Huntington. His studies ranged widely, but the central hypothesis, *the climatic hypothesis of civilization*, held that climate ranks "as one of the three great factors in determining the conditions of civilization" (Huntington, 1915, p. 385). His studies were based on international comparisons, on analyses of the rise and fall of civilizations, and on a detailed examination of data relating individual achievement to weather conditions.

Huntington's approach is shown in Figure 1, which is reproduced from the original (Huntington, 1915, p. 125). This shows the results of numerous tests and measurements of the effect of outside temperature on physical and mental performance from 1905 to 1913. The top eight curves (A through H) show variations in wages for operatives, where wages reflect physical productivity as the operatives were paid on a piece-rate basis. The bottom curve shows performance on tests in mathematics and English by 1560 students at the US military academies. From these data, Huntington concludes that maximum productivity for physical effort occurs at a temperature between 59°F and 65°F, while "people do their best mental work when the (outside) temperature ranges from freezing to about 50 ..." (Huntington, 1915, p. 128).

Many other findings spring from Huntington's imaginative interpretation of his and others' data. One entertaining finding concerned the role of sunlight. At that time, an army surgeon, C.W. Woodruff, wrote a tract, *The Effect of Tropical Light on White Men*, in which Woodruff speculated that the backwardness of tropical countries is due to excessive sunlight. Woodruff's theory held that sunlight at the blue end of the spectrum would fall upon the human body and overstimulate cell growth – like a fruit exposed to too much ripening. Huntington examined data on factory operatives and found




A. 800 Men in Two Connecticut Factories, 1910-13.
B. 196 Girls in One Connecticut Factory, 1911-13.
C. One Man (P) in Denmark, June-December, 1906.
D. One Man (L) in Denmark, June-December, 1906.
E. 380 Cigar-makers in Factory B at Tampa, Fla., 1913.
F. 400 Cigar-makers in Factory A at Tampa, Fla., 1913.
G. 3 Children Typewriting in New York, 1905-6.
H. 880 Cigar-makers in Factory B at Tampa, Fla., 1912.
I. 1560 Students in Mathematics and English at West Point and Annapolis, 1909-1912.

NOTE. All the curves except G and I are drawn on the same scale. The maximum in every case is reckoned as 100.

**Figure 1.** Weather and economic activity: Performance and weather. Source: Huntington, 1915, p. 124.

no or at best only slight effects of light. Huntington was able to uncover other patterns, however (Huntington, 1915, p. 143).

> Taking the year as a whole, uniformity of temperature causes low energy; a slight rise is beneficial, but a further rise is of no particular value; the beginning of a fall of temperature is harmful, but when the fall becomes a little larger it is much more stimulating than a rise; when it becomes extreme, however, its beneficial qualities begin to decline.

Having reviewed these results, Huntington turns to his climatic hypothesis of civilization. Three important conclusions emerge here and in his other works. The first hypothesis is a cyclical view that attributes to climate change a key role in the rise of important civilizations, using Greece as a principal example. I quote the entire summary to give a flavor for the reasoning (Huntington, 1915, p. 27f).

> To sum up the whole hypothesis of the relation of climate to civilization, here are the factors as I see them at present. Most parts of the world are so well populated that any adverse economic change tends to cause distress, disease, and a high death rate; migration ensues among the more energetic and adventurous people. Perhaps the commonest cause of economic distress is variations in weather or climate which lead to bad crops or to dearth of grass and water for animals. Such economic distress almost inevitably leads to political disturbances and this again is a potent cause of migrations. The people who migrate perforce expose themselves to hardships and their numbers diminish until only a selected group of unusually high quality remains. Such people, either as warlike invaders or in small bands, enter a new country. They may find it well populated and merely impose themselves as a new ruling class, as seems to have happened several times in India, or they may find it depleted of people as in Attica. When the period of climatic stress is ended and the climate improves, the dominant newcomers not only possess an unusually strong inheritance, but are stimulated by unusually good economic conditions and by improved conditions of health and energy. Moreover since the population is apt to remain below the saturation point so long as the climate improves, the standards of living tend to rise and to become relatively high. Thus many people are freed from the mere necessity of making a living and have the opportunity to devote themselves to the development of new ideas in literature, art, science, politics, and other lines of progress.

We see here the long shadow of Rev. Malthus interacting with crude Darwinism and Huntington's dynamic, climate theory.

Secondly, Huntington sometimes appears to fall into a kind of climatic fatalism. He worries that in the South of the US "we find less energy, less vitality, less education, and fewer men who rise to eminence than in the

North, not because southerners are in any way innately inferior to northerners, but apparently because of the adverse climate." However, in "the far West people seem to be stimulated to such a degree that nervous exhaustion threatens them." He worried then as we do today of Russia, asking "what shall we say of Russia, weighted down with benumbing cold and comparative monotony or with changes so extreme that they are harmful" and frets about China by inquiring, "what of China under a much heavier handicap of monotony; or of tropical lands burdened most heavily of all?"

The third feature of Huntington's thought lifts his work out of the ordinary run of climatic (or other) mechanistic theories and provide a linkage to modern economic views of climate change. How comes it to be that Hong Kong or Japan – far down Huntington's scale of climatic potential – could break free of their climatic chains and prosper close to or perhaps even beyond the ideal climate of Manchester or Boston? Huntington notes a remarkable article by GilFillan, "The Coldward Course of Progress" which shows how technological change "has enabled mankind to advance farther and farther into regions of low winter temperature."

Huntington then goes on to speculate that further progress may change man's relation to climate: "In the past great inventions have helped chiefly in enabling man to overcome low temperature; in the future, perhaps, they will help him in equal measure to overcome high temperature, dryness, and monotony". He sees two potential future changes that could lead to great improvements, particularly for tropical countries. The first is that millions of people may move back and forth among different climates – perhaps every week: "Their work may be arranged so that almost every family can spend week-ends in the highlands and the rest of the time in the lowlands."

While this first proposal seems far from the mark, a second speculation has an uncanny foresight for a book written well before the freon revolution:

> In the warmer parts of the earth there is another side to the question. Mankind needs ... cooling the interiors of houses. Today this is done on a small scale by shutting out the sun and sprinkling water to cause evaporation. There is no reason why the same result should not be produced on a large scale. We already know how to cool houses as well as to heat them. We do it in ice-plants. A thousand years ago men would have laughed at the idea that hundreds of rooms would some day be heated by a single fire, yet we see it in every office building or hotel. In equatorial regions there is as much reason for equipping the houses with coolers as there is in temperate regions for equipping them with heaters.

He concludes loftily that "if we can conquer climate, the whole world will become stronger and nobler."

Huntington's *Climate and Civilization*, along with a small library of other scholars a century ago, is a healthy reminder of how our fundamental models of human activity are prisoners of conscious or unconscious models of social systems. In Huntington's case, Malthusianism and Darwinism were mental constraints within which his theory of climate and civilization had to fit. It is surprising that he did not ask whether the climatic effects shown in Figure 1 were *de minimis* in the light of the economic pace of human invention that he described. The difference in performance of his operatives between the 60 "optimal" temperature of New York and an 80 average temperature in a tropical region hardly exceeds 2%. Yet real wages and productivity during this period were routinely growing at that rate every year. The real but unseen puzzle for a climatic determinist like Huntington was why productivity in the tropics was so much lower than was predicted by his wage-temperature curves. Had he asked that question, he might have become a development economist!

## 3. The Impact of Climates Present

Modern views of economic development give short shrift to climate as the basis for the differences of the wealth of nations.[2]. A review of a handful of textbooks on economic development shows that climate is confined to a few lines in hundreds of pages.[3] The modern view of economic growth presents development as a vehicle driven by the four wheels of capital, labor, resources, and technology, and only with a major stretch of interpretation would we equate resources with climate. The recent wave of studies of international differences in productivity have never included climate as a determining variable. Modern trade theories have had difficulty finding empirical evidence of the power of Heckscher-Ohlin trade theories that emphasize that international trade is based on a region's resource base, which base would include climate along with other factor endowments.

[2] A notable exception is a study by Kamarck (1976). This essay attempts to explain why it is that countries in the tropical regions are so burdened by laterite soils, weeds, locusts, parasites, and heat stress that, "all other relevant factors being equal, the pact of development in tropical countries tends to be slower" (Kamarck, 1976, p. 4)

[3] For example, see Streeten (1972), Nafziger (1990), Todaro (1991). Perhaps the most striking irony is the treatment by Todaro. He states, "*It is a historical fact that almost every successful example of modern economic growth has occurred in a temperate-zone country.*" (Italics in original) He then takes nine lines of a large tome, with not a single reference, to speculate on this remarkable "fact".

How can we rationalize modern attitudes toward climate? One possible reason for ignoring the importance of climate is that there seems little point in studying the influence of so exogenous a variable. A more serious possibility is that human societies can adapt to whatever climate is dealt by nature. We explore briefly in this section this view and then examine some economic and geophysical data to determine whether they support the earlier climatic determinism or the alternative adaptive view.

In opposition to Huntington's climatic hypothesis of civilization would be what might be called the *adaptive theory of climatic impact.* The adaptive theory holds that in the very long run, humans are essentially nomadic toolmakers. *Homo adaptus* thrives in every climate from Hong Kong to Helsinki: with a few exceptions of diminishing importance, humans can invent products or processes that can offset the disadvantages of climate, or can by trade turn apparent disadvantage to economic profit. At the extremes of cold, Sherpas make a relatively good living leading people up Mt. Everest, while deserts, free of dreaded ice and snow, are increasingly attractive places to old folks as places to putt and putter during their retirement. And in the end, if some region is so barren as to attract no conventional economic activity, it will probably become attractive as a wilderness retreat.

In the short run, of course, life can be full of surprises and dreadful climatic shocks. *Homo adaptus* will still be rendered homeless if hurricanes destroy flimsy structures, if storm surges break across land that is not meant for risk-free habitation, if farmers cultivate drought-prone land, or if civil wars destroy the land or dampen entrepreneurial impulses. To say that humans are adaptive says nothing about whether the adapted standards of living are high or low, whether nations are at war or peace, whether the climatic shock is the straw that breaks the camel's back, or whether the appropriate policies are to prevent the laying of that last straw through massive investments to slow climate change rather than to lighten the load from other burdens so that occasional climate shocks are nuisances rather than catastrophes and therefore break nothing.

Figure 2 illustrates the adaptive view of climatic impacts. The horizontal axis represents a synoptic climate variable such as average temperature, while we measure a region's productivity on the vertical axis. The horizontal line LR represents the *long-run* productivity of a region and suggests that productivity is independent of the climate. In the short run, however, productivity will be maximized at the "design climate" – we therefore represent $SR_0$ as the productivity curve that corresponds to capital, management, infrastructure, and localized technologies that are designed for climate $T_0$. If climate were to change to $T_1$, cool-weather crops would wilt, ski areas

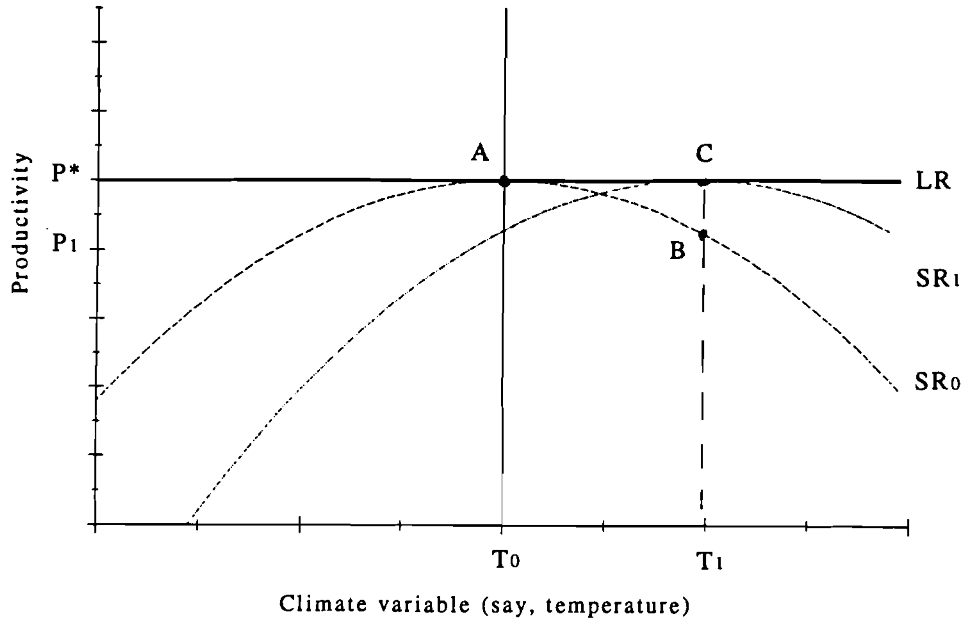



**Figure 2.** Productivity in an adaptive economy.

would fail, and other signs of a mal-adapted technology would emerge, with the equilibrium moving from A to B and productivity falling from P* to $P_1$. Over time, however, the economy would adapt as tropical fruits replace temperate grains and campers replace skiers. Once all the adaptations had taken place, productivity would rise to point C, with a productivity equal to the initial level and with a new short-run productivity curve of $SR_1$.

Figure 2 makes two other important points about adaptive systems. The first and not surprising corollary is that large shocks have a bigger short-run impact than do small shocks. The second and surprising implication is that, to a first-order of approximation, small shocks have no impact; more precisely, a small climate shock in the short run, before any adaptation has taken place, has the same impact as a long-run shock, or one after adaptation has taken place. In terms of Figure 2, a small shock will move along the short-run productivity curve, which is tangent to the long-run productivity curve at the initial point.

There are many potential objections to the adaptive view shown in Figure 2. One valid and enduring objection is simply that some aspects of social or natural systems cannot adapt or adapt so slowly that significant damages cannot be avoided. Forest ecosystems, coral reefs, cultural treasures like

Venice, wildlife refuges like Yellowstone – for these, the possibilities of adaptation seem dubious, so the short-run curve in Figure 2 might well be for 2 centuries rather than 2 years. A second class of objection is that the long-run curve is not horizontal but would show marked losses as climate changes. Such a case might arise if climate change involves global glaciation, if there is a shift in ocean currents that changes the climate of the North Atlantic communities into that of Alaska, or if midcontinental warming and drying destroys the globe's grain belts.

Using modern income concepts, we might examine very simply the relationship between certain geophysical variables and different economic measures. For geophysical data to represent climate, we use two very simple variables, latitude and average temperature. The latitude variable, measured as the latitude of the geographical center of the country for 77 countries, is a crude way of representing average temperature and other variables related to solar intensity. The temperature variable is the average of the July and January maxima and minima for forty countries. Clearly these variables are too aggregated for large countries like the United States, which spans 52° of latitude from Hawaii to Barrow, Alaska. But for smaller countries like Belgium or Gabon, the climatic variables not mask great diversity.

For economic variables, we begin with 1987 per capita GNP, using the purchasing-power parity corrected exchange rates developed by the international income comparison project. We have adjusted these to reflect more realistic data on the per capita incomes of the formerly centrally planned economies. Figures 3 and 4 show the relationship between the geophysical variables and per capita incomes. The circles on the graphs are of three different shapes. The largest circles are for countries with 1987 GNPs of more than $100 billion; the medium circles are for those countries with 1987 GNPs of between $20 and $100 billion; and the smallest circles are for countries with 1987 US GNPs of less than $20 billion.

Figure 3 indicates that the zone from 10° South to 20° North is an economic desert, with virtually no countries that have achieved high levels of per capita income. However, in the latitudes poleward from 35° North or 25° South, there is virtually no relationship between latitude and economic performance.

Figure 4 shows the relationship between per capita income and temperature for a smaller sample of countries. Over most of the range, from a mean temperature of 40°F to around 65°F, there is no relationship between mean temperature and income per capita. Above 65°F average temperature there is only a handful of countries, but it is interesting to note that no countries

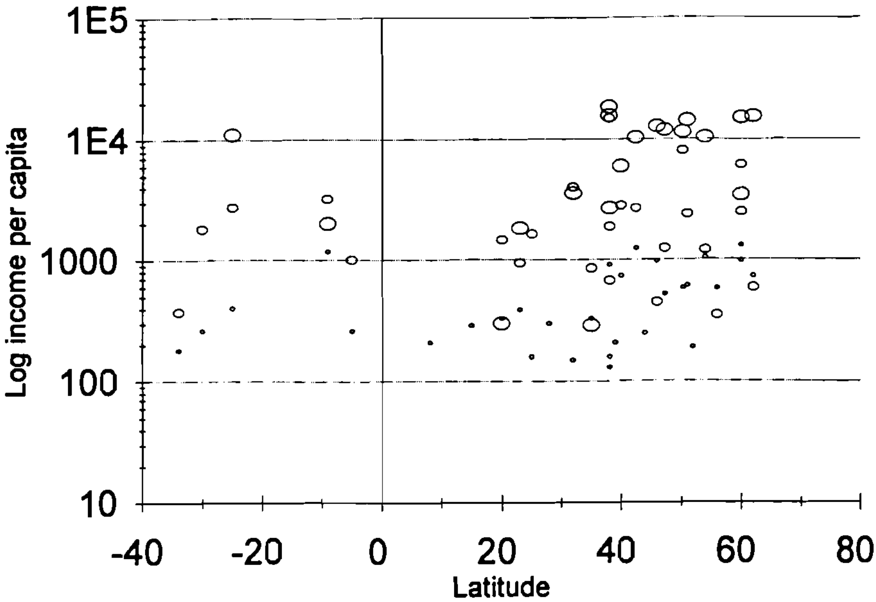



**Figure 3.** Geography and income (latitude and income per capita).

in this sample with a mean temperature of over 65°F has risen above the $2000 per capita income level.

The measure of income per capita is defective in that human migrations will over a scale of centuries tend to equalize incomes in different regions (although the tendency is clearly quite weak in light of current findings on the lack of convergence among countries). In 1980, Alaska has the highest per capita income of any of the 50 United States, and we might therefore mistakenly conclude that the state of Alaska has a very fertile climate. A better measure of the economic clemency of a climate would probably be the "Ricardian rent" that land in any area yielded. Failing that, we could examine the income per unit area, measured as a country's GNP per unit area (in 1987 US dollars per square kilometer).

Figures 5 and 6 show the results of this calculation. Figure 5 shows the same latitudinal results as Figure 3 – that there is an economic desert in the lowest latitudes. But the interesting new feature here is to show that the economic return per unit land peaks in the middle latitudes – say between 40 and 50 North and around 30 South – and then seems to decline again at the highest latitudes. This result reflects the sensible result that the highest latitudes (Alaska, Northern Canada, Siberia) may have high incomes per person but few persons are able to earn a high income there.

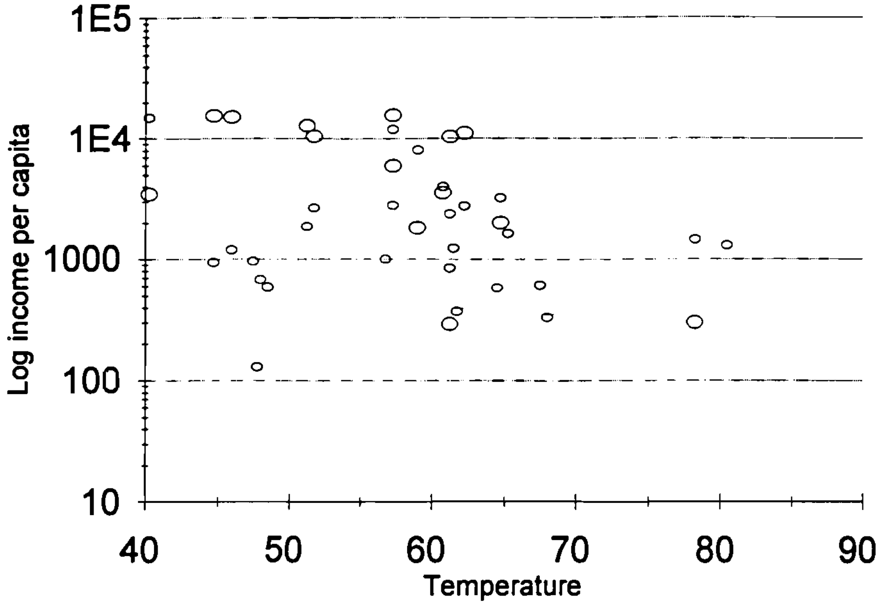



**Figure 4.** Geography and income (temperature and income per capita).

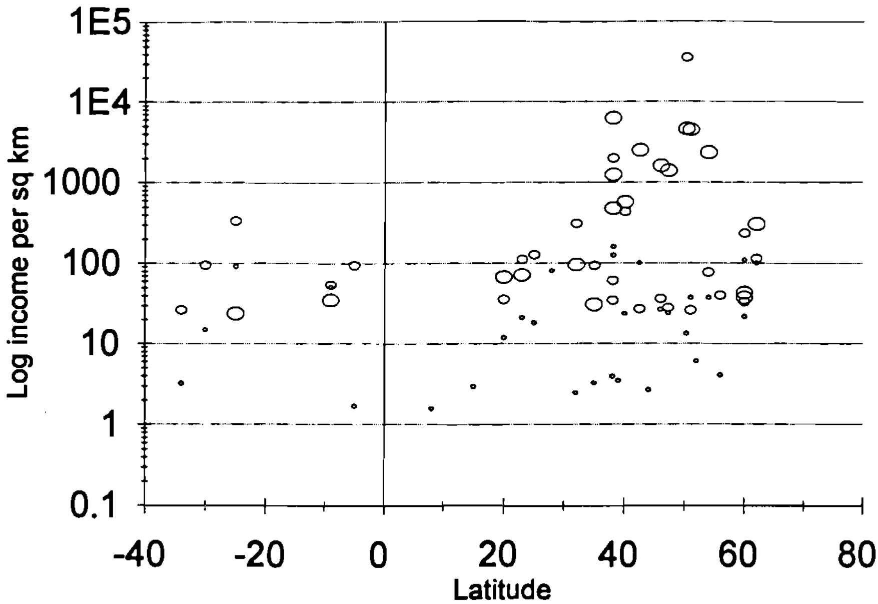



**Figure 5.** Geography and income (latitude and income per area).

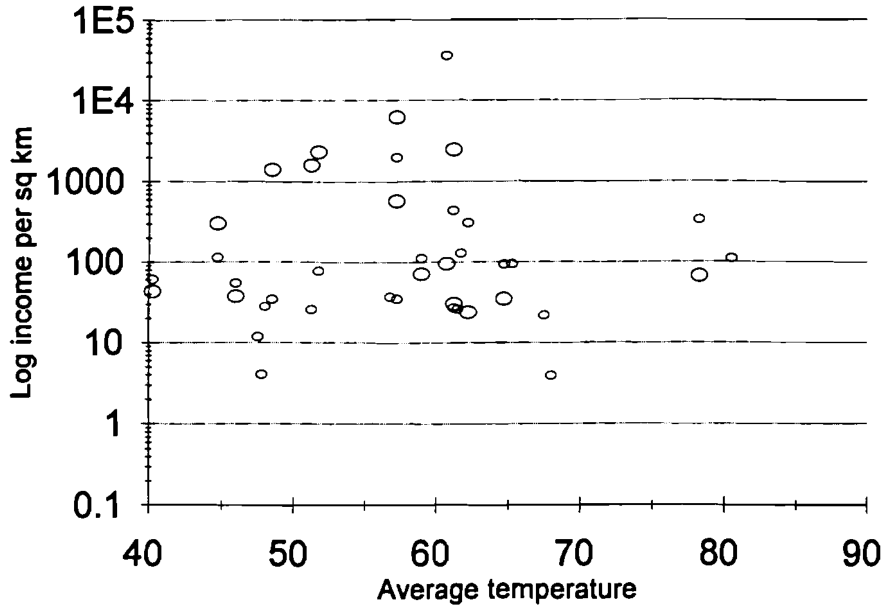



**Figure 6.** Geography and income (temperature and income per area).

Figure 6 seems more of a standoff between the variables. Income per unit area is highest in temperature ranges that are more moderate, and there is a modest hump-shaped relationship. But no clear threshold appears in these data.

A final word should be added to put these geophysical variables in a larger context. Climate may have an effect upon incomes, but on the whole the effect is swamped by other variables. Looking at Figure 5, we see that incomes per square kilometer vary from a low of about \$31 for China to a high of about \$30,000 for Hong Kong, or from \$37 per kilometer in Indonesia to \$6200 in Japan. Latitude explains less than 1% of the variance in income per capita or per area. We should surely look to factors other than climate to explain most differences in the wealth or poverty of nations.

## 4. The Scientific Background on Global Warming

What is the greenhouse effect? The greenhouse effect is the process by which radiatively active gases like $CO_2$ selectively absorb radiation at different points of the spectrum and thereby warm the surface of the earth. The greenhouse gases (GHGs) are transparent to incoming solar radiation but absorb significant amounts of outgoing radiation. There is no debate about the importance of the greenhouse effect, without which the Earth's climate would resemble the moon's.[4]

Concern about the greenhouse effect arises because human activities are currently raising atmospheric concentrations of greenhouse gases. The major GHGs are carbon dioxide (emitted primarily from the combustion of fossil fuels), methane, and chlorofluorocarbons (CFCs). Scientific monitoring has firmly established the buildup of the major GHGs over the last century. Using the standard metric of the "$CO_2$ equivalent" of GHGs, atmospheric concentrations of GHGs have risen by over half of the pre-industrial level of $CO_2$.

While the historical record is well established, there is great uncertainty about the potential for future climate change. On the basis of climate models, scientists project that a doubling of the atmospheric concentrations of $CO_2$ will in equilibrium lead to a 1 to 5°C warming of the earth's surface; other projected effects include an increase in precipitation and evaporation, a small rise in sea level over the next century, and the potential for hotter and drier weather in mid-continental regions such as the US midwest.

To translate these equilibrium results into a projection of future climate change requires a scenario for emissions and concentrations. Using rudimentary economic modeling, the Intergovernmental Panel on Climate Change (or IPCC), an international panel of distinguished scientists, projected that "business-as-usual" would produce a 3 to 6°C warming in 2100 with the best guess being slightly over 4°C (see Figure 7). I have recently used a dynamic optimization model (described more fully in a later section) to develop a distribution of future temperature increases, and the 10th, 50th, and 90th percentiles of the distribution are compared with the IPCC estimates in Figure 7. Economic models tend to show lower emissions and temperature trends that the extrapolative approaches often used. However, virtually all projections are worrisome because climate appears to be heading out of the historical range of temperatures witnessed during the entire span of human civilizations.

Climate models resemble large macroeconomic models in their ability to answer virtually any question that modelers care to ask; it is not clear that their reliability for forecasting climate change is any better. Forecasting climate changes at particular locations has proven intractable, and many

[4] A non-technical description of the science underlying the greenhouse effect is contained in NAS (1992). A thorough survey, full of interesting figures and background, is contained in IPCC (1990).

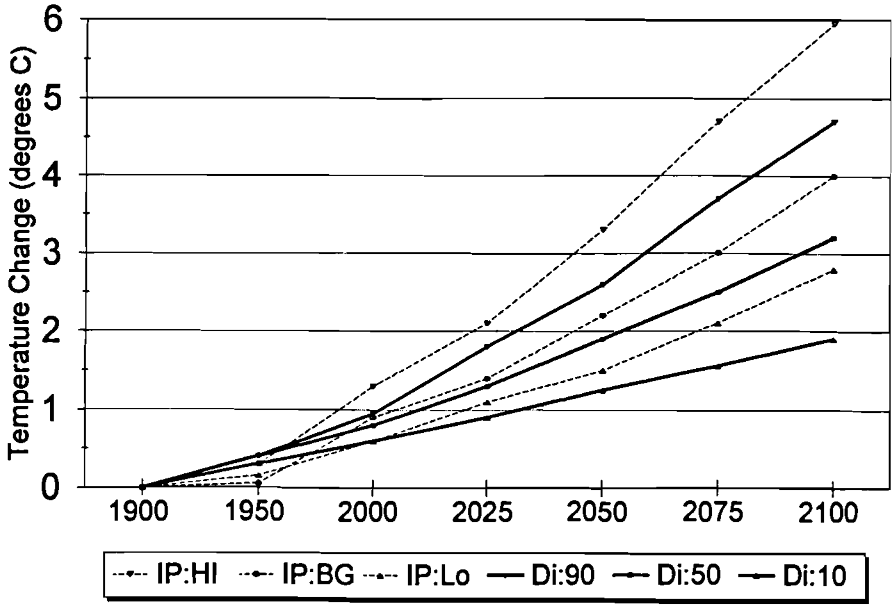



**Figure 7.** Projected temperature change (IPCC and DICE model).

climate modelers do not expect to be able to forecast regional climates accurately in the foreseeable future. Some believe that there may be "regime changes" in which the climate may flip from one locally stable system to another, say because of changes in ocean circulation. Elaborating bigger and better models will provide fruitful full employment for climatologists well into the next century.

## 5. Impacts of Climate Change

What are the likely impacts of projected climate changes such as those shown in Figure 7? To begin with, we should recognize that in the long march of economic development, technology has increasingly insulated humans and economic activity from the vagaries of climate. Two centuries ago, work and recreation were dictated by the cycles of daylight, the seasons, and the agricultural growing season; even today, we see vestiges of climate's imperatives in the academic calendar.

Today, thanks to modern technology, humans live and thrive in virtually every climate on earth. For the bulk of economic activity, variables like wages, unionization, labor-force skills, and political factors swamp climatic considerations. When a manufacturing firm decides between investing in Hong Kong and Moscow, climate will probably not even be on the list of factors considered. Moreover, the process of economic development and technological change tend progressively to reduce climate-sensitivity as the share of agriculture in output and employment declines and as capital-intensive space heating and cooling, enclosed shopping malls, artificial snow, and accurate weather or hurricane forecasting reduce the vulnerability of economic activity to weather.

In thinking about the impact of climate change, we must recognize that the variable focussed on in most analyses - globally averaged surface temperature - is relatively unimportant for impacts. Variables that accompany or are the result of temperature changes - precipitation, water levels, extremes of droughts or freezes, and thresholds like the freezing point or the level of dikes and levees - will drive the socioeconomic impacts. Mean temperature is chosen because it is a useful index of climate change that is highly correlated with or determines the more important variables.

## 5.1. Impacts in high-income regions

What do empirical studies of the economic impact of climate change produce? It must be emphasized that impact studies are in their infancy and that studies of low-income regions are virtually non-existent. This survey of impacts will concentrate primarily upon high-income regions because that is where the evidence is most abundant.

Climate change is likely to have different effects on different sectors.[5] In general, those sectors of the economy that depend heavily on unmanaged ecosystems - that is, are heavily dependent upon naturally occurring rainfall, runoff, or temperatures - will be most sensitive to climate change. Agriculture, forestry, outdoor recreation, and coastal activities fall in this category. In reality, however, most economic activity in high-income countries has little direct interaction with climate. For example, cardiovascular surgery and microprocessor fabrication are undertaken in carefully controlled environments and are unlikely to be directly affected by climate change. More

[5] The most careful studies of the impact of greenhouse warming have been conducted for the United States, and this review will therefore concentrate here. An early review, emphasizing the potential costs of climate change, is contained in EPA (1989). A more balanced approach, emphasizing the potential for adaptation, is contained in NAS (1992).

**Table 1.** Comparison of estimates of impact of global warming (in billions of 1988$ and percent of total output).

| | United States | | | | Global | |
|---|---|---|---|---|---|---|
| | Nordhaus | Cline | Fankhauser | Other | Fankhauser | Other |
| *Heavily affected sectors* | | | | | | |
| Agriculture | 1 | 15.2 | 7.4 | 1.2[b] | 39.1 | 12.3[b] |
| Coastal areas | 10.7 | 2.5 | 2.3 | | | |
| Energy | 0.5 | 9 | 0 | | | |
| *Other sectors* | 38.1 | | | | | |
| Wetland and species loss | [a] | 7.1 | 14.8 | | | |
| Health and amenity | [a] | 8.4 | 30.3 | | | |
| Other | [a] | 11.2 | 12.1 | | | |
| Total (billions of $) | 50.3 | 53.4 | 66.9 | | | |
| *Percent of output* | 1.0 | 1.1 | 1.3 | | 1.5 | 2.8[c] |

[a]These are included in the total for "other sectors."
[b]From Reilly and Hohmann (1993), with full adaptation and $CO_2$ fertilization.
[c]From a survey of experts currently being processed.
Sources: Nordhaus, 1991; Cline, 1992; Fankhauser, 1993.

generally, underground mining, most services, communications, and manufacturing are sectors likely to be largely unaffected by climate change – sectors that comprise 80 to 85% of GDP in high-income countries.

There have been a number of studies that have estimated the impact of a $CO_2$ doubling (2.5 to 3°C) on the United States, and the results of three such surveys are shown in Table 1. The first column of Table 1 shows the results of Nordhaus (1991) updated to 1988 prices. The other two comprehensive studies by Cline (1992) and Fankhauser (1993) use largely the same data base but extend the Nordhaus analysis to other sectors.

Cline has performed the most detailed economic analysis of the potential impact of climate change on a number of market and non-market sectors, and the overall results are shown in the second column of Table 1. It should be noted, however, that these results are often very fragile and may lean toward overestimating the impacts. For example, Cline's estimates assume that storms become more severe whereas both the IPCC and the National Academy studies concluded that the effect of warming on storm intensity is ambiguous. Another example of potential exaggeration lies in species loss, where Cline takes a very costly decision (that of the spotted owl) and uses that as the basis for valuation. At the end of the day, Cline's estimates of impacts are marginally above those in the Nordhaus survey (1.1% of GNP for a 2.5°C warming in Cline as opposed to 1% of GNP for a 3°C warming in Nordhaus).

A third approach is a compilation by Fankhauser (1993). This study uses much the same methodology as Nordhaus and Cline but uses additional studies and extends the analysis to the OECD countries and to the world. Fankhauser's results are very close to those in other studies, finding a 1.3% impact of a 3°C warming for the USA and a 1.5% impact for the world.

Two other approaches are shown in Table 1. A study by Reilly and Hohmann (1993) embeds the crop-yield models that are used to develop the impact estimates for agriculture in a model of international trade. They find that trade tends to reduce the impacts by a factor of twenty, as reactions of supply and demand buffer production shocks. The estimated impact of a substantial (30%) yield shock, buffered by the adaptive response in markets, produces a negligible impact on US and world incomes. This careful study is a good lesson on how impact estimates often tend to exaggerate losses while ignoring gains and adaptation.[6]

A final estimate, more qualitative in nature, is a survey of experts. Because estimating the impacts of climate change has proven extremely difficult, the present author is in the process of undertaking a survey of experts on the economic impacts of climate change. For a 3°C warming in 2090, the "trimmed mean" of the responses has estimated damages of 2.9% of world output, while the median is 1.8% of world output. One major concern of most respondents is that the impact is thought to be considerably higher for low-income countries than in high-income countries.

## 5.2. Impacts in low-income regions

A full assessment of the impact of greenhouse warming must, of course, include the poorer regions of the globe. To date, studies for other countries

[6] One might suspect that there is an unconscious thrust in some research to find costs and ignore benefits of climate change. A comparison of two sets of studies is instructive in this respect. Almost two decades ago, a series of studies was undertaken to investigate the impact of flights in the stratosphere on global cooling. Studies by d'Arge and others (summarized in National Research Council, 1979) found that global cooling of 1°C would impose costs in a number of areas. Of the nine areas of costs identified in the global cooling studies (agriculture, forest products, marine resources, health, locational preferences, fuel demand, housing, public expenditures, and aesthetics), only two were examined in the 1989 EPA study of global warming and none were calculated by the EPA to produce benefits. The largest estimated cost in the global cooling studies was the amenity effect of cooling, determined through regional wage differentials. This topic was completely ignored in the EPA studies. One is tempted to say that environmental impact studies can find the cloud behind every silver lining.

are fragmentary, and it is not possible to make any general conclusions at this time.

One source of information about the differential impacts by regions comes from the previously-mentioned survey of experts on the impact of climate change. In that survey, respondents were asked the following question: "In thinking about your response, could you provide an estimate of the impact on countries or regions with different levels of income and development? More precisely, could you estimate the impact on the top quintile and the bottom quintile of the world income distribution?"

In general, all respondents were of the view that the developing countries (i.e., the lowest quintile) would be more seriously affected than the high-income countries. The mean ratio of the impact of the bottom to the top quintile ranged from 1.75 to 10. This signifies that the respondents felt that the economic damage to the bottom quintile from a 3°C global warming over the next century would range from 1.75 to 10 times the damage to the top quintile.

Explicit economic studies of the impact of climate change on developing countries are extremely rare, but I will mention two to give some flavor for the results. A study by Liverman and O'Brien uses projections from five climate models to estimate the impact of global warming on Mexican agriculture. Their work is limited to showing that the impact will be that "soil moisture and water availability may decrease over much of Mexico" (Liverman and O'Brien, 1991, p. 351). From this they conclude that there will be "serious consequences for rainfed and irrigated agriculture, urban and industrial water supplies, hydropower and ecosystems" (Liverman and O'Brien, 1991, p. 351). While this substantive economic conclusion is consistent with the quantitative findings, it is not actually a result of the model.

A second study, of China, similarly takes seven climate-model projections to investigate the impact of a global-warming scenario for China in the year 2050 (China, 1992). It concludes that because of the warming, the prevalence of hot triple cropping will rise from 1 to 7% of acreage, the prevalence of triple cropping will rise from 12 to 29%, and the prevalence of single cropping will fall from 62% to 39% The study notes that the diversification due to increased multiple cropping would appear to be favorable, although the impacts on precipitation and runoff patterns may mitigate this favorable impact on Chinese agriculture.

Three general factors should be weighed when considering the impact of greenhouse warming on developing countries. First, poorer countries tend to have a larger fraction of their economies devoted to agriculture, especially rain-fed agriculture, and this means that they are more subject to the vagaries of climate change. Countries classified by the World Bank as "low-income economies" had 31% of GDP produced in the agricultural sector in 1987; these countries hold 2.8 billion people. There is no strong presumption in my mind that the net impact will be everywhere negative, but the dependence upon agriculture means that developing countries have a larger economic exposure to climate change than to industrial countries.

Second, there is a potentially strong mitigating factor for agricultural nations in the fertilizing effect of atmospheric $CO_2$. $CO_2$ is a natural fertilizer that has been used in greenhouses to stimulate plant growth. $CO_2$ fertilization is particularly important for the C3 plants, such as forest trees, rice, wheat, potatoes, and beans; moreover, $CO_2$ fertilization appears to be particularly important in areas where water is a limiting factor. (C4 crops like corn have a smaller response to $CO_2$ fertilization.) There are today numerous controversies about the extent and quantitative importance of $CO_2$ fertilization, but the balance of the evidence suggests that this might be a potential plus for countries that are heavily dependent upon agriculture.

A third general issue, about which there would seem to be little mitigating offset, is the potential for sea-level rise. Current scientific evidence sees the potential for sea-level rise of between negligible and one-half meter over the next century (this being in addition to any local geologically induced sea-level rise or fall). It is hard to see any good that can come from this impact of global warming, for the sea coasts tend to be heavily populated with a significant fraction of the world's capital infrastructure. On the other hand, given the slow pace of sea-level advance, intelligent planning for defense or retreat could reduce the costs of sea-level rise significantly.

## 6. The Balancing Act in Climate-Change Policies

The greenhouse effect is the grand daddy of public goods problems – emissions affect climate globally for centuries to come. Because of the climate externality, individuals will not produce the efficient quantity of greenhouse gases. An important goal of economic research is to examine policies that will find the right balance of costs of action to slow climate change and the benefits of reducing future damages from climate change.

We can analyze the costs and benefits of the climate-change policies in terms of the marginal benefit and marginal cost of emissions reductions. The benefits of emissions reductions come when lower emissions reduce future climate-induced damages; we described the damages from climate change in the last section. To translate these into a marginal benefit function, we

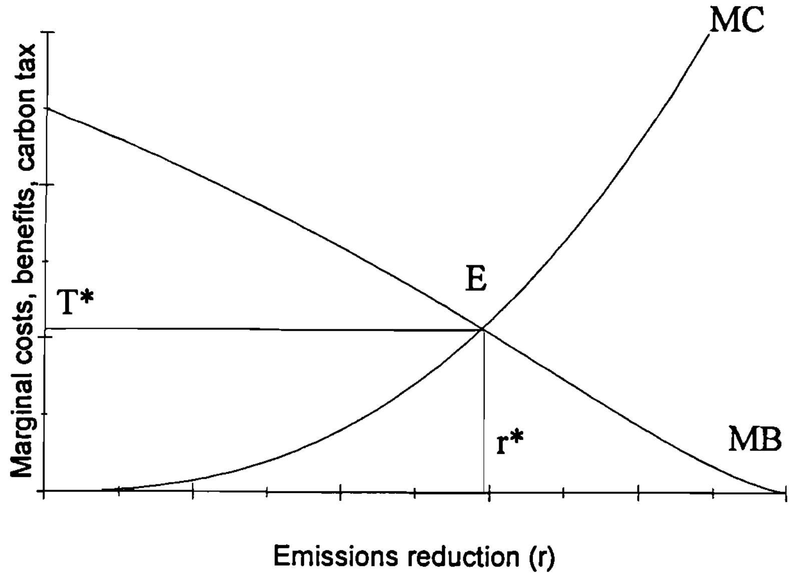



**Figure 8.** Marginal costs and benefits of greenhouse gas emissions controls.

trace out the emissions through GHG concentrations to economic impacts and then take the present value of the impact of an emission of an additional unit. Graphically, we can depict the marginal damages averted per unit of emissions reduction as the downward-sloping marginal benefit (MB) curve in Figure 8.

The second relationship is the marginal cost of emissions reduction, which portrays the costs that the economy undertakes to reduce a unit of GHG emissions (or the equivalent in other policies that would slow greenhouse warming). A wide variety of approaches are available to slow climate change. Most policy discussion has focussed on reducing $CO_2$ emissions by reducing the consumption of fossil fuels through energy conservation, alternative energy sources (some would even contemplate nuclear power), and other measures. Such policies could be implemented through carbon taxes, while some prefer regulations such as tradable emissions permits. Other approaches include reforestation to remove $CO_2$ from the atmosphere and putting even more stringent controls on CFCs. Another option, definitely not in the environmentally correct package, would be to offset greenhouse warming through climatic engineering, primarily through measures to change the albedo (reflectivity) of the earth. Whatever the approach, economists emphasize the importance of cost-effectiveness – structuring policies to get the maximal reduction in harmful climatic change for a given level of expenditure. Figure 8 shows schematically the marginal cost of emissions reduction as MC.

The shape of the cost function for reducing $CO_2$ emissions has been thoroughly studied, and the effort discussed by Gaskins and Weyant (1993) represents the most careful comparative examination of the results of different models. In addition, policies should include other cost-effective measures, and a recent National Academy of Sciences Panel has compared the costs of a wide variety of measures, including rough estimates of the costs of climate engineering (NAS, 1992).

From an economic point of view, efficient policies are ones in which the marginal costs are balanced with the marginal benefits of emissions reductions. Figure 8 shows schematically how the efficient rate of emissions reduction and the optimal carbon tax are determined. The pure market solution comes with emissions reductions at 0, where MB is far above the zero MC. Point E represents the efficient point at which marginal abatement costs equal marginal benefits from slowing climate change. The policy can be represented by the efficient fractional reduction in emissions, r* on the horizontal axis, or by the optimal carbon tax, T* on the vertical axis.

## 7. Empirical Modeling of Optimal Policies

Sketching the optimal policy in Figure 8 demands little more than pencil, paper, and a rudimentary understanding of intermediate economics. To move from theory to useful empirical models requires developing a wide variety of empirical economic and geophysical models. Work has progressed to the point where the economics and natural science can be integrated to estimate optimal control strategies. In one study, I developed a simple cost–benefit analysis for determining the optimal steady-state control of $CO_2$ and other greenhouse gases based on the comparative statics framework shown in Figure 8 (Nordhaus, 1991). This earlier study came to a middle-of-the-road conclusion that the threat of greenhouse warming was sufficient to justify low-cost steps to slow the pace of climate change.

A more complete elaboration has been made using an approach I call the "DICE model," shorthand for a Dynamic Integrated model of Climate and the Economy.[7] The DICE model is a global dynamic optimization model for estimating the optimal path of reductions of GHGs. The basic approach is

[7]The basic model and results are presented in Nordhaus (1992a, 1992b), while complete documentation and analysis are forthcoming in Nordhaus (1994).

to calculate the optimal path for both capital accumulation and reductions of GHG emissions in the framework of the Ramsey model of intertemporal choice (Ramsey, 1928). The resulting trajectory can be interpreted as the most efficient path for slowing climate change given inputs and technologies; an alternative interpretation is as a competitive market equilibrium in which externalities or spillover effects are corrected using the appropriate social prices for GHGs.

The question addressed in the DICE model is whether to consume goods and services, invest in productive capital, or slow climate change via reducing GHG emissions. The optimal path chosen is one that maximizes an objective function that is the discounted sum of the utilities of per capita consumption. Consumption and investment are constrained by a conventional set of economic relationships (Cobb-Douglas production function, capital-balance equation, and so forth) and by a novel set of aggregate geophysical constraints (interrelating economic activity, GHG emissions and concentrations, climate change, costs of abatement, and impacts from climate change). The impact function is based on the discussion in the last section, while other relationships are drawn from sources in economics and the natural sciences.

To give the flavor of the results from the DICE model, we will consider the economic optimum and compare it to two alternative policies that have been proposed by governments or by the environmental community. The three options are (1) economic optimization as described in the last paragraph; (2) stabilizing GHG emissions at 1990 levels, a target that was endorsed at the Rio Earth Summit by the US and other governments; and (3) stabilizing climate so that the change in global average temperature is limited to no more than 0.2°C per decade with an ultimate limitation of 1.5°C (compare this with the projections in Figure 7).

Solving the DICE model for the three policies just described produces a time sequence of consumption, investment, GHG emissions limitations, and carbon taxes. The carbon taxes can be interpreted as the taxes on GHGs (or the regulatory equivalent, say in auctionable emissions rights) that would lead to the emissions that would attain the policy objectives described in the last paragraph.

Figure 9 shows the resulting carbon taxes. For calibration purposes, in the United States, a carbon tax of $100 per ton would raise coal prices by about $70 per ton, or 300%, would increase oil prices by about $8 per barrel, and would raise around $200 billion of revenues (before taking account of emissions reductions). The economic optimum produces relatively modest carbon taxes, rising from around $5 per ton carbon to around $20 per ton by the end of the next century. The stabilization scenarios require much more

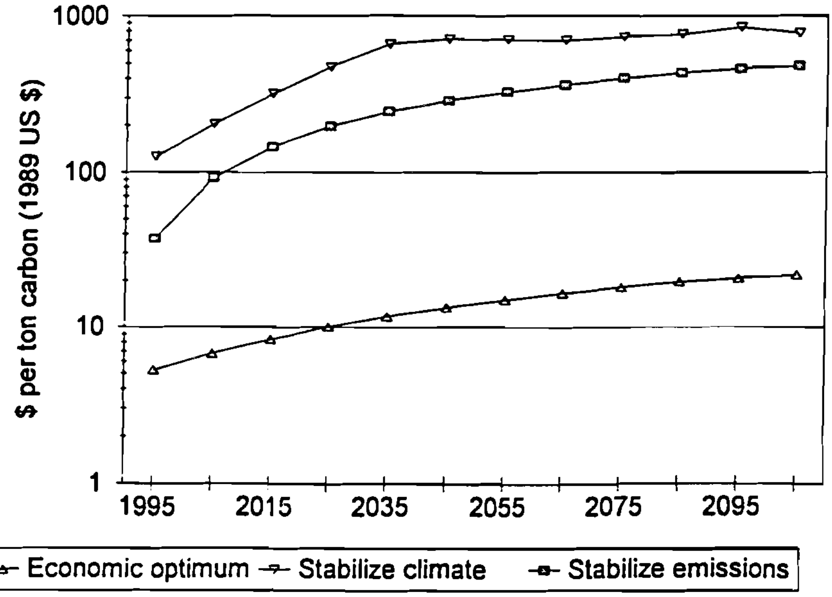



**Figure 9.** Carbon tax rate (tax in \$ per ton C equivalent).

stringent restraints. For emissions stabilization, the carbon tax would rise from around \$40 per ton currently to around \$500 per ton carbon late in the next century; climate stabilization involves current carbon taxes over \$100 per ton today rising to nearly \$1000 per ton by the end of the next century.

We can also inquire into the estimated net economic impact of alternative approaches in the DICE model. For the global economy, the economic optimum has a value over no controls (in terms of the discounted present value measured in 1990 consumption) of \$270 billion. On the other hand, stabilizing emissions at 1990 levels leads to a net present-value loss of around \$11 trillion relative to the optimum while attempting to stabilize climate would have a net present-value cost of around \$30 trillion. If we annualize these at a discount rate of 6%, these represent, respectively, a gain of 0.8% and losses of 3 and 9% of today's annual gross world output.

At present, there are several other economic studies of efficient approaches to slowing global warming. The studies of Manne and Richels (1990, 1992), Peck and Teisberg (1992), and Kolstad (1993) find conclusions that are roughly similar to those reported here. The studies by Jorgenson and Wilcoxen (see especially (1991)) show a lower set of carbon taxes needed to stabilize GHG emissions that those shown here, in part because of the induced innovation in the Jorgenson-Wilcoxen model.

Three studies – those of Cline (1992), Peck and Teisberg (1992), Kolstad (1993) as well as earlier studies by the present author (1979, 1991) – also determine the optimal emissions control rates and carbon taxes. With the exception of Cline (1992), all the earlier studies show optimal policies in the general range of those determined here. A study by Hammitt, Lempert, and Schlesinger (1992) traces out alternative control strategies to attain certain temperature constraints; while not determining an optimal path, this study concludes that a "moderate reduction strategy" is less costly than an "aggressive" approach if either the temperature response to GHG concentrations is low or if the allowable temperature change is above 3°C. The study by Cline (1992), by contrast, proposes much higher control rates. The more stringent controls in the Cline study are due to a number of features – primarily, however, because the Cline result is not grounded in explicit intertemporal optimization and assumes a rate of time preference that is lower than would be consistent with observed real interest rates.

## 8. Uncertainties and Anxieties

Most economic studies of the impacts and policies concerning climate change are based on scenarios like the smooth and gradual warming depicted in Figure 7. And, as indicated in the last section, the conclusion that emerge from most economic studies is to impose modest restraints, pack up our tools, and go on to other more pressing problems. Given the high costs of controls and the modest projected impacts of a 1 to 3°C warming over the next half century, how high is global warming on an international agenda that includes exploding population in the South, nuclear proliferation in the Middle East, collapsing economies in the East, increasing cycles of poverty and drug use along with stagnating incomes in the West, and sporadic outbreaks of violence and civil war just about everywhere?

Given the modest estimated impact of climate change along with our other urgent concerns, we might conclude that global warming should be demoted to a second-tier issue. Yet, even for those who downplay the urgency of the most likely scenarios for climate change, there remains a deeper anxiety about future uncertainties and surprises. Scientists raise the specter of shifting currents turning Europe into Alaska, of mid-continental drying transforming grain belts into deserts, of great rivers drying up as snow packs disappear, of severe storms wiping out whole populations of low-lying regions, of surging ice sheets raising ocean levels by 20 to 50 feet, of northward migration of old or new tropical pests and diseases decimating the temperate regions, of environmentally induced migration overrunning borders in search of livable land. Given the potential for catastrophic surprises, perhaps we should conclude that one of the major concerns, if not the major concern, lies in the uncertainties and imponderable impacts of climate change rather than in the smooth changes foreseen by the global models.

Once we open the door to consider catastrophic changes, a whole new debate is engaged. If we do not know how human activities will affect the thin layer of life-supporting activities that gave birth to and nurture human civilization and if we cannot reliably judge how potential geophysical changes will affect civilization or the world around us, can we use the plain vanilla cost–benefit analysis (or even the Haagen Dazs variety in dynamic optimization models)? Should not we be ultraconservative and tilt toward preserving the natural world at the expense of economic growth and development? Do we dare put human betterment before the preservation of natural systems and trust that human ingenuity will bail us out should Nature deal us a nasty hand?

Faced with this dilemma, we might be tempted to say that such questions are beyond the capability of rational analysis and turn the decisions over to philosophers and politicians. But, in fact, natural and social sciences have an important role to play in analyzing potential future outcomes and delineating potential responses. Society often requires that decisions be made in the absence of complete information, whether the decisions be military strategy, oil drilling, or research and development. In each case, a reasoned decision process involves listing the events that may occur, estimating the consequences of the events, judging the probabilities that each of the events will occur, weighing the expected value of the consequences against the expected costs under different courses of action, and choosing the action that maximizes the expected value or utility of the outcome.

Reasoned decision making under uncertainty is no different for climate-change policy than for other areas, although it may be more complex and require crossing traditional disciplinary boundaries more often. In thinking through the appropriate treatment of future surprises, to the natural scientists falls the crucial task of sorting through the apocalyptic scenarios and obtaining rough judgments as to the likelihood of different geophysical outcomes so as to distinguish between the likely, plausible, possible, and virtually impossible. To the social scientist falls the issue of assessing the probabilities, determining the values of different outcomes, and devising sensible strategies in the face of such massive uncertainties. To our leaders falls the burden of ultimately deciding how to weigh future perils against present costs. For all, this is a fruitful use of our collective talents, full of intellectual challenges and practical payoffs.

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# Looking Back Ten Years

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## Abstract

This paper could be described as an update of the science of global warming. The point of departure is 1983 with the publication of the National Research Council/National Academy of Sciences report (1983) *Changing Climate*. The advances (or retreats) in the overall science are reviewed with special emphasis on those that have critical policy implications.

## 1. The Carbon Cycle and Atmospheric Chemistry

It was accepted in 1983 and is accepted today without question that atmospheric $CO_2$ is rising steadily and exponentially since the beginning of the modern industrial era. However, the direct measurement of the rise has only been made with any precision for about forty years. As of ten years ago, the guesses for the value of the concentration about the year 1890 ranged between 260 and 290 parts per million of $CO_2$ in the atmosphere. From a policy viewpoint this variation left much to be desired. The lower value implied, at the time, that the global warming should have been observed, the upper value implied that the rate of growth was too slow for any effects to be seen above the noise. Since that time, and as predicted, the analysis of gas bubbles in the ice cores of the Antarctic have fixed this 1890 value with greater precision but we are still left uncertain as to when the global warming effects will clearly emerge from the general climate noise.

Another question related to this growth of $CO_2$ in the atmosphere is how long does the increase, which is presumed to be of anthropogenic origin, persist? As of 1983, the literature (not the NAS report) cited long lifetimes of the order of one thousand years, derived from various lines of reasoning, among them being tritium isotope variation with depth but undoubtedly influenced by the measured $^{14}C$ ages of the very bottom ocean waters. Since then, with the advent of coupled atmosphere-ocean climate models, the duration has dropped to fifty years although that is an oversimplification. (The present picture is that of a sum of exponential decays with the fastest being of the order of fifty years.)

The originally stated long lifetime meant that, if the effects of an increase in $CO_2$ were serious, they would remain for a long time. They would be permanent for all practical considerations. If it is assumed that the available fossil carbon fuel would be consumed in a short period compared to this lifetime – say two or three hundred years – a small reduction in anthropogenic output, say 20%, for example, would have a negligible effect on the peak effects. However, with the short lifetime – short compared to this period of total consumption of fossil fuel – the picture changes drastically. On one hand, any reasonable cutback in emissions would show correspondingly reasonable beneficial effects. On the other, there is reduced urgency for drastic action for if, in fact, adverse climate changes appear, action could be taken in the full expectation that the correction would also appear in reasonable time.

Another serious question whose implications were widely discussed and analyzed ten years ago was that of sea level rise. Putting aside some grossly exaggerated predicted changes that were as high as twenty-five feet, the Academy report settled on a rise of two feet, that is 60 centimeters, as a result of an equivalent doubling of $CO_2$ concentration of greenhouse gases. In fact, that was the number used in the first IPCC report. This calculated rise was composed of two approximately equal parts. One due to the estimated deglaciation and the other due to the thermal expansion of the upper ocean.

However, it appeared that the thermal expansion had not been correctly calculated. The Hamburg atmosphere-ocean coupled model first showed that the properly calculated thermal expansion was much less. This was largely due to the fact that the thermal coefficient of expansion of sea water nearly vanishes at $0^\circ$ Celsius and this near zero number is the correct one to use rather than the average ocean temperature because the polar waters are the primary sinks for the excess heat. The deglaciation effect had been empirically estimated but the improving models all seem to yield increasing precipitation in the Antarctic and that implies increasing, rather than decreasing, ice cap depth which, in turn of course, implies a decrease in ocean height. Satellite observations, taken so far, indicate increasing ice thickness and little change in sea level, of the order of one millimeter per year.

The early concern expressed by geologists and oceanographers related more to the possible melting and disappearance of the Western Antarctic Ice Sheet (WAIS). This would result in an increase in sea level of the order of twenty feet which would severely impact highly developed coastal areas. The principal concern was derived not just from geological deductions that the sheet had disappeared in relatively recent geological times but more that these disappearances may have taken place during a relatively short period of a few hundred years or even less. This possibility was carefully examined in the Academy report with the conclusion that it was unlikely to happen in the next hundred years but it has not been ruled out as a possibility in the longer term.

In the early analyses, like the Academy's, one accepted the expressed view of the geochemists that the disposition of the man-made $CO_2$ was well understood, namely that there was a complete balance between the amount of carbon emitted by power plants and other human sources, the fraction that remained in the atmosphere and the amount that went into the oceans. The geochemists believed that the carbon reservoirs represented by the forests, the humus, and the inorganic carbon in the oceans changed very slowly compared to the flux generated by man despite the fact that the rate of exchange between the oceans and the atmosphere as well as the exchanges between the forests and the atmosphere were about fifteen times the man-made emissions. They were literally dealing with small differences between large numbers.

To complicate matters, from the very beginning many sylvanologists believed that the forests were not constant reservoirs of carbon but were yielding carbon to the atmosphere at a rate commensurate with the other emissions, primarily due to a rate of human destruction of the world's forests greater than natural restoration. Leaving aside some early highly exaggerated rates of forest destruction, the Academy report accepted a rate of disappearance of forests equivalent to between 2 and 4 gigatons of carbon per year or about half the emissions due to power generation. The Academy report specifically recognized this dilemma as not resolvable at the time and a necessary subject for further investigation.

The status has not changed and, to mix a metaphor, the carbon balance estimate is in a state of flux and perhaps may have been reversed. The situation has since changed to being described as that of the "missing carbon". The results of direct measurement of the flow of $CO_2$ from the atmosphere into the upper ocean (Tans *et al.*, 1990) showed a much reduced flow than that needed to add to the airborne fraction to balance the man-made input. The original report was quite extreme, proposing that the flow of carbon into the ocean was reduced by two thirds to 1 gigaton per year. Other analysts have since suggested a somewhat lesser reduction but it still represents a substantial amount of "missing" carbon. The complete analysis strongly suggests that the carbon is going into land areas in the northern hemisphere – presumably the forests. This contradicts the earlier deductions of the sylvanologists. Also, and subsequently, papers have been published establishing a 2 gigaton per year growth of forests in western Europe which could help reestablish the balance. Resolving this series of questions is important for policy implications for the manipulation of forests is a frequently proposed mitigation procedure.

It was understood from the very beginning of analysis of global warming that by far the largest contribution to the warming of the earth by the interaction of solar radiation with the atmosphere was due to the water in the atmosphere. The direct effect of greenhouse gases is small compared to the possibly induced feedback on the generation of clouds, their specific physical characteristics such as height and thickness, and the change in the water vapor content in the atmosphere. The lack of solid scientific knowledge on the phenomena involved was the most serious issue blocking progress in developing useful models and unfortunately the situation remains the same today. There is wide disagreement among the experts on the feedback, not only the magnitude but even the sign.

Another contributing atmospheric constituent that was noted at the time was the aerosol. Little of numerical value was then available. Knowledge has developed considerably in the intervening ten years and it has become an active research area on many fronts. One of the strong incentives is the surmise among many workers in the field that the smaller change in average surface temperature over the last one hundred years as determined from surface stations compared to the model predictions is due to the compensating effect of aerosols. The reduction in the greenhouse effect would simply be due to the scattering of solar radiation by the aerosols. The analysis is complex because a fraction of the aerosol content is anthropogenic, particles from power plants, for example, and some is generated biologically over the oceans. The effects depend not only on the density of the particulate matter but on the size of the particles. Over the years, it has not been possible to achieve a reasonable correlation with the observed temperature change.

To rationalize the observed temperature rise and its less than predicted value, other factors have been looked at. An obvious one is the possibility of variations in solar energy output. In the early stages, it was generally excluded as a possibility by most researchers. Statistical correlation of the temperature change with sunspot number, for example, revealed no connection between the two and it was assumed that that settled the question. Yet a Danish group (Fris-Christensen and Lassen, 1991), using the same data, but correlating the length of the sunspot cycle to the hundred year temperature data found a remarkable agreement. This result has been severely attacked, mostly because the agreement is too good! In any event, the sharp divergence of the results of the two methods at the least puts both in doubt.

Somewhat earlier, Newell *et al.* (1989) published an analysis of ocean surface temperatures that showed no change over the one hundred year period and, as a byproduct, established a small solar effect.

To gain further insight into the possibility of solar variations being a factor, a group of solar astronomers have been studying a number of stars similar to the sun and observe changes over time periods commensurate with the ones associated with the greenhouse climate phenomenon.

The Academy report recognized the importance of other greenhouse gases. The two most prominent ones were the CFC's (Chlorofluorocarbons) and methane. The origin of the CFC's was clear. They are man-made. They result from the use of Freon as a refrigerant, others as industrial cleaners and so on. The growing emissions are estimated to account for 25% of the current greenhouse potential. This is considerable in view of the relatively small volume of these atmospheric components compared to $CO_2$. This smallness is compensated by the fact that the $CO_2$ fraction in the atmosphere is so great that there is a saturation effect. The result is that the induced change in greenhouse potential is proportional only to the logarithm of the change in $CO_2$ concentration. In contrast, the corresponding change due to the change in the CFC's is not only linear but is enhanced due the unusually high absorption activity in the infrared at the molecular level for some of the species.

The CFC's may disappear as a global warming problem, however, because of international agreements restricting their use to prevent their effect of thinning the protective stratospheric ozone layer. It remains to be seen if the substitutes that are being introduced are more climatically benign. The situation with respect to methane has become more confused. Until recently, the methane has been growing at a steady exponential rate. This rate of growth has not only decreased but the actual curve has developed a definite concavity toward the time axis. The source of this atmospheric methane has always been hard to pin down. Rice fields, cattle, termites and the like have been proposed as primary sources but the numbers have never been clear and even less so with the new functional behavior. This dip in rate is not comforting to some for there always is a consideration of an instability due to the worldwide presence of clathrates in the oceans and in the Arctic tundra (MacDonald, 1992). If warming temperatures penetrate deeply enough, sufficient methane could be released at a rate that would feedback positively through the greenhouse behavior of the released methane.

## 2. Average Temperatures vs. Climatic Extremes

There has been a persistent difficulty in presenting the anatomy of the problem of global climate change and that has been the widely used surrogate measure – the average global surface temperature. Taken by itself, a small change in this quantity has very little meaning as far as climate change goes. What is relevant are changes in the statistics of regional environmental phenomena such as periods of sustained droughts as has just occurred in California, the statistics of the frequency and intensity of hurricanes in Florida, for example, the frequency and severity of storm surges, as happens in Bangladesh and so on. Nor are we talking about averages but about changes in the statistical distribution, the variance for example. In these and other matters, very little progress has been made in the modeling arena. Very great efforts, in time, money, and manpower have been and are being expended in developing general circulation models of the globe in many countries. Great ingenuity in programming and the most advanced computing power is being used but little progress has been achieved in assessing the effect of the growth of greenhouse gases on predicting the behavior of regional climate or even predicting today's precipitation.

To emphasize the surrogate nature of expressing climate change in terms of changes in average global temperature, we can visualize a model where the increased greenhouse forcing has such a strong negative feedback that increased cloudiness results in a change in albedo that just cancels a possible temperature increase. There are such proposals. One can hardly say, however, that there has been no climate change. Just the increased cloudiness is a clear climate change and, since it most likely will not be globally uniform, some have indicated (Raval and Ramanathan, 1989, for example) that there would be a spectrum of regional climate effects.

In fact, the spread in predicted average temperature due to an equivalent of doubling $CO_2$ concentration in the atmosphere as calculated by the models ten years ago was approximately between 1 and 4 degrees centigrade. This was what was reported in the first IPCC report and the spread has not significantly decreased. This discrepancy is generally assigned to the different approaches in dealing with the water in the atmosphere. This may or may not be the only source of the discrepancy but the situation remains fairly much the same today. One result is that massive efforts are being made to deliberately compare the workings of the different models to get at the root cause of this behavior.

The generally recognized deficiency was the lack of an equivalent dynamic ocean model coupled to the atmospheric one. There has been some success in this area in that many of the models now incorporate a coupled ocean model although the ocean part is not as advanced as its atmospheric counterpart. This has resulted in the improved understanding and value of the resident lifetime of anthropogenic $CO_2$ in the atmosphere that was put forward earlier.

The major advances in our thinking relative to global warming in these last ten years have been largely made outside the model environment. They have been accomplished via field measurements, some of which have been very ingenious. Among them are the ice core work in the Antarctic (now also in Greenland), the measurement of aerosol concentrations (much more is needed), the direct measurement of the flow of $CO_2$ into the ocean from the atmosphere, vertical temperature probes into the Canadian Shield (Lauchenbruch and Marshall, 1986; Lewis, 1992) and the now continuing measurement of the surface temperature at the earth's surface (Spencer and Christy, 1990) via satellite observations.

The latter series of measurements now cover a slightly larger time span than 10 years to the present. They show no change in average surface temperature over that period of time which is in contradiction to the behavior of the ground station averages. This difference has to be resolved. The measurements, in a sense, cost nothing. They are a byproduct of measurements on spectral emission lines of molecular oxygen. They have the virtue of being composed of a huge number of observations blanketing the entire surface of the earth with virtually no gaps.

The results from the bore holes in the Canadian Shield present still another view on what may be happening. The authors used old and new vertical logging temperature data from abandoned oil prospecting holes to calculate the surface temperature backwards in time for a few thousand years from its diffusive penetration into the earth's surface. The analysis is complicated but they do indeed observe a recent significant rise that, however, follows a minimum in the last century. The effect is more pronounced in Eastern Canada than in the west. This result is somewhat comforting because all models, from the simplest to the most complex, predict increases in the polar regions significantly larger than the average and particularly the equatorial values. The ground station observations do not show this difference and this had been held to be still another model deficiency.

Included in this category of recent advances in understanding the set of phenomena are the aerosols and the changes in visualization of the carbon cycle that were mentioned earlier. These subjects are by no means closed and we will comment on recent developments in the carbon balance later.

Still, for the time being, the giant computer models offer the only apparent road to estimating regional climate changes due to perturbations, man-made or natural. One weakness, that of the effect of changes in atmospheric water content, is being attacked by means of a major field program in the United States, ARM (Atmospheric Radiation Measurements). It is a large complex of instruments that eventually is to be established in a variety of locations to measure the radiation patterns under the normal variety of weather conditions. Again we must wait and be patient.

A totally different set of problems are now being examined that go to the mathematical foundations of the equations that are fed into the computers. These equations are composed of many independent variables connected in a highly non-linear environment. From the famous work of Lorenz on the similar equations for predicting weather we already know that there are problems with the solutions to these equations. But we are also aware of the possible chaotic behavior of coupled non-linear equations. Just what that means in this application is not at all clear. The worst scenario is that viable solutions may not exist.

What is clear is that solutions often tend to drift and artificial boundary conditions have to be employed to stabilize the solutions. When the coupled ocean model was introduced, it was found necessary to use altered values for the wind stress on the ocean surface to obtain non-drifting solutions. As an aside, there is a very difficult problem to overcome in that the time scales for the ocean are far longer than those for the atmosphere and, conversely, the length scales for the ocean are far shorter than those for the atmosphere. A good boundary match is very difficult to achieve. Withal, the computer models achieve a surprisingly good picture of the earth's climate. But this method of "tuning" the models to obtain today's climate is probably not adequate to evaluate changes in climate due to perturbations such as those due to the anthropogenic introduction of greenhouse gases.

This extra detail on models is intended to advance to the next topic which is that of mitigation. To have a successful mitigation program it is necessary to be assured with certainty that the program carries no harmful or unacceptable side effects. To put forward a general statement – although a mitigation procedure is an intended perturbation unlike that of global warming due to $CO_2$ emissions, it is, nevertheless, a perturbation that has to be analyzed with the best analytic tools available, namely the GCM's.

However, from the preceding discussion, we can only be sure that we cannot foretell the regional climate consequences with any degree of reliability and, we may, in fact, unleash a whole series of "unintended consequences", to intentionally borrow a term from the economists. This makes the entire concept of mitigation a precarious one.

This thesis can be made a bit clearer by examining a popular example, that of planting large expanses of trees sufficient in area to take up the increase in $CO_2$ via the excess of photosynthesis over respiration. It is feasible and has certain additional attractiveness if the forests are systematically harvested for fuel, particularly in the form of methyl alcohol. However, there have been several analyses of this stratagem indicating that the change in albedo that would result would just about balance the resultant decrease in greenhouse forcing due to the uptake in $CO_2$. This would appear to be harmless enough except that the reforesting would be concentrated in specific areas of the globe and, while the $CO_2$ forcing is, in some sense, uniform over the globe, the change in albedo would be highly variable over the surface. The asymmetry produced would clearly have variable regional climate changes despite the maintenance of a constant average global surface temperature.

There is another, somewhat more subtle, example of the difficulty in achieving a proper mitigating action. One of the odd features of the 0.5 degree rise in surface temperatures in the last one hundred years is that the rise has been manifested in the nighttime temperature averages. The daytime temperature averages show no change. The GCM models do not show this effect. The implication is that the use of artificially introduced stratospheric aerosols, another popular proposal, would not achieve the same asymmetry and, again, the mitigative effect would not be neutral .

There is a curious parallel to this discussion of the natural phenomenon of global warming in the approach that economic modelers take. After all, one half the problem of global warming is predicting the economic behavior of the peoples of the planet for the next one hundred years. The equations used by the economists have the same ill-natured behavior as the climate ones in being of many dependent variables and highly non-linear. They suffer the same predictive weaknesses and the combination of the two does not engender great optimism.

It is instructive, then, to bypass the complexities of both the climate and economic models by the following argument. We look back and accept that the rate of exponential growth of atmospheric $CO_2$ for the last one hundred years as a given and use it to predict the future growth at the same rate. Since we know that the greenhouse effect of $CO_2$ will increase only logarithmically with the concentration, we would expect an increase in global temperature in the next one hundred years of the same amount as for the last one hundred years namely 0.6 degrees centigrade, assuming that the temperature rise was indeed due to the rise in $CO_2$. This is safe reasoning but unfortunately tells us nothing of the regional climate changes. This also predicts something less than doubling of the $CO_2$ concentration in that period.

## 3. Recent Developments

There is no reason to believe that we are at the end of surprises in this very complicated set of phenomena. At this very time we are being exposed to two very radical concepts. The first is derived from the very recent measurements on the Greenland ice cores. This is a natural sequence to the researches on the Antarctic cores and the wealth of information that ensued. The Greenland cores are more informative because the greater precipitation yields time resolution of the order of one year. The extraordinary result, which is now widely disseminated, is that the earth's climate, as revealed by the cores, was extremely variable on nearly a year to year basis with abrupt changes in average temperature of the order of several degrees centigrade. This pattern abruptly ceased about ten thousand years ago and the temperature (and thus presumably the climate) has remained relatively quiet since. There are several implications or one can more properly speak of surmises. The one is that we are, and have been for several thousand years, in an abnormal climatic state. Another is that we are liable to leave this state and return to the more "normal" one of constant fluctuation at any tine.

The difficult part, if these observations hold up, is that our models give no indication of the existence of an earth with this kind of fluctuating climate. While there has been much talk and some examples of an earth with more than one "stable" climate, mostly in connection with attempts to explain the ice ages, they have not been very convincing The explanation may be straightforward and more comforting. This fluctuating behavior occurred during a period of glacier recession. There is no reason to believe that the glaciers receded uniformly and it is more likely that they alternated in receding from year to year. If so, Greenland would be subject to frequent reversals of winds that are symptomatic or causal of abrupt climate changes. Examination of the particles trapped in the cores may tell the story (Lindzen, 1993).

Questions have also recently arisen in another area. That concerns the source of the rise in $CO_2$ concentration as measured by Keeling. By ignoring the seemingly close correlation between the shape of the known $CO_2$ emissions and the Keeling curve and starting *ab initio*, the startling conclusion can be reached that the anthropogenic component is only part of the rise and the remainder is due to shifts in the much larger natural reservoirs and fluxes. There is some debate swirling around this result but, if it too holds up, then the mitigation and adaptation issues change radically. The problem does not necessarily go away because the changes we may face are not man-induced. They may become even more serious. It is one thing to plan mitigation against man's intervention into the environment. It is another to discuss mitigation against natural global climate change.

Climate change is a fascinating and enjoyable topic when it is drawn away from policy and political considerations. The history of vineyards in Great Britain, the disappearance of Indian complexes in the United States Southwest, the abandonment of farming in the deserts in Peru and many other examples have induced great intellectual curiosity, research, and entertainment. I feel that I should add a brand new one drawn from the observation that the earth had a highly variable climate until about ten thousand years ago. This change coincides closely with man's development of an agricultural basis for existence. Until that time there is no archaeological evidence of any agricultural activity. Human life was that of hunting and gathering. We could surmise that only when the year to year climate remained reasonably stable in a given area that it became possible to experiment, to select, and to draw reasonable return from the efforts.

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# The Stability of the Climate System in Light of Recent Ice Core Measurements

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## Abstract

Recent results from ice cores drilled in Greenland indicate that during the last glacial–interglacial cycle the climate was generally unstable. Rapid shifts in climate conditions during the last glacial period have already been reported. These instabilities, as far as is known, were caused mainly by the buildup and disintegration of extended ice sheets in the northern hemisphere. They altered the circulation of the oceans and thus the atmospheric circulation. Since such internal climate forcings were absent during the warm interglacials, these climatic periods were expected to be more stable. Based on the new results, however, it seems that this concept has to be revised. Very likely, rapid changes also occurred during the last interglacial, the Eemian. Two deep ice cores, drilled only 28 km apart at the highest point of the Greenland ice sheet, reach back to the penultimate glaciation, and cover the last interglacial with sufficient resolution to detect changes on a scale of decades. Although it is possible that the lower sections of the ice cores have been partly influenced by faulting, the findings cast doubts on the stability of warm interglacials. According to these climate records, which cover the last 250,000 years, the last 10,000 years seem to have been exceptionally stable. Nevertheless, from continental data we know that the climate also changed during the Holocene, with tremendous impacts on the environment on a regional scale. The history of the Saharan wetlands, for instance, is linked to shifts in the position of the monsoon belt, as well as to today's climatic conditions for agriculture in China. In such regions, human welfare and development are highly vulnerable to even slight changes in the water cycle. The reported changes in climate during Eemian times can be explained by a higher variability in the hydrological cycle. If the large and abrupt climatic fluctuations during the Eemian are corroborated, as has been done for the glacial, this could also have impacts on policies related to anthropogenic greenhouse gas emissions. Model scenarios for sustainable global socioeconomic development based on a smooth increase in global temperature should

therefore be considered to take into account the possibility of abrupt climate instability.

## 1. Introduction

Due to the enhanced greenhouse effect, climate and environment are expected to change to a degree that exceeds human experience. In addition to conducting predictive climate model experiments to provide scenarios for mitigation and adaptation, there is a critical need for more detailed information on how, and how fast, the natural systems of climate and environment have changed in the past. Important natural archives, which expand our 140 year long instrumental record of climatic data to the last glacial–interglacial cycle, are polar ice cores. Ice sheets and continental glaciers are essentially products of atmospheric processes. Because of the low temperatures, the polar ice sheets record the history of atmospheric gases and aeorosols. They store the original information nearly undisturbed over a long time period. The pronounced seasonality of the isotope ratios $^{18}O/^{16}O$ or $^{2}H/^{1}H$ in the water molecule have long been used as palaeoindicators of atmospheric temperature and for dating purposes by counting individual annual layers (Figure 1). In addition, their relationship in terms of the deuterium excess, $d_{ex}$ = $\delta^{2}$H-$\delta^{18}$O, gives information on atmospheric moisture circulation. Recent results from the two newly drilled ice cores in Greenland are now drawing attention to the rapidity of major climate changes in the past. The time scales of such changes are reported to have been in the range of centuries to decades; their onset or termination could even have taken place within a few years. In the following we summarize these new findings and attempt to relate them to our present climate conditions.

## 2. Climatic Records of the Last Glacial–Interglacial Cycle

A variety of climatic data have been extracted from ice, marine and continental deposits. Their integrative assessment has led to a better understanding of the complex interplay between the climate and environmental systems. An illustrative summary is given by Lorius and Oeschger (1994), from whom Figure 2 is taken. In general, the different climatic parameters underwent more or less parallel changes during the reported 140 kyr timescale. The transition from the glacial maximum to our present interglacial was accompanied by an average global warming of 4–5°C. This can be

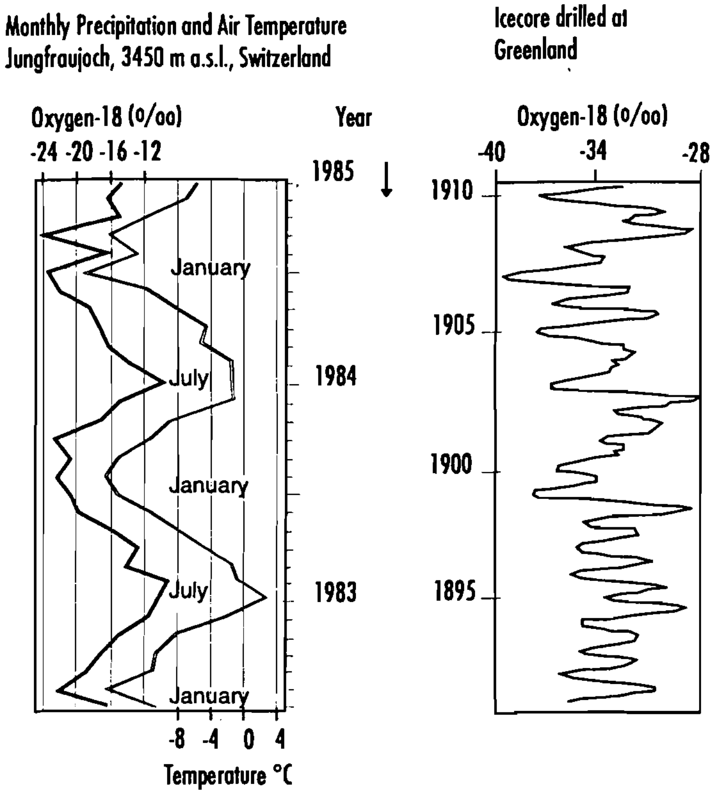


**Figure 1.** Oxygen-18 in monthly precipitation versus mean air temperature at a high altitude station in Switzerland (left). The close correlation allows to reconstruct past air temperatures, the seasonality of the signal makes it possible to count annual layers and establish a time scale for ice cores.

deduced from the oxygen-18 record in Greenland and in Antarctica. The sea level, recorded by changes in oxygen isotopes of marine sediments, rose by about 120 m. The continental pollen record of La Grande Pile indicates that precipitation varied at least by a factor of two. The greenhouse gases, carbon dioxide and methane show parallel rises and falls with temperature. During the warming from the last glacial to the present interglacial, the increase was on the order of 40% for $CO_2$ and almost a doubling for $CH_4$. These changes are linked to the climate–biosphere–ocean system and express modifications of their sources and sinks. Atmospheric $CO_2$ concentrations are governed by ocean circulation, sea surface temperature (SST) and the productivity of mainly the marine biota, whereas those of methane reflect more the biotic activity of continental wetlands. As shown by the shaded parts in

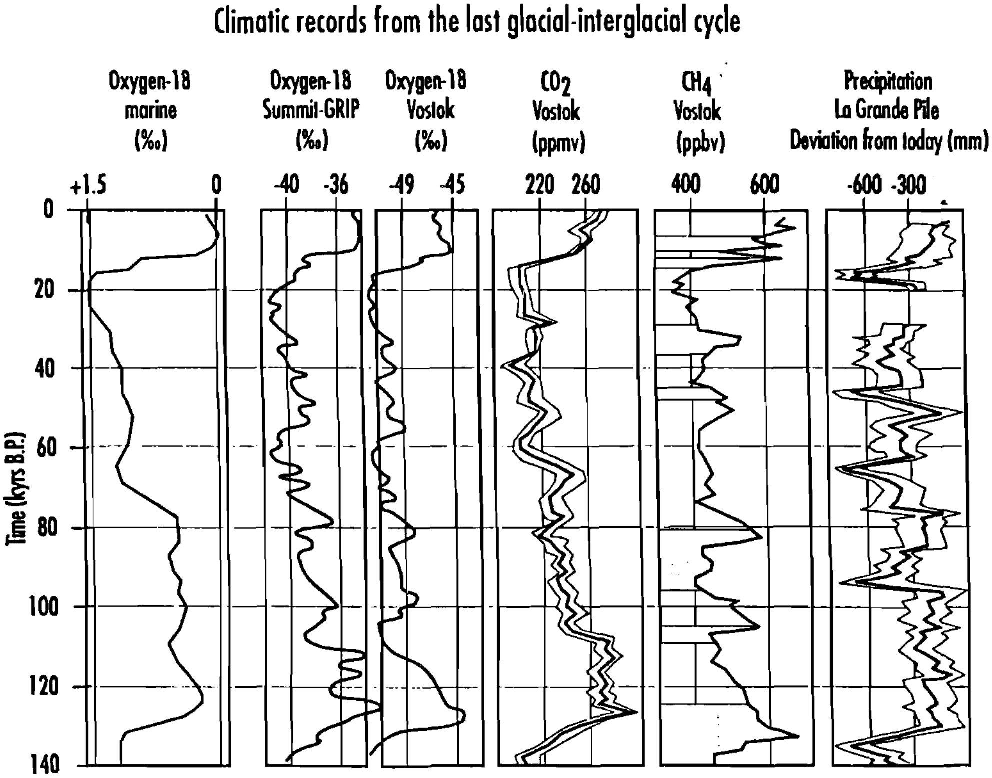


**Figure 2.** The climatic evolution of the last 140,000 years is stored in various natural archives. Oxygen-18 in marine sediments records rise and fall of sea level, ice cores from Greenland (Summit-GRIP) and Antarctica (Vostok) store information about the interhemispheric evolution of atmospheric temperature and greenhouse gas concentrations. The precipitation patterns can be reconstructed from continental pollen records.

the methane record of Figure 2, there is a remarkable correlation between the dated periods of wetland expansion and methane-producing swamps in the Sahara and adjacent areas, and those of high methane concentration in the ice cores (Street-Perrott, 1994). The close relation between $CO_2$ and $CH_4$ concentrations and the climate of the last 140,000 years can be quantified. The recorded change in greenhouse gas concentrations from the last glacial–interglacial transition is equivalent to a change in the Earth's radiation balance of about 2.5 W $m^{-2}$. Due to model considerations this could explain 30–50% of the glacial–interglacial temperature change (Gallée *et al.*, 1992). Unfortunately, until now the poor time resolution of these data has allowed neither a differentiation of leads and lags in the course of greenhouse gas concentration–atmospheric temperature, nor of their interhemispheric coupling. For this purpose, new ice cores have recently been drilled in the Antarctic at sites with sufficient accumulation, and in Greenland. These ice cores are now drawing attention to another aspect of the climate system – its instability over the last 250,000 years.

## 3. The Climatic Record of Oxygen-18 in Summit, Greenland

The successful efforts of both the Greenland Ice Core Project (GRIP) and GISP 2, the Greenland Ice Sheet Program, have provided detailed information on the behavior of the climate system in regions that are influenced by the North Atlantic. These findings will alter our concept of stable climate modes on a global scale. The first results from the GRIP core gave evidence for a general instability of climate in the North Atlantic region over the past 250,000 years (GRIP Members, 1993; Dansgaard *et al.*, 1993). Although rapid changes in climate were already known to have occurred during the last glacial or the transition to the present interglacial (Dansgaard *et al.*, 1989), the new ice core analyses of isotopes and chemical constituents suggest that the last interglacial period was also interrupted by a series of severe cold periods. In late 1993 the results from the GISP 2 core were published. They confirm the earlier GRIP findings in the upper 90% of the core, but differ in its lower section, which contains part of the Eemian and the penultimate glaciation (Grootes *et al.*, 1993; Taylor *et al.*, 1993). From the data obtained so far it seems possible that ice flow has overprinted the climatic signal to a certain extent. Folding can alter the chronological order and may create artificial patterns of climatic information. Figure 3 compares the oxygen-18 record of the GRIP and GISP 2 cores. Since oxygen-18 varies only within a narrow band of 1–2 permille in both cores, the Holocene climate seems to have been convincingly stable. From the air temperature – $\delta^{18}O$ relation for Greenland (Johnsen *et al.*, 1989), the temperature has changed by about $\pm 1.5°C$ on a timescale of centuries; no abrupt and extreme changes are recorded. In the lower half of the cores, which extend to the penultimate glaciation, the $\delta^{18}O$ fluctuates over a much larger range. Shifts in temperature range up to 7–10°C, for longer lasting, relatively stable periods like the Holocene are missing. The reason for the unstable behavior during glacial times was an intense ice sheet–ocean–atmosphere coupling of

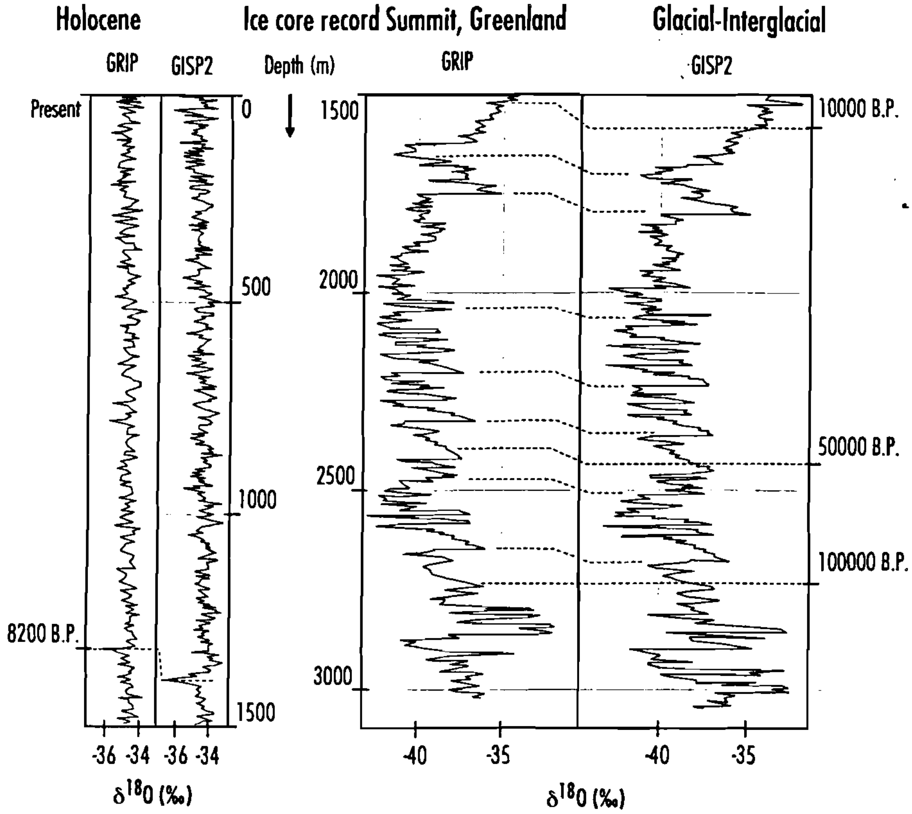


**Figure 3.** Comparison of the GRIP and GISP 2 ice cores from Greenland. Dotted lines indicate major climatic events identified in both oxygen-18 records. The correlation of the data gets poorer below 2800 m depth.

the North Atlantic climate system. The repeated buildup and disintegration of the Laurentian ice sheets most probably caused the asymmetrical cooling cycles, which are also recorded in polar ice and marine sediments. The sawtooth shape of the oxygen-18 series in Figure 3 is repeated in the carbonate shells of cold-tolerant fauna in sediments of the subpolar Atlantic (Bond *et al.*, 1993; Lehman and Keighwin, 1992). The length of such a cycle, with cooling followed by a sudden warming, is on the order of several thousand years, and corresponds to the timescale of the ice cores.

The new data now show that the large fluctuations in climate did not end at the transition to the Eemian interglacial. Although the correlation between the two ice cores is poorer within the last 300 meters, the GRIP record seems to be undisturbed to a greater depth. No severe disturbances due to ice flow are reported for the part that covers most of the Eemian interglacial. Since extended ice sheets did not exist in this warm period, the cause of these climatic fluctuations must have been other than ice sheet instability. A reasonable explanation can be found in an intensified hydrological cycle. Model experiments show that this leads to enhanced variability of the thermohaline circulation, which in turn alters the heat transport in the ocean (Weaver and Hughes, 1994; Stocker, 1994). This again causes changes in atmospheric circulation patterns, which are most likely responsible for the onset or abrupt termination of rapid events that generally punctuate the long-term fluctuations.

## 4. Rapid Events

Climatic oscillations on timescales of decades frequently show up not only in the stable isotope record, but also in dust and chemical traces. Changes in insolation or global ice volume cannot account for these oscillations because of the longer response times involved. The question arises as to what climatic mechanisms could have caused temperature shifts of up 10°C in such short periods. A well studied example of a rapid climate event is the termination of the Younger Dryas at the end of the last glaciation.

The Bølling–Allerød–Younger Dryas sequence has been known from continental climate indicators for a long time. The warming at the end of the last glaciation was interrupted several times by abrupt returns to glacial conditions, culminating in the cold spell of the Younger Dryas. The main forcing for this last major shift in global climate was the disintegration of the Laurentian ice sheet. Its abrupt termination is characterized by large shifts in stable isotopes and other environmental parameters (Dansgaard *et al.*, 1989; Johnsen *et al.*, 1989; Alley *et al.*, 1993; Chappelaz *et al.*, 1993). Figure 4 illustrates these changes over time. From the Dye 3 ice core data (top left) it is obvious that the change in atmospheric circulation was much faster than the general warming. The 5 permille increase in oxygen-18 corresponds to an increase in air temperature of about 7°C that took place within 50 years, but the deuterium excess, accompanied by atmospheric dust concentrations, shifted to lower levels within only 20 years. The warming caused a quick retreat of sea ice cover, the polar front moved northwards from its Younger Dryas position, and a relatively cold water body opened up as a new source of moisture. The intermediate temperatures between the tropical and polar waters lowered the latitudinal temperature gradient and thus the degree of storminess. The latter is described by a reduction in dust concentrations

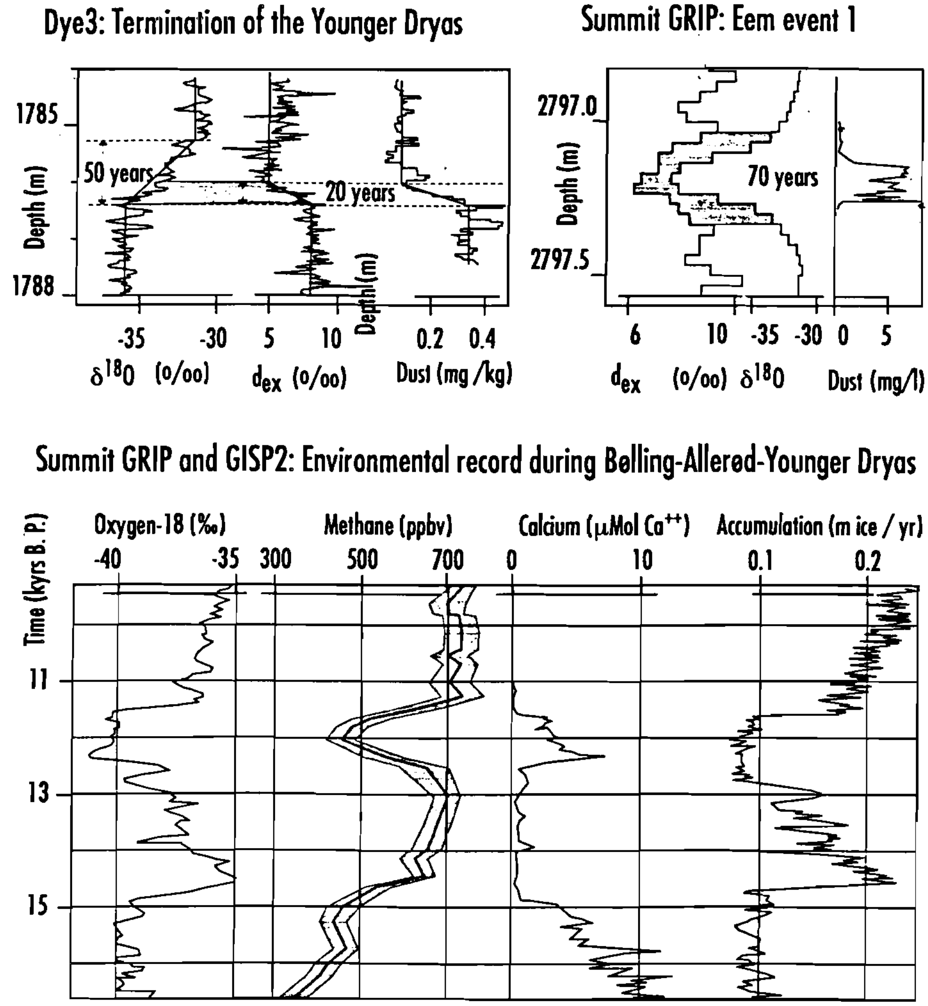


**Figure 4.** Change in atmospheric circulation pattern during rapid climatic events. The similar trend of methane during the Bølling-Allerød-Younger Dryas sequence underlines the global significance of the data.

by a factor of three. This dramatic shift in atmospheric circulation patterns in the northern hemisphere is even more underlined by the change in precipitation. The snow accumulation data from the GISP 2 core (lower right part of Figure 4) have been used to reconstruct the Bølling–Allerød–Younger Dryas sequence. By multiparameter analyses it has been possible to identify annual layers to high accuracy. This layering suggests that the amount of precipitation not only changed very rapidly at the transition to the Bølling–Allerød warm period, but it almost doubled at the termination of the Younger Dryas event within only three years. These short timescales place severe constraints on the subtle mechanisms that lead to such large changes in atmospheric circulation. There must be some thresholds or triggers in the subtle interplay between the thermohaline circulation and the advection of heat and salt in the North Atlantic climate system.

On the same timescale, rapid events also took place in the Eemian. The example of event 1 in Figure 4 (top right) is taken from an undisturbed part of the GRIP record, 59 m above the section where the layering starts to become inclined. All parameters show behavior similar to those of the Younger Dryas, except the deuterium excess signal, which parallels the $\delta^{18}O$ record throughout the Eemian, but is strongly in antiphase during the late glacial and the Younger Dryas. This implies general differences in the sources of atmospheric moisture and their circulation patterns during the interglacial as compared to the Younger Dryas example. The rapidity of these shifts again points to a highly variable ocean with changing heat and moisture transport. Thus the questions arise as to whether such extreme events are restricted to the North Atlantic climate system, and also whether such shifts in our stable climate conditions could be triggered by human interference.

At least the first question can be answered to some extent. Since methane is a climate parameter of global relevance, the Summit record also provides a link between ice cores and tropical climates.

## 5. Ice Cores and Tropical Climates

Although up to now the sample frequency of methane cannot be compared with the high-resolution records of other climatic parameters, it is obvious from the lower part of Figure 4 that this indicator of biotic activity underwent similar changes during the Bølling–Allerød–Younger Dryas period. The record in Figure 5 confirms the earlier Vostok data with a better time resolution in the northern hemisphere. It is obvious that atmospheric methane concentrations more or less paralleled the Greenland climate from 40,000 BP to the Holocene. Changes in concentration also follow the course of the observed warm interstadials. The increase in $CH_4$ concentrations to Holocene levels occurred at a time when the northern wetlands were still ice-covered, which implies another methane source was the spreading wetlands at low latitudes, as pointed out earlier by Street-Perrott (1994). Indeed, there is increasing evidence of a link between the North Atlantic SST and rainfall patterns in the tropics. Deepwater formation in the North Atlantic drives a

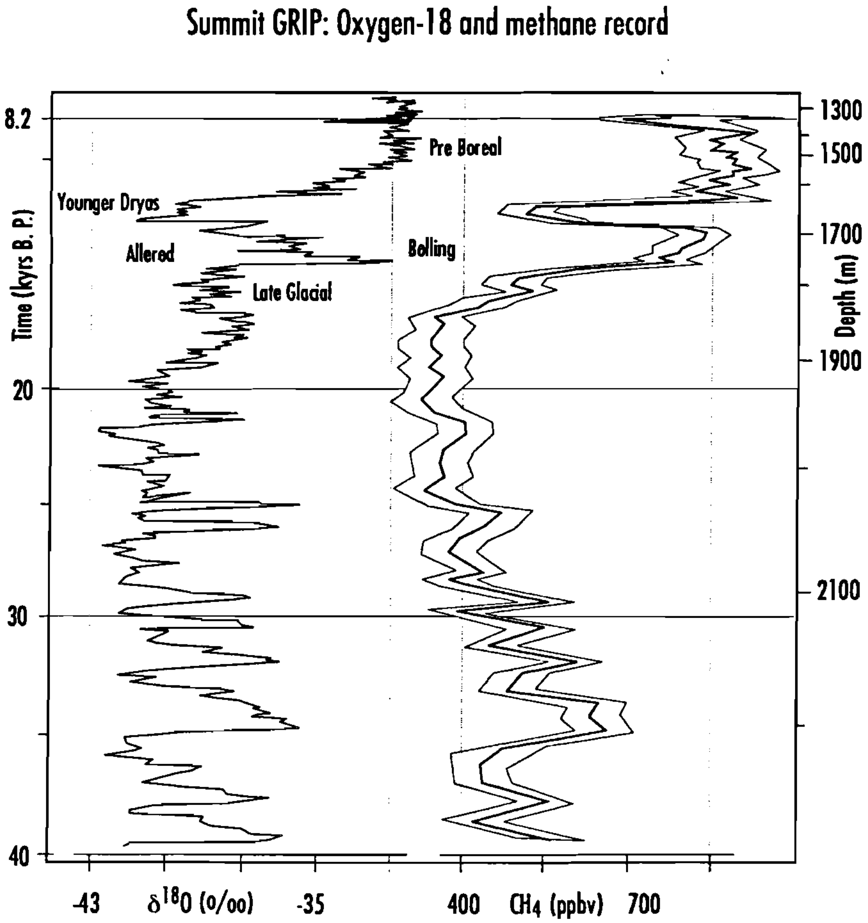


**Figure 5.** Evolution of atmospheric temperature and methane from 40,000 B.P. to Holocene levels. All major warm periods are accompanied by high methane levels. A rapid climatic event at the beginning of the Holocene is marked by the shaded area at 8,200 B.P.

large-scale ocean circulation system, which transports heat across the equator. A shutdown of this huge thermohaline conveyor belt can be caused by low salinity surface waters, as happened for instance during the Younger Dryas. This steepens the temperature gradient between North Atlantic, South Atlantic, and Indian Oceans, which in turn drives the equatorial rain belts. The reconstruction of past salinities in the North Atlantic (Duplessy *et al.*, 1992) showed that a low salinity event also occurred around 8000 BP, corresponding to a known interval of low lake levels in Africa (Street-Perrott *et al.*, 1983). In the top part of the record in Figure 5 a sharp drop in temperature coincides with a lower methane concentration in the ice core.

# 6. Outlook

The extreme dynamics of atmospheric circulation in the past, and the rates of changes in temperature and precipitation as revealed by the new ice core measurements, cast a shadow on impact scenarios for anticipated climate and environmental change. The obvious stability of the present climate compared with that of the past glacial–interglacial cycle is not an isolated conclusion drawn from environmental data from a remote region. The findings are of global significance. We are therefore confronted with the question of whether the rapid events of the past could also be triggered by human interference today. In 1756 Voltaire stated: *Three things influence human thought: climate, politics and religion.* At least for the climate issue, the link between thinking and acting is still missing.

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# Global Warming

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## Abstract

Past and present climate changes are discussed in this paper. Special attention is given to the possible consequences of the present increase in $CO_2$ concentration in the atmosphere.

## 1. Paleohistorical Changes

Analyses of changes in the chemical composition of the atmosphere in the geological past have shown that throughout most of the Earth's history, the $CO_2$ concentration has tended to decrease (Budyko *et al.*, 1985). The decrease in atmospheric $CO_2$ content has had pronounced effects on the biosphere, causing a decrease in the mean surface air temperature due to the weakening of the greenhouse effect. This, in turn, led to the onset of glaciation first in the high, and then in the middle latitudes, as well as to increased aridity of large areas in the low latitudes.

At the same time, the $CO_2$ decrease resulted in a lower intensity of photosynthesis, apparently causing the total biomass on the planet to decrease. These processes were especially pronounced during the Pleistocene glacial epochs when the atmospheric $CO_2$ concentration was often close to 200 ppm. This value is only slightly higher than the two extreme low $CO_2$ concentration values, one of which corresponded to the global glaciation. Although the physical mechanism of global glaciation is not yet clear, calculations revealed such a possibility before the completely glaciated satellites of large planets were discovered during space flights. The second extreme value of $CO_2$ concentration corresponded to a decrease in photosynthesis when autotrophic plants could not survive (Budyko, 1980). Without going into detail, it should be noted that the possibility that the biosphere could be destroyed by natural processes seems to be quite real.

It is interesting to compare this conclusion with the one about high $CO_2$ concentrations in the past, which increased the intensity of photosynthesis of autotrophic plants. This factor, as well as the warmer and more humid climate, provided favorable conditions for most living organisms, including giant land animals that later became extinct.

There is a hypothesis that global cooling during the last 10 million years was an important factor in anthropogenesis (Budyko, 1986). The level of cooling varied with latitude: the high latitudes experienced the most significant reductions in temperature and $CO_2$ concentrations, while in the low latitudes the temperature changed comparatively little. The increase in the difference in temperatures at the equator and at polar latitudes resulted in the expansion of a high-pressure zone situated at tropical and subtropical latitudes. As high-pressure zones are characterized by low precipitation, this area is now occupied by areas of desert, steppe and savannah, which were much smaller in the past warm epochs. As global cooling progressed, the humid tropical forests in many regions of low latitudes disappeared and were replaced by more xerophytic vegetation (usually savannah). In some regions in the low latitudes, arid steppes and deserts appeared. According to paleogeographical data, over the last few million years, the increasing aridity was most pronounced in Africa.

Later, similar climatic fluctuations occurred many times, being especially pronounced in the Pleistocene glacial and interglacial epochs. The deterioration of natural conditions posed new problems for human ancestors, which were first solved during biophysical evolution and then by technical and social progress.

## 2. Modern Climate Change

The conclusion that pronounced changes in the biosphere could occur with relatively small global climatic fluctuations highlights the importance of the rapid increases in atmospheric $CO_2$ concentrations detected not long ago. Over the last 100 years, the $CO_2$ content in the atmosphere has increased by 25%. By burning large amounts of coal, oil, and other carbon-based fuels, man has unintentionally begun to restore the chemical composition of the atmosphere that was inherent to past warm epochs. It can be supposed that the increase in $CO_2$ concentrations has already caused the mean global temperature to rise by about 0.5°C. During the next decades, the $CO_2$ content is expected to double compared with the pre-industrial value, resulting in a mean global temperature increase of several degrees (Budyko, 1972; Budyko and Izrael, 1987; Budyko *et al.*, 1992, etc.). This climate change is likely to have pronounced effects on human life, some of which will be positive and others negative.

In recent decades, the global population has grown very rapidly (it doubled during the last 35 years) to its current level of 5.3 billion. The problem of providing this population with necessary resources has often been discussed, particularly the need to increase the productivity of agricultural crops; this will need to be doubled (compared with the current value) in the next few decades. There is no firm guarantee that enough food will be available if the population increases by several billion.

Maintaining living standards in the next century will also be complicated by the necessity to increase considerably the production of consumption goods, some of which will require additional agricultural resources. This prospect leads us to focus attention on the possibility of restoring the more favorable conditions for living organisms that existed in the past when the atmospheric $CO_2$ concentration was higher than at present.

By burning larger amounts of coal, oil and other fuels, man has unintentionally halted a dangerous decrease in $CO_2$ concentration ($CO_2$ is the main resource from which autotrophic plants produce organic matter), and has made possible the increase in primary productivity which is the basis for the existence of all heterotrophic organisms, including man. It can be supposed that the 25% increase in $CO_2$ concentration compared with the pre-industrial value, has already provided a noticeable increase in total bioproductivity; the increase solely due to the direct effect of $CO_2$ on photosynthesis could amount to 5–7% (Menzhulin, 1992). This means that the recent increase in $CO_2$ concentration could be providing food for about 300 million people.

If by the middle of the next century the $CO_2$ concentration doubles, compared with its pre-industrial value, and if no restrictive measures are taken to reduce fossil fuel consumption, then the increase in crop productivity is likely to provide enough food to meet the requirements of approximately 1 billion people. It is more difficult to assess quantitatively the role of anthropogenic climate change. It is quite possible that the additional global increase in crop productivity due to higher precipitation and temperature will be comparable with the increase due to direct impacts of the increase in $CO_2$. Assuming that progress in agrotechnology during the next 50 years will increase total crop productivity by 60%, we can assume that the $CO_2$ concentration increase will provide food for about 2 billion people in 2025–2050.

These conclusions about the beneficial effects of the $CO_2$ concentration increase in the productivity of the plants that provide sources of energy for almost all living organisms should not be underestimated. This again attracts attention to the prospect of returning to an epoch of more fertile biosphere, when increased vegetation productivity could support a considerable increase in the biomass of heterotrophic organisms. In the very near future, billions of people could turn out to be additional heterotrophic organisms, while the energy basis for their existence has not yet been secured.

The choice of the strategy for economic activity during the period of global warming will have significant economic, social, and political impacts. However, a substantiated choice is impossible without reliable information on future climatic conditions. Nevertheless, even with no such information, many attempts have been made to determine the optimum strategy.

Most of these attempts are based on the assumption that although the features of future climate change are unknown, the consequences of such changes may be catastrophic and should be avoided. The reduction of greenhouse gas emissions, especially of $CO_2$, the influence of which on global warming is the most significant, is considered to be the most effective way of achieving this goal. Calculations show that relatively small reductions in greenhouse gas emissions are unlikely to have a pronounced effect on future temperature changes. To slow down global warming noticeably, greenhouse gas emissions should be reduced immediately by several tens of percent, which will require expenditures that many countries can not afford. The supporters of this strategy advocate economic hardship now in order to avoid unproven climate catastrophe in the future.

At the same time, the possible negative consequences of climate warming for some regions should be remembered; (these include more severe drought, floods, inundation of low-lying coastal and island zones due to sea level rise, etc. Thus, considerations of the problem of climate change should take into account its complex character. However, it is very important to assess the major global impacts of climate warming and to find effective ways of preventing negative consequences.

## 3. Research Needs

A simple approach to choosing the optimum strategy for economic development is the best justified. Bearing in mind that economic calculations for the future are to a large degree conventional (the forms of economic activity are constantly changing) and the prevention of catastrophic food shortages is a priority, other consequences of global warming can be considered less important than the need to provide the increased population with food.

To fulfill this task, it is necessary to obtain reliable information on forthcoming climate changes in different regions during the coming decades. The simplest way to verify the reliability of this information is to compare the results obtained by at least two independent methods of determining anthropogenic climate change to see whether they agree. In the first successful application of this approach, the results of calculations of the expected increase in mean surface air temperature carried out in 1971 (Budyko, 1972), were compared with observational data from the meteorological station network for the 1970s and 1980s (Budyko et al., 1992). The latter report (as well as some other recent papers) also presents conclusions based on the comparison of observational data on climate change in the 1980s and estimates of expected regional climate changes obtained from studies of warm climates in the past (paleoanalogues). These conclusions give hope that reliable estimates of future climate can be obtained soon.

There are three major conclusions concerning the rational strategy in this situation. First, the level of scientific investigation of the problems associated with global warming should be increased to include a wider range of problems than are currently being considered. Second, it is desirable that the most effective, safe, and economically reasonable ways of adapting economic activity to global warming should be substantiated. Solutions to this problem could be found during the investigations mentioned above. Third, there is probably no sufficient scientific substantiation for changing modern tendencies in global power industry development, particularly for reducing carbon fuel consumption.

The most urgent tasks concerning future climate change are as follows:

1. To assess the likely increases in $CO_2$ and trace gas concentrations in the atmosphere in the next century.
2. To assess expected regional changes in precipitation and air temperature on all continents in the next century.
3. To calculate the correspondence between future crop productivity increases and the need to resolve the problem of food shortages.
4. To analyze other consequences of future global warming.

The results of earlier studies of these problems have been presented in many papers in recent years, including a series of collected Russian and Russian–American reports (Budyko and Izrael, 1987; Budyko *et al.*, 1990, etc.). Continuation of the study will allow a more complete report to be prepared by the end of 1994 that will be important for long-term planning of economic activity.

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# The Caspian Sea Level Rise: A Case Study of the Impacts of Climate Change

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## Abstract

The Caspian Sea is the world's largest inland reservoir affected by climatic fluctuations. The total area considered is over 2 million km$^2$: about 400 000 km$^2$ is the area of the sea itself, and the rest is the watersheds of rivers that feed it. In the 1930s the level of the sea fell by 1.75 m. An additional decrease by more than 1 m (with fluctuations) was observed during 1940–1977, the last year being the minimum. Since then the level has risen steadily and in 1993 it was 2.1 m higher than its lowest level in 1977. The level would be about 1.5 m higher if water had not been taken from the feeding rivers for irrigation. The rise has caused extensive damage to roads, port facilities, cities, beaches, etc. This paper addresses the causes of the rise, and describes attempts at mitigation and adaptation. The problem is complicated by the present geopolitical situation, now involving five independent states: Russia, Azerbaijan, Iran, Turkmenistan, and Kazakhstan. The problem described can also serve as a model case study of the impacts that might be generated by the global sea level rise.

## 1. Introduction

Perhaps the most dramatic example of the impact of the current climate change at the regional level is the rise of the Caspian Sea level. Since 1977 it has risen by 2 m and if water had not been taken for irrigation from the rivers feeding it, the level would be about 1.5 m higher than it is now. Another 10 cm are expected to be added in 1993. Extensive damage has already been caused to roads, port facilities, buildings, cities, beaches, etc., and many thousands of people have been relocated from the shores of the sea. The local authorities urgently need help, advice on what to do, and forecasts of what can be expected in the future.

The problem involves not only compiling risk assessment, and working out strategies for coping with the impacts of climate change, but also obtaining the funds (in US dollars) required for mitigation and adaptation. The Caspian Sea could serve as a good case study of the impacts of the expected rise in the global sea level and the effectiveness of response strategies. In this paper, we briefly discuss the paleogeography of the area, the causes of the changes, and what kind of scientific effort could be developed, how and when, to try to forecast these changes.

## 2. The Water Balance of the Caspian Sea

The Caspian Sea is the world's largest inland lake, a closed reservoir with a surface area of just under 400,000 $km^2$, about equal to the areas of Germany and Austria combined. The sea is fed by several rivers, and about 80% of the runoff is from the Volga River, the largest river in the European part of Russia and in the whole of Europe. Throughout this century the flows of the major rivers have been measured by monitoring stations; the annual mean runoff into the Sea is close to 300 $km^3$, which corresponds to a depth of about 75 cm at the present surface area. The annual mean precipitation over the surface is about 20 cm. A partial natural regulator of the level of the Sea is the bay of Kara-Bogaz-Gol (KBG) on its eastern coast. Water flows into the bay via a narrow channel, and is then evaporated intensively in the surrounding desert. The volume of water flow into the KBG depends on the level of the Sea but at the high levels observed in the first quarter of this century it could consume up to 30 $km^3$ annually, or up to 7.5 cm of the Sea level.

Another debit part of the Sea water balance is evaporation from the surface. Using meteorological information from 17 monitoring stations along the shore and on few islands (see Figure 1), the evaporation from the Sea can be estimated if the sea surface temperature (and, therefore, the absolute humidity at the surface), the humidity at the level of the measuring instruments, and the wind speed are known. After some extrapolation and interpolation procedures it can be extended over the whole Sea surface (see Golitsyn and Panin, 1989; and Panin *et al.*, 1992) to obtain the annual mean depth of water that is evaporated. Between 1900 and 1975, it was about 90 cm per year. Of course, there are interannual variations in all components of the water balance, leading to fluctuations of the water level.

Knowing the river runoff, the area of the Sea as a function of its level, and with estimates of precipitation (from a limited number of monitoring

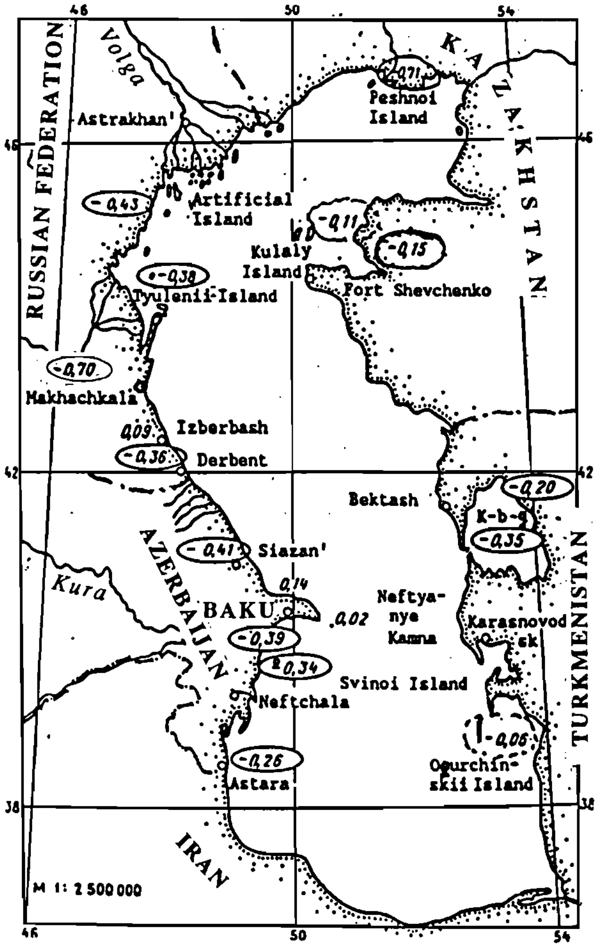


**Figure 1.** Map of the Caspian Sea and the locations of meteorological monitoring stations. The numbers in ellipses denote the significant values at the 95% level of confidence for the linear trend in annual mean wind speeds in m/s/10 years (see text and Figure 4).

stations) and evaporation, one can compare the estimated sea level changes with those actually observed. Figure 2 presents the calculated changes in annual mean sea level ($\Delta H_{\rm est}$) versus the observed changes ($\Delta H_{\rm obs}$) for 1930–1986. There is a natural spread of points, but the regression is close to unity with a correlation coefficient $r = 0.87$. The agreement is better when we calculate the accumulated changes for several consecutive years: for the 1930s the calculated change was 170 cm versus the observed 175 cm, and for

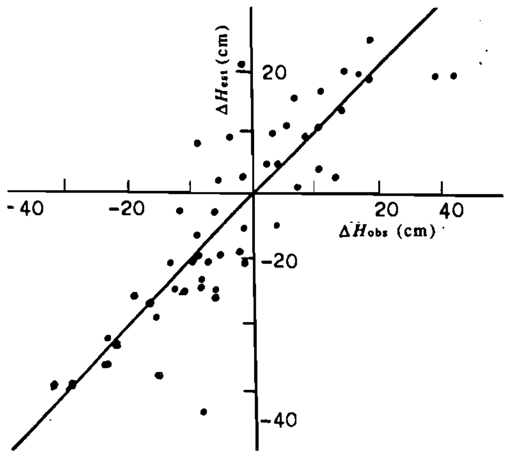


**Figure 2.** Observed versus calculated values of the changes in the Caspian Sea level, 1930–1986, based on the climatic water balance. The correlation coefficient $r = 0.87$. Source: Golitsyn and Panin, 1989.

the period 1977–1986 the calculated change was 103 cm versus the observed 117 cm. These calculations support the argument that the changes in sea level have been caused by changes in the climatic water balance, leaving little room for other causes such as geological movements of the sea floor, or the release of water from, or seepage into, the underlying rocks.

The instrumental measurements of the Caspian Sea level started in 1837 in Baku and until recently there were eight posts along the shoreline and on some islands in the former Soviet Union. The level also undergoes seasonal fluctuations with a maximum in summer and a minimum in winter, with a range of some 40 cm. The record of annual mean values since 1837 is presented in Figure 3; the data from the Baku station are given here because other stations began operations only during this century. During the first 100 years, the level was within –25 and –26 m (minus means that the level is below the global mean sea level, msl), and a dramatic drop occurred in the 1930s. The minimum of –29 m was reached in 1977, and since then there has been a steady rise. In 1992 the level was close to –27 m.

Water is taken from major rivers feeding the sea for irrigation and other purposes; in the 1970s and 1980s estimated abstraction rate was around 40 km$^3$/yr and less in preceding years. Estimates made by the Institute of Water Problems in Moscow (and supplied to the author by its Directors, Professor M.G. Khublaryan) indicate that if the water had not been used for

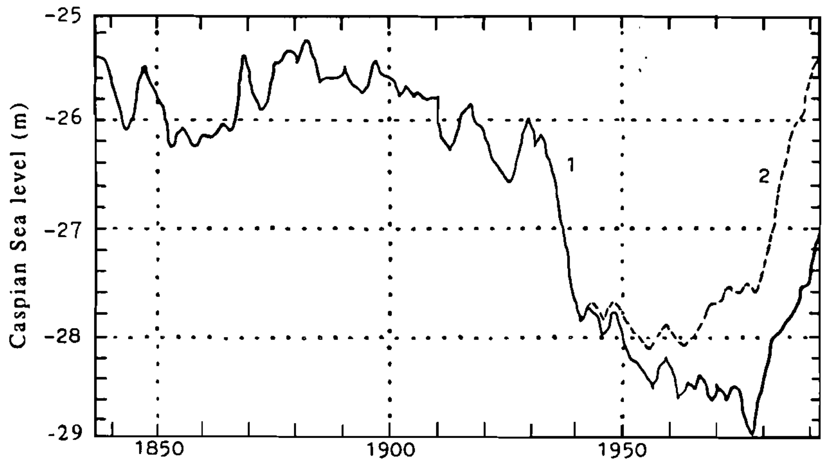


**Figure 3.** The annual mean Caspian Sea level for 1837–1992 in Baku (1); the dashed curve (2) shows the level reconstructed for 1940–1992 for the case if water had not been taken from the rivers feeding the Sea.

these purposes the level of the sea would have started to rise much earlier, and would be 1.5 m higher than it is now.

Our analysis (Golitsyn and Panin, 1989) has revealed that during periods when fluctuations of the level are greater than the general trend, there is no statistically significant correlation between runoff and estimated evaporation, while in the period of the most recent changes there has been a strong negative correlation between runoff and evaporation: in the 1930s the reduced runoff was accompanied by increased evaporation and in 1978–1987 the increased runoff was observed together with reduced evaporation. About 40% of the rise of 1978–1987 can be explained by increased runoff, 40–45% by increased precipitation (which for the period was 20 mm higher than the average over the preceding 50 years), and 15–20% by the dam that cut off the bay of KBG in 1980.

The construction of the dam closing the channel to the bay is an excellent example of how damaging a large-scale project can be to the environment without a full understanding of the regional climate and the lack of its forecast. In the 1970s and 1980s the Ministry for Water Management of the former Soviet Union always favored grand projects such as big canals, diversion of rivers, etc. The fall of the Caspian Sea level in the 1970s (and before) presented a big opportunity to save it from further decreases. As a first step, the dam to cut off the Kara-Bogaz-Gol Bay was proposed, although at the low levels of the late 1970s it was consuming only 1.5–2 cm of the Sea level.

The authorities and scientists of the Republic of Turkmenistan, in whose territory the KBG Bay lay, were against the dam. They argued that without the flow of water into the bay it would dry up in a few years and thus would kill the nearby chemical industry which used the brine of the evaporating water as a raw material. They also feared that the dam would cause dust and salt storms, raising material from the dried-up bottom and transporting it hundreds of kilometers away. But their arguments were ignored by the central government and the dam was built rather hastily in 1980. (In June 1993, the independent Turkmenistan blew up the dam.) During 1980–1992 the presence of the dam contributed about 40 cm to the observed rise of the Caspian Sea level by 2 m.

In an analysis of the causes of the reduced evaporation from the sea Panin *et al.* (1991) unexpectedly found that the wind speed over most meteorological stations had decreased since 1960. Data from 12 of the analyzed 17 monitoring stations showed statistically significant negative trends since about 1960 (these are shown in the solid ellipses in Figure 1; the two numbers in broken ellipses on the eastern shore present small negative trends and three numbers in squares on the western shore show small positive trends. The rate of evaporation is proportional to the differences in humidity just above the surface and at the measurement height (usually at 2 m), and the wind speed. Neither humidity difference nor the sea surface temperature revealed any significant trend, but the wind speed did. Panin and his colleagues (Panin, 1992) then analyzed the wind speed data from several dozen meteorological stations in the Volga basin and found that a majority also revealed statistically significant negative trends in wind speed for the last few decades. This finding should be of interest to energy researchers because the wind speed determines the heat exchange between the atmosphere and buildings, ground surface, etc., and calls for a thorough analysis of the wind field changes. Figure 4 gives an idea of the wind speed changes, based on data from all 17 monitoring stations around the Caspian Sea, averaged over the sea area. Figure 4 clearly shows that the moduli of the wind speeds were positive for the first half of the period and negative for the second half.

Supporting evidence for declining evaporation has been presented by Professor I.A. Shiklomanov, Director of the State Hydrological Institute in St. Petersburg. The Institute has obtained data on direct measurements of evaporation using so-called evaporimeters, dishpans with precise level measurements instruments. Figure 5 presents just three cases out of many showing statistically significant reductions in evaporation from stations on the upper and middle reaches of the Volga River, and on the nearby Don River, about 200 km west of Volgograd. Both pieces of evidence – the weakening

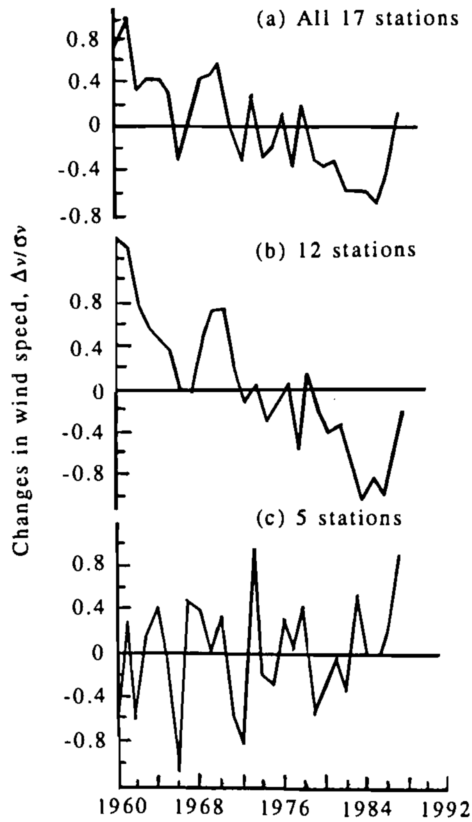


**Figure 4.** Time dependence of the changes in annual mean wind speed ($\Delta_v$) normalized by its variance ($\sigma_v$, recorded at stations on the Caspian Sea for 1960–1987. (a) Values for all 17 stations; (b) for 12 stations at northern and southwestern parts of the Sea with considerable negative trends; and (c) for five stations with small negative or positive trends (numbers in broken ellipses and squares, respectively, in Figure 1.)

wind speed and the reduced evaporation – show good correlation, although thorough analyses of cyclone tracks and their intensities, radiation balance, etc., are required before these data can be fully understood.

Paleogeographic reconstructions of the last few thousand years show that the level of the Caspian Sea has fluctuated from −36 to −22 m, although there are large uncertainties associated with both the dating and the amplitude of these changes (Kaplin, 1992). Fluctuations of the level in the present century may not bear any relation to global warming due to the increase in greenhouse gas concentrations, although both the fall of the 1930s and the

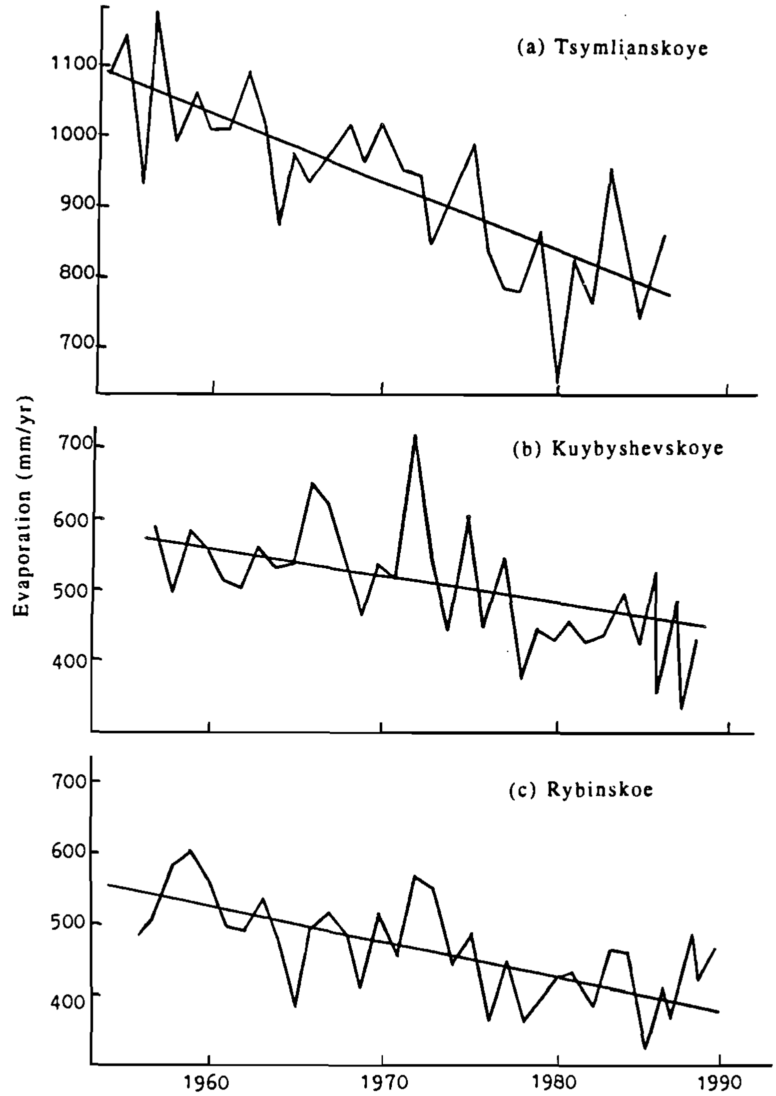


**Figure 5.** Evaporation from three reservoirs on the Volga and Don Rivers during the warm season, 1963–1990. (a) Tsymlianskoye reservoir, 48°N; (b) Kuybyshevskoye reservoir, 52°N; and (c) Rybinskoye reservoir, 58°N.

present increase seem to have occurred more rapidly than any reconstructed changes. The situation only stresses the need for a deeper understanding of climate variability on a regional scale. This is precisely the goal of CLIVAR, a new project in the development of the World Climate Research Program.

One projection of the future Caspian Sea level up to the year 2050 was performed by Budyko *et al.* (1988). They used a scenario in which an equivalent doubling of $CO_2$ would be reached by greenhouse gases by the year 2030. The climate behavior was assumed to be similar to the paleoanalogues: as an optimum of the holocene in the 1990s, the Eemian in the first quarter of the twenty-first century and the Pliocene in the second quarter. For the Volga basin these periods have been studied in relation to both temperature and precipitation patterns, providing estimates of the runoff and the water balance of the Caspian Sea. These procedures gave a slight decrease of the level in the 1990s (not yet observed) and an increase of the level up to about –23 m in the year 2050.

## 3. Coping with Caspian Sea Level Changes

There is anecdotal evidence that rulers of medieval states on the western shore of the Caspian Sea found a very simple and efficient way of coping with the problems of the changing level of the Sea: they strictly forbade the construction of dwellings within a certain distance of the shoreline. Those who broke the rule were beheaded and their dwellings were destroyed. The rule rarely needed to be enforced; people knew they should not do it. This practice is no longer possible, so that other ways of adaptation and/or mitigation have to be found.

In September 1993, the author interviewed a young woman from Baku, the capital of Azerbaijan, to find out how the rise of the sea is perceived and experienced by the local people. According to the woman, all the beaches have gone, the groundwater level has risen, many basements are flooded, people from many fishing villages have been relocated, many roads have been damaged by water driven by onshore winds, the central plaza of Baku with government buildings facing the sea is now often under water during storms, and the construction of dikes has started. Of course, most people are preoccupied by the war with neighboring Armenia and the deteriorating economic situation, but those living close to the Sea are suffering.

The Republic of Dagestan, a member of the Russian Federation, has a shoreline of 490 km and a population of 1.8 million. All the large cities and towns – Makhachkala, Derbent, Kaspiysk, Sulak – are affected by the rising level of the Sea. A typical proposed adaptation measure is the construction of dikes. Hundreds of kilometers of dikes will be necessary up to a level of –23 m, with the possibility that they will need to be raised in the future. Many of the dikes are supposed to serve as roads. Such measures were proposed in the so-called technical-economic report issued in 1992 (see Kaplin, 1992) and more detailed projects are now being designed. The scientific, economic, social, international, and even psychological aspects are expected to be considered in 1994–1995 and large-scale implementation, at least in Russia, is planned for 1996–2000, together with immediate actions taken before 1996.

Of course, having only 695 km of the shoreline of the Sea of the total 7000 km, Russia cannot do everything by itself. But there are important and far from resolved problems regarding the legal status of the Caspian Sea: whether it is a lake, or an international sea, what are the property rights of the five coastal states, etc. These issues need to be fully negotiated, leading to a treaty, but the process has not yet even started and no resolution can be expected in the immediate future.

## 4. Conclusions

The most important conclusion is that the rise of the Caspian Sea is a real problem related to regional, if not global, climate change whatever the reasons: climatic variability or, partly, global changes due to increasing concentrations of greenhouse gases. The problem does not require a risk assessment because real damage is already being experienced, worse can be expected. Positive actions are already being taken, and must continue, together with careful planning for the near future. For the scientific community involved in research in the areas of mitigation and adaptation to climate change, the Caspian Sea level rise is a unique case study of the impacts of sea level rise that is expected on considerably smaller scales in the middle or late next century. The people living around the Caspian Sea need international help, but the scientific community involved in investigations of the likely impacts of global climate change (both natural and socioeconomic) could and should learn much about how people behave, adapt to, and cope with this problem.

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# Part 2
# Integrated Models and Assessments

# Integrated Assessment of Climate Change: An Incomplete Overview

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## Abstract

Integrated assessment is a trendy phrase that has recently entered the vocabulary of folks in Washington, DC, and elsewhere. The novelty of the term in policy-analysis and policy-making circles belies the longevity of this approach in the sciences and past attempts at their application to policy issues. This paper is an attempt at providing an overview of integrated assessment with a special focus on policy motivated integrated assessments of climate change. Section 1 provides an introduction to integrated assessments in general. In Section 2 of the paper, the bounds to the climate change issue are discussed. Section 3 is devoted to a taxonomy of the policy motivated models. In Section 4 the integrated assessment effort at Carnegie Mellon is described briefly. A perspective on the challenges ahead in successful representation of natural and social dynamics in integrated assessments of global climate change is presented in Section 5.

## 1. Introduction

The motivation for integrated assessment (IA) is the immediate need for policy decisions on how to prevent and/or adapt to climate change, and how to allocate scarce funds for climate research. In order to address these needs we need to move beyond isolated studies of the various parts of the problem. Analysis frameworks are needed that incorporate our knowledge about precursors to, processes of, and consequences from climate change. This framework also needs to represent the reliability with which the various pieces of

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the climate puzzle are understood and be able to propagate uncertainties through the analysis reflecting them in the conclusions (Dowlatabadi and Morgan, 1993a).

The last generation of integrated assessments were developed with a focus on the acid rain issue. The RAINS model (Alcamo *et al.*, 1990) was one of the more successful among these earlier studies. RAINS was used to address the contentious issue of acid rain in Europe. Despite the tensions that this transboundary problem engendered, this integrated assessment was part of the process adopted to arrive at a Europe-wide agreement to control acid rain precursor emissions. Similar attempts in the US (e.g., the Acid Deposition Assessment Model (Rubin *et al.*, 1992a), and other models) were either not adopted by decision makers or were mired in interagency disputes (Rubin *et al.*, 1992b).

More recently, the challenge of global climate change has prompted the development of a new flight of models. The path leader was the IMAGE model developed by Rotmans (Rotmans, 1990). The effort in Europe has continued with the Environment Directorate of the European Economic Commission actively supporting the development of the progeny of IMAGE – ESCAPE, and a probabilistic model with an emphasis on policy questions – PAGE. Meanwhile, in the US, the mantle of leadership was assumed by the Electric Power Research Institute which has been supporting IA research of climate change since 1991. Federal funding and mechanisms for support is promised for 1995 (Corell, 1993; Gibbons, 1993).

In scientific research, there has always been a tension between the holistic and reductionist philosophies. The holistic approach attempts to retain its proximity to the world as we know while puzzling out various interactions and causations. Reductionism has been applied to artificially constructed systems where interactions of interest have been isolated and studied. This is more plausible in the natural sciences where specific forces dominate the interactions at various scales. In the social sciences, the various interaction forces are often of similar magnitudes and where interactions may have significant consequences, ethical restraint has ruled out controlled experiments. Integrated assessments motivated by scientific objectives are used to put knowledge gained through the reductionist approach (and otherwise) to the test of predicting the behavior of systems as they occur in nature. These integrated studies pose challenges in representation of both natural and social dynamics.

## 2. The Bounds of the Climate Change Problem

The climate change problem has a number of interesting characteristics. It is a long-term problem. The climate system response is likely to be slow. If there is to be a decision to avoid the possible consequences of climate change prompt action may be needed shortly. The issue is further complicated by the relatively well-known prompt abatement costs and diffuse future benefits. Finally, the actual policy design will have to consider these issues as well as the distributional characteristics of the costs and benefits.

A synoptic perspective of this problem requires consideration of all precursors to climate change.

- There is need to model anthropogenic emissions of greenhouse gases and land-use and land-cover change over the long term. This necessitates understanding and modeling: demographics, social, economic and technological processes. It needs to include relevant information on demographic transition, labour supply and quality, technical change, and other social and economic issues.
- There is a need to understand and quantify the impact of emissions and land-use change on biogeochemical processes and climate. It needs to include the relevant scientific knowledge for modeling the atmospheric-fraction and lifetime of various gases and aerosols, their radiative properties and the response of the climate system to perturbations to earth's radiative balance.
- There is a need to evaluate the impact of the changed environment and climate (as a consequence of anthropogenic emissions and land-use). This evaluation should be as comprehensive as possible, taking into account impacts on market and non-market goods.

These three elements are the necessary foundation for a description of the climate change problem. Their successful integration is a challenge in its own right. However, for policy motivated IA this is only part of the story. In policy research, a decision framework is also needed before relevant issues can be addressed. When considering the climate problem, decision makers can choose from four categories of policies:

*Abatement* – reduce emissions of greenhouse gases or restrain alterations of land cover.
*Adaptation* – adapt to a changed climate and environment.
*Geoengineering* – maintain a subset of climate variables close to some desired level through direct manipulation of the biogeochemical system.

*Research* – invest in research leading to a better understanding of the problem and the properties of the various policy solutions.

The mechanism and the level at which each of these decisions are implemented is a matter that is either simulated or calculated as an optimization problem within integrated assessments.

It is clear that building a single model capable of addressing all the nuances of this problem is not possible. Different approaches need to be adopted to address different questions. Any single model of the whole problem will by design have to treat many issues at a high level of abstraction. Much of the remaining discussions will focus on this special class of integrated assessment models. It is important to note that there are many other integrated assessments aimed at specific aspects of the climate change issue. For example, the GENESIS model being developed by Thompson et al. is an integrated assessment of the biogeochemical cycle and climate. Other integrated assessment efforts are underway for combining the knowledge we have accumulated on ecosystem responses and socioeconomic issues.

## 3. Integrated Assessments for Policy Evaluation

It is inappropriate to treat integrated assessments as if they were the analytical equivalent of Swiss Army knives. A consistent set of objectives need to be defined before an integrated assessment model can be developed. For example: should a cost-effectiveness or cost-benefit framework be developed?; should all four categories of policy choices (identified above) be considered?; should the model calculate an optimal strategy?; should the model be used as a pedagogical tool?; how transportable (across computation platforms) should the model be?; should the model address the issue of value of information and research prioritization?; etc. Various research groups have adopted different lists of desiderata and their models reflect this diversity.

A simple taxonomy of models is presented in Table 1. This is by no means a complete review of all models used to address the climate change problem. The models reported are chosen as being representative of a particular approach to problem structuring. This taxonomy is based on the decision framing of the models. The three categories of models are those where policies are chosen on: (i) the basis of cost-effectiveness, (ii) the basis of a limit to acceptable physical impacts (or a trade-off between abatement costs and physical impacts), and (iii) the basis of a cost-benefit framing.

Only the development of cost-benefit models demands that the dynamics of social and natural systems be represented within an integrated framework

**Table 1.** A taxonomy of integrated assessment models.

| Model name | Opt /Sim | Spatial character | Temporal character | Decision variables | Comments |
|---|---|---|---|---|---|
| *Cost Effectiveness Framing* | | | | | |
| DGEM | S | US with a ROW sector | 1985–2050/ 1 yr steps | abatement | Inter-temporal general equilibrium model of economy with 35 production sectors, 5 energy supply sectors, and 672 households (Jorgenson and Wilcoxen, 1990a, 1990b; Jorgenson *et al.*, 1992). |
| Edmonds Reilly Barns | S | 9 world regions | 1975–2095/ 15 yr steps | abatement | Regional energy economies that trade fossil fuels (Edmonds and Reilly, 1985; Reilly *et al.*, 1987). |
| Gemini | S | US | 1990–2030/ 5 yr steps | abatement | Inter-temporal general equilibrium of energy markets with 19 economic activity sectors. |
| Global 2100 | O | 5 world regions | 1990–2100/ 10 yr steps | abatement | Five regional energy economies with inter-regional trade in oil (Manne and Richels, 1992). |
| Markal | O | US | 1990–2030/ 5 yr steps | abatement | LP model, rich in end-use and supply technologies |
| OECD – Green | S | 8 world regions | 1985–2020/ 5 yr steps | abatement | Inter-temporal general equilibrium with 8 production sectors, 4 consumption categories. |
| *Cost–Impact Framing* | | | | | |
| Hammitt *et al.*, 1992 | O | Global and 2 region models | 2 periods with 10 year time interval | abatement and temperature change | A two stage decision model with resolution of uncertainty at second decision point (Hammit *et al.*, 1992). |
| IMAGE | S | Impacts for The Netherlands | 1900–2100/ 0.5 yr steps | abatement and physical impacts | Emissions from Edmonds Reilly, followed by biogeochemistry, climate, sea level and impact modules (Rotmans, 1990). |
| MBIS | S | Mackenzie Basin, Canada | 1970–2050/ 10 yr steps | abatement and impacts | Detailed regional impacts, market and non-market impacts estimated. |

**Table 1.** Continued.

| Model name | Opt /Sim | Spatial character | Temporal character | Decision variables | Comments |
|---|---|---|---|---|---|
| *Cost–Benefit Framing* | | | | | |
| CETA | O | Global/ 2 region | 2200/ 10 yr steps | abatement | Costs and precursors based on the Global 2100 model. Benefits based on DICE.* |
| DICE | O | Global | 1965–2105/ 10 yr steps | abatement | Full integration of economic activities and impacts of climate change (Nordhaus, 1992a, 1992b). |
| ICAM-1 | S | Global/ 2 region | 1975–2100/ 25 yr steps | abatement, adaptation, geo-eng. | Probabilistic formulation, integration of economy and damages, market and non-market damages (Dowlatabadi and Morgan, 1993b). |
| PAGE | S | Global/ 2 region | 1990–2100/ 5–25 yr steps | abatement, adaptation | Probabilistic, Multi-attribute utility functions to display subjectivity (Hope *et al.*, 1993). |

of assessment. This does not nullify the value of cost-effectiveness and cost-impact models. Indeed, if criteria for past policy decision making are a guide (especially in the US), decisions to protect environmental quality have never been based on a cost-benefit analysis. More often, a decision to "do something" is informed by cost-effectiveness studies.

Interestingly enough, even these cost-effectiveness studies have played a relatively minor role in the level of the "something" finally agreed to and implemented. Ideally, the cost-benefit models can be used to inform the initiation and progress of the sequence of decisions and actions related to climate change policy – i.e., the policy motivated research needs as well as the climate policy.

## 4. Integrated Assessment of Climate Change at Carnegie Mellon University

The Global Climate Change Integrated Assessment Program at Carnegie Mellon is an inter-disciplinary group engaged in a number of research initiatives focused around the climate change issue. The guiding principles for our effort are:

- To explore the whole problem, focusing on policy relevant questions.
- To develop a set of coordinated studies exploring various aspects of the problem. Characterize and quantify the uncertainties. Take the essence of these findings and feed these into an all encompassing quantitative framework.
- To keep it simple. Iterate on the details only where needed to address policy relevant questions and permitted by available knowledge.

Our work is designed to address four questions:

1. Given our current level of knowledge, can we differentiate between different policies designed to mitigate climate change?
2. What drives the system and how may the most effective intervention strategy be identified?
3. In which area do uncertainties most hamper the design of better policies?
4. What would constitute an informed policy-driven research strategy?

Consideration of uncertainties in the design of the model and our intent to make the integrated assessment user friendly have placed strictures on the computation environment and design of the Integrated Climate Assessment Model (ICAM-1). The consideration of uncertainties also demand that a balance be struck between precision and accuracy. Unfortunately, all too often the precision of models is taken to imply accuracy of forecasts. However, the opposite is usually true. Precise predictions require a great deal more information about system dynamics and these are simply not available. This is a particularly pernicious problem in policy motivated research where decision makers ask: "what happens to my constituents?"

We have designed ICAM to capture the uncertainties in our knowledge about the precursors, processes, and consequences of climate change. It can be used to simulate abatement activities, adaptation to a changed climate, and geoengineering activities. In its first iteration, the Integrated Climate Assessment Model (ICAM-1) has been configured to simulate economic and climate change for two global regions (high latitude/developed and low latitude/developing) using 25-year time steps over the period 1975 to 2100. The differentiation between high and low latitudes makes it possible to examine the gross differences in the magnitude of climate change, as well as different economic circumstances and availability of resources needed to adapt to a changed climate. Illustrative runs of ICAM highlight how uncertainties confound the choice of a GHG abatement policy, and how key factors in determining the character of the problem and key uncertainties in making informed judgments can be identified. More detailed information on ICAM is published elsewhere (Dowlatabadi and Morgan, 1993b).

## 5. Challenges Ahead

There are three different challenges on the horizon for integrated assessment studies of climate and global change. The first of these is related to the basic science which provides the fundamental information used in developing IA frameworks. The second is in the methodologies for integrated assessment. The third is in learning what matters to decision makers and designing integrated assessments so that they inform the decision making process and are adopted by decision makers in their activities.

*Basic Scientific Challenges*

In the modeling of socioeconomic aspects of IAs, we suffer a dearth of basic data outside democratic countries. For example, there are no incentives for collection of representative demographic data outside democratic societies. A spectacular example of this issue was found in Nigeria where in anticipation of democratic rule a new census was taken in 1991. This found 88.5 million Nigerians rather than the UNs estimate of 126 million (Central Intelligence Agency, 1992). Furthermore, the models we have developed to describe social dynamics have only been tested in the context of the democratic subset of the world. More generally, our knowledge of key dynamics of social systems is limited. These limitations include, but are not limited to:

- What brings about demographic transition, and how may population changes be predicted over the next century or more?
- What are the roots of technological innovation and diffusion?
- What has led to rapid industrialization in some countries and how have other countries failed to grow?
- How are preferences formed and do they evolve through time?
- Finally, a question common to all these issues. Can these be manipulated through specific initiatives?

In the realm of the natural systems we are faced with similar problems. The dynamics of the climate system continue to be far from well understood.

The real difficulty arises from the dearth knowledge about the internal dynamics of this system. After all, greenhouse gases (other than water vapor and ozone) contribute about 5% of the global warming effect that permits life on earth. The remaining 95% is due to water vapor and ozone whose behavior is internal to the climate system. The challenge in climate modeling is two fold: (i) establishing some measure of confidence about the state of the climate system in the absence of anthropogenic influences, and (ii) predicting the response of the 95% to perturbations in the 5%. The nascent nature of climate science is typified by a continuing stream of "surprise" findings and continuing disappointment in solving what were once thought to be tractable problems. For example:

- We are still at a loss as to how to model clouds (Cess *et al.*, 1990).
- Balancing the "carbon-cycle" remains a challenge, made more difficult with recent evidence of a new reservoir of organic carbon in the oceans (Benner *et al.*, 1992; Toggweiler, 1992).
- CFCs, once thought to be the most potent greenhouse gases, are now believed to have a negligible net warming effect (Wigley and Raper, 1992).
- Fuel and biomass burning as well as biogenic sources lead to emission of greenhouse gases and aerosols. The former lead to long wave radiation being trapped in the atmosphere and "warming." The latter lead to reflection of short-wave radiation. Estimating the magnitude of this cooling effect continues to be a difficult challenge (Kaufman *et al.*, 1991; Charlson *et al.*, 1992).
- We have long known about the central role of ocean circulation in the global climate, but new evidence calls into question long held beliefs on the cause and effect in that relationship (Zahn, 1992).
- And finally, there is paleoclimatic evidence of abrupt climate change and multiple stable states of climate (at least on a regional and possibly on the global scale) but there is insufficient data on what may have triggered these (Dansgaard *et al.*, 1993; Veum *et al.*, 1992).

In plant response studies, we have learned about the importance of $CO_2$ fertilization effect on plants. However, even the first steps towards an understanding the ecological consequence of this matter are yet to be completed. A sensitivity analysis of a leading plant physiology model suggests the impact of changed $CO_2$ concentration to be greater than the impact of climate change (temperature, precipitation, and photosynthetically active radiation) (Shevliakova *et al.*, 1993). However, the most advanced global ecosystem modeling efforts continue to seek impacts on ecosystem distributions as a consequence of changes in temperature and precipitation (Smith and Shugart, 1993). This is an unsatisfactory situation when it is not even clear if our present characterization of ecosystems would persist.

*Methodological Challenges*

In the realm of methodological challenges, there are three frontiers to push back. The first is the frontier of computational techniques for probability and uncertainty analysis in large integrated models. A typical challenge may involve a model such as ICAM-1 being used to explore the issue of research prioritization. The value of research will be dependent on the path of the discovery and concurrent path of investments in mitigation and adaptation activities. All of these factors are uncertain. This makes the optimization possibilities a large combinatorics problem and a computational nightmare. We need to develop efficient algorithms and robust heuristics for solving such problems.

The second problem is that of elicitation of knowledge from experts where the quantified models are unsatisfactory. This is unquestionably a potentially powerful tool. However, the successful practitioners exercise a black art and myriad basic and other problems have never been systematically investigated.

The third challenge is in representation of ignorance in models. This is one step beyond the consideration of uncertainties. To date, most of the major models Global 2100, Edmonds Reilly, CETA, and DICE have been run with stochastic sampling of their input parameters. However, there are only two climate IA models that have considered uncertainties in their design (PAGE and ICAM-1). Furthermore, strict Bayesian theory does not permit the definition of ignorance about a parameter. Some mechanisms exist for getting around the definition of a parameter about which one may be partially ignorant. We need to capture both uncertainties and ignorance in IA models. We especially need to capture ignorance where we have developed well-behaved models of processes (over a limited range of observations) and suspect non-linearities, discontinuities, or bifurcations just around the corner.

*The Challenge of Meeting Policy Maker Needs*

Two issues need to be considered before integrated assessments can be made more useful to policy makers. The first is to recognize that climate change is one of many possible issues decision makers must grapple with. The second is that policy makers do not seem to have made their decisions on the basis of cost-effectiveness or cost-benefit analyses in the past. Past evidence suggests that absolute costs and their distribution matter. Who the beneficiaries are also matters. Finally, policy responses are often triggered by extreme events and rarely by secular trends in key parameters.

These observations suggest that model predictions need to be presented alongside measures of other global change and their impacts. This will help decision makers calibrate their level of effort and reactions to climate change issues. In addition, integrated assessments need to predict distributional characteristics of costs and benefits. Finally, non-linearities and bifurcations need to be incorporated into the assessments. This is a tall order, but aiming to be valuable to the point of being indispensable is a lofty goal.

## 6. Conclusion

In the preceding discussions, an overview of the history and philosophy of integrated assessment has been presented. A number of conclusions can be drawn:

- Support integrated assessments of climate change has already materialized in Europe for such projects as IMAGE, ESCAPE, and PAGE. Support for similar North American integrated assessment efforts is promised for 1995.
- More satisfactory and representative of the dynamics of social systems, ecological systems, and natural systems are needed before integrated assessments can be made more realistic. In addition, non-linearities, bifurcations, and ignorance about systems need to be incorporated into integrated assessment frameworks.
- We do not know how far integrated assessments are from providing the information decision makers use. While this is the case, success of this powerful tool in the policy arena will be a matter of chance.

So the agenda is set for the various parties. The disciplinary scientists need to develop better models of the dynamics of processes they study; integrated assessment teams need to study the decision making of policy makers; and policy makers need to decide if integrated assessment is a useful tool that they would like to endorse and use more widely.

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# Policy Analysis of the Greenhouse Effect: An Application of the PAGE Model*

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## Abstract

In this paper we introduce a comprehensive model for Policy Analysis of the Greenhouse Effect (PAGE). We apply the PAGE model to assess the merits of policies to prevent global warming (by controlling the emissions of greenhouse gases), and policies to adapt to any global warming that occurs. The results confirm that it is difficult to overcome the problem of global warming by taking preventive action alone. The argument for introducing an aggressive adaptive policy is very strong. We calculate the valuation that would have to be placed upon non-economic environmental and social impacts, for a combined strategy of preventive and adaptive policies to be considered a worthwhile option, both for individual regions and for the world as a whole. We also show that uncertainties in all four groups of inputs to the model (scientific, costs of control, costs of adaptation, and valuation of impacts) have a great influence on the costs and impacts of the combined strategy.

*The PAGE model was developed for the Environment, Nuclear Safety and Civil Protection Directorate of the Commission of the European Communities. However, the views expressed in this paper should not be taken to be those of the Commission. A large team of researchers at Environmental Resources Management, the Climatic Research Unit at the University of East Anglia, and the Environmental Change Unit of the University of Oxford provided the data required for the study. The authors wish to thank particularly Hilary Sunman, Sarah Bell, and Maryanne Grieg-Gran at ERL, Prof Tom Wigley, Mike Hulme, and Sarah Raper at CRU, and Prof Martin Parry at ECU.

PAGE is implemented on a desktop computer with a fully interactive graphical user interface so that multiple analyses can quickly and easily be performed, and the model can be used by policy makers and analysts as well as technical experts. Potential users of PAGE should contact Paul Wenman for details.

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# 1. Introduction

There is a current consensus that emissions of greenhouse gases, if allowed to continue to increase, will lead to a rise in global mean temperature. The causal chain from emissions to temperature rise is complex, and even the best scientific estimates of the likely temperature rise by the end of the next century have a range of from 2 to 5°C (Houghton *et al.*, 1990).

There is also much dispute about what damage a global temperature rise of a few degrees over a century or so would cause; regional climatic changes, sea level rise, natural resource and ecological impacts have all been suggested as possible consequences. Some influential groups are sufficiently alarmed to have called for global agreements to stabilize (Joint Ministerial Declaration on $CO_2$ Emissions, 1990) or cut (Fighting Against the Greenhouse Effect by Imposing a Levy on Non-renewable Energies, 1991) the emissions of greenhouse gases.

Others claim that the direct costs of such aggressive control measures would not be justified, and that adapting to a changed climate would be the best policy (Nordhaus, 1990). Policy negotiations are further complicated by the global nature of the problem; if a country, or even a major trading block, decides to reduce emissions of a greenhouse gas, any benefit would also be felt in other parts of the world that do not share in the direct costs of control.

These issues are clearly ones which would benefit from appropriate modeling activity, and models of parts of the problem have been constructed over the past few years.[1] The PAGE model (for Policy Analysis of the Greenhouse Effect) differs from these existing models in its scope. It is a first attempt at what Mors calls "a comprehensive approach covering all the dimensions of the problem" (Mors, 1991). The next section describes the main features of PAGE. Following sections report an application of PAGE to assess the

[1]The state of the art in modeling the science of global warming is contained in Houghton *et al.* (1990) and its recent revisions. Many of the models representing the state of the art in modeling the economics of global warming are gathered together in a special issue of Energy Policy (March 1993). In addition, a model of the costs of controlling emissions in the USA is described in Manne and Richels (1990); extensions to explore uncertainty and look at other regions have also been published in Manne and Richels (1991a and 1991b). Models of the impacts of global warming are at a less advanced stage. Nordhaus (1991a) contains a very simple model based on the vulnerability of economic sectors. Some of the most detailed impact modeling to date has been carried out for the European Community as part of the same project that led to the development of PAGE, and is described in CRU (1992a).

merits of policies to prevent global warming by controlling the emissions of greenhouse gases, and to adapt to any global warming that occurs.

## 2. Outline of the PAGE Model

PAGE contains equations that cover:

- The EC and the whole world. Although PAGE was developed for European Community (EC) policy makers, the greenhouse effect is a global problem. EC emissions of carbon dioxide are only 13% of the world total. PAGE takes account of the gains to the EC of emission controls in the rest of the world. The global mixing of greenhouse gases also means that no region can justify large cutbacks in greenhouse gas emissions by reference to the benefits in that region alone. PAGE takes into account the effect on the rest of the world of EC emission controls. Calculations in PAGE are therefore made for four world regions (currently implemented as the EC, Rest of the OECD, the former USSR and Eastern Europe, and rest of the world).
- The whole of the next century. Dynamics are important. Greenhouse gases emitted today will continue to have a warming effect for decades. The discounted costs of emission controls are much higher if they are made in 2000 rather than 2050. The analysis in PAGE covers the period 1990 to 2100.
- All major greenhouse gases. Global temperature change is calculated not just from the emissions of carbon dioxide, but also from the emissions of methane, CFCs and HCFCs.
- The impacts of global warming. Changes in global mean temperature are compared to the maximum changes that can be tolerated, and weighting factors applied to calculate the impacts brought about by global warming in up to ten sectors of the economy (in the application reported in this paper, seven sectors are used to represent economic impacts, and an eighth to capture non-economic environmental and social impacts).
- The costs of emission controls. Comparison with reductions in the impacts of global warming give an indication of the justification at a regional and global level for policies which would control the emissions of greenhouse gases.
- The costs of adaptation. Comparison with reductions in the impacts from global warming give an indication of the justification at a regional and global level for measures to adapt to a changed climate.

- The effects of uncertainty. The challenge for all greenhouse gas models is to say something useful for policy makers in a situation of profound uncertainty. The only way to meet that challenge was to incorporate uncertainty into PAGE from the start. More than 80 key input parameters are expressed as probability distributions, and all uncertainties are carried through the calculation so that their effect on any result can be found.

The comprehensive scope of PAGE, combined with the need to make the model accessible to policy makers, implies that the simplest credible functional forms should be used throughout; anything else would lead to an impossibly unwieldy model, and would probably not be justified by the quality of data available. This caution applies even more strongly to any attempt to calculate global optimum solutions to the global warming problem, and consequently there is no optimization in PAGE; policies are specified by the user, and PAGE calculates their implications.

The strengths of PAGE flow directly from these design criteria. Scientific opinions that see global warming as inevitable or dismiss it as groundless; top-down or bottom-up estimates of the costs of control; detailed econometric or simple subjective estimates of the damage from global warming; PAGE can use estimates for temperature change, costs of control and impacts that incorporate all of these opinions, because at present none of them can be proven to be mistaken. This ability to calculate with inputs from a variety of other studies is demonstrated in the application whose results are reported in the rest of this paper.

# 3. An Application of PAGE

The general form of the PAGE model is shown in Figure 1. In this application, the base year for the input data is 1990, with PAGE accepting inputs and calculating results for ten analysis years of 1995, 2000, 2005, 2010, 2015, 2020, 2025, 2050, 2075 and 2100.

## 3.1. Preventive policies

A preventive policy is defined by a single value for each of the four gases in each of the four world regions in each of the ten analysis years, giving the emissions as a percentage of the base year emissions of each gas in each region.

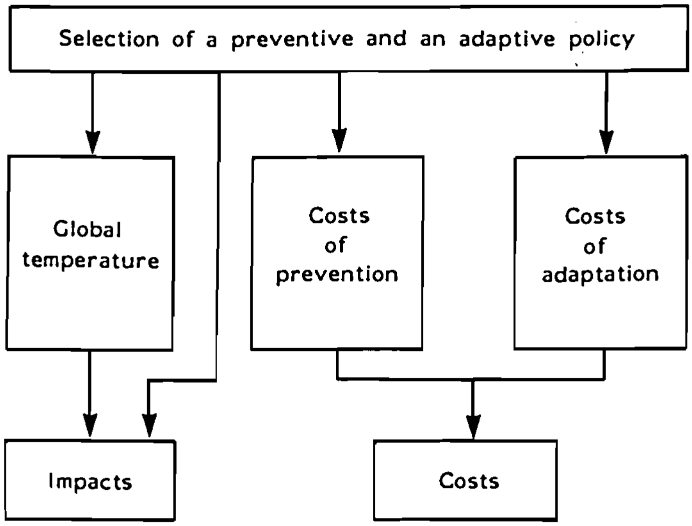


**Figure 1.** The form of the PAGE model.

Two preventive policies are examined in this application with PAGE. There are clearly many other possible policies, but these two are chosen as reasonable representatives of the emissions that might result from unconcern and concern about global warming respectively:

1. A "no-action" policy, with no special measures being taken to reduce or slow the growth in emissions of greenhouse gases in the EC or any other world region.
2. An "aggressive" policy, based on a global package of stringent controls including a carbon tax, a shift to low carbon fuels and improved energy efficiency.[2]

The carbon dioxide emissions of the two policies in the four world regions are shown in Figure 2. With "no-action", emissions rise in all four regions, but the greatest growth by far is seen in the developing countries of the 'rest of the world' region. Global emissions of carbon dioxide rise by about 200% from their 1990 levels by 2100.

[2]In the "no-action" policy, CFC emissions do decrease up to 2025, resulting from implementation of the London amendment to the Montreal protocol by those countries currently responsible for the majority of emissions, but then begin to rise again as CFCs start to be used more abundantly by industrializing countries. This temporary decrease is ascribed to concerns about the ozone layer not global warming. The two policies are described fully in Annex B of CRU (1992b).

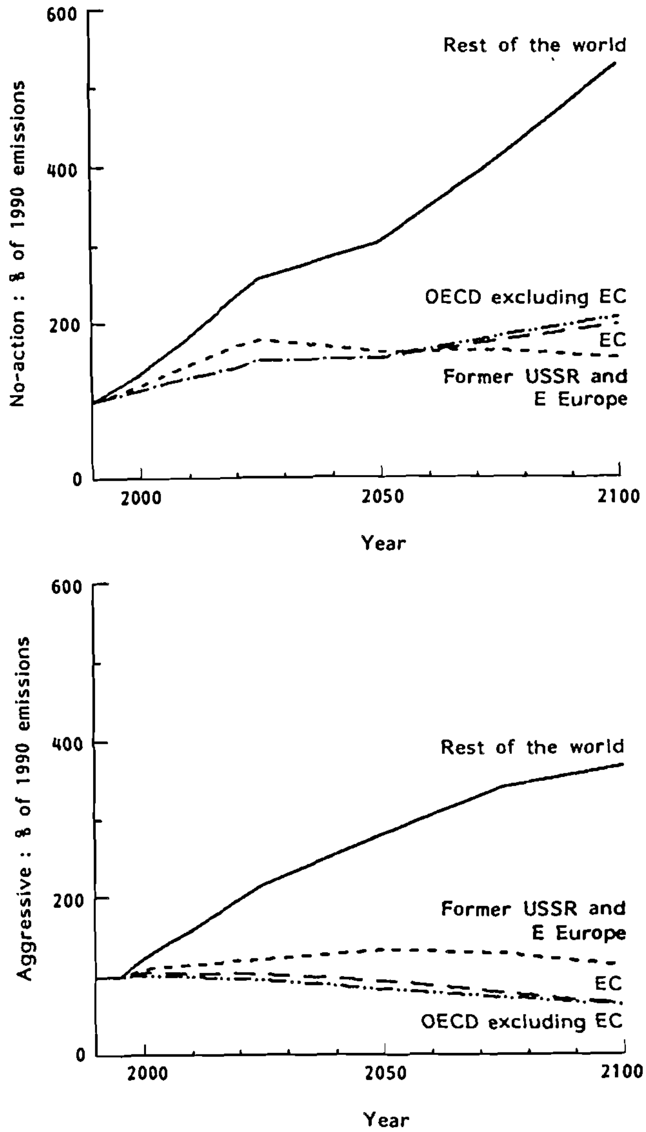


**Figure 2.** The carbon dioxide emissions of two preventive policies.

With an "aggressive" policy, emissions still rise in the developing countries, but at a much slower rate, and absolute emission reductions are seen in other regions. In the world as a whole, carbon dioxide emissions still rise by about 60% from their 1990 levels by 2000.

**Table 1.** Global temperature change parameter values.

| Parameter | Units | Minimum value | Modal value | Maximum value |
|---|---|---|---|---|
| $CO_2$ to air | % | 55 | 80 | 90 |
| $CO_2$ residence | Years | 100 | 120 | 150 |
| $CO_2$ stimulation | Gt/°C | −6 | −2 | 4 |
| Warming from $2\times CO_2$ | °C | 1.5 | 2.5 | 4.0 |
| Global response | Years | 25 | 45 | 70 |

Sources: All these values with the exception of the stimulation of natural $CO_2$ are discussed fully in Hope (1992). The values for natural $CO_2$ stimulation should be compared with 1990 anthropogenic emissions of about 29 Gt of $CO_2$. The modal value implies that there are negative feedback loops at work which inhibit the temperature rise that would otherwise be seen, but the effect is only slight. The minimum and maximum values imply moderate negative and positive feedbacks respectively, which would lead to a damping down or amplification of global temperature rise, as suggested in Balling (1990) and Houghton *et al.* (1990).

## 3.2. Global temperature change

This part of PAGE has been described in some detail elsewhere (Hope, 1992). It retains the essence of the scientific processes leading to increased concentrations, radiative forcing, and a rise in global temperature, but in a highly simplified form.

Most of the parameters take single values, but the five most significant have triangular probability distributions. These five are:

- The percentage of global $CO_2$ emissions that reach the atmosphere.
- The half-life of $CO_2$ in the atmosphere.
- The stimulation of natural $CO_2$ emissions by increased global temperature.
- The equilibrium global warming from a doubling of atmospheric $CO_2$ concentration compared to pre-industrial levels.
- The half-life for global mean temperature to respond to an increase in radiative forcing.

The values used for these five parameters in this study are shown in Table 1.

The parameter values in Table 1 are applied across all policies, and have been calibrated against Scenarios A and D of the Intergovernmental Panel on Climate Change (IPCC), which represent upper and lower bounds

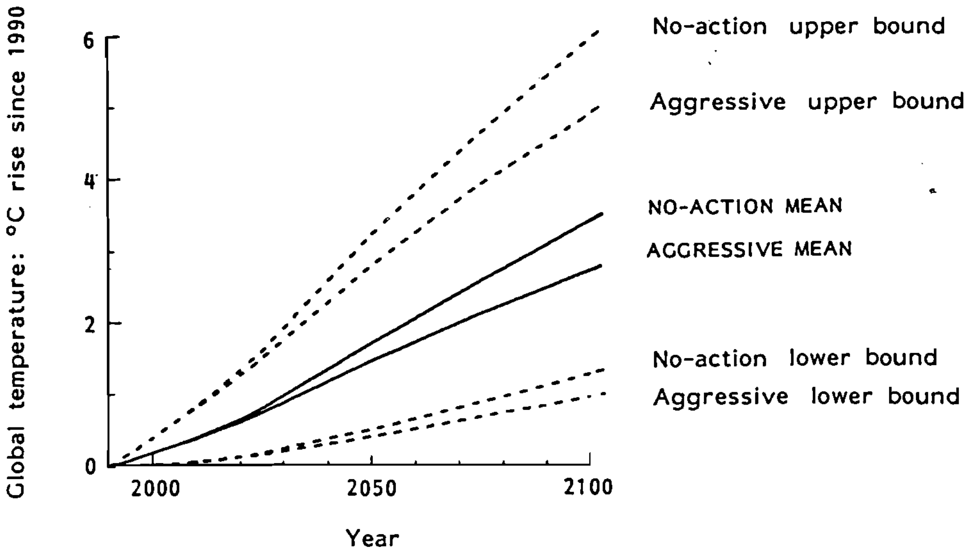


**Figure 3.** The rise in global mean temperature under two preventive policies.

respectively within which actual future emissions are likely to lie (Houghton *et al.*, 1990).[3]

Figure 3 shows two global temperature outputs from PAGE, for the "no-action" and "aggressive" preventive policies whose $CO_2$ emissions were shown in Figure 2. Since PAGE works with probabilistic representations of the parameters of global warming, as shown in Table 1, its calculation of global temperature change is also probabilistic. Figure 3 shows the path of the upper and lower bounds, as well as mean results, over time. Full probability distributions of the global temperature in any analysis year can also be produced.

With "no-action", the mean estimate from PAGE is that global temperature will rise by about 3.4°C between 1990 and 2100, but the range of possible outcomes is broad. The extreme lowest and highest results shown in Figure 3 are 1.3 and 5.9°C respectively; the 5% and 95% points on the

[3]Of course as scientific knowledge improves, users of PAGE can adjust parameter values accordingly. Users cannot add other pollutants, such as Nitrogen Oxides, to those explicitly considered in PAGE, although the excess radiative forcing that they cause is implicitly taken into account in the global temperature change calculation.

probability distribution are 2.0 and 5.1°C. This broad range mirrors the diversity of forecasts that have been made by both mainstream and alternative researchers.[4]

As would be expected, the rise in global temperature is more gentle with the "aggressive" preventive policy than under "no-action", with a mean estimate of a 2.7°C global temperature rise by 2100, a 5% point of 1.6°C and a 95% point of 4.1°C.

The mean improvement achieved by "aggressive" prevention is thus about 0.7°C, or 20% of the expected increase with "no-action", by 2100. This result echoes the often repeated observation that the long time lags in the global ocean/atmosphere system, and the difficulty of moving society away from dependence on fossil fuels, imply that global temperatures will continue to rise for many decades.

The important question is whether this result also implies that efforts to control emissions, as in the "aggressive" policy examined here, are therefore not worthwhile. This is essentially a matter of weighing up costs, benefits, and risks. The remaining PAGE outputs, described below, are designed to assist this difficult process.

## 3.3. Tolerable global temperature change

Small or slow changes in global temperature may not cause any appreciable damage in particular sectors of particular regions, both because the temperature in any region may change less than the global average, and because natural adaptation may be possible for modest changes in climate.

This is modeled in PAGE by using two parameters for each of the impact sectors. The two parameters are input directly for the EC region. The first is called the slope parameter, and gives the maximum rate of change in global temperature that can be tolerated in an impact sector without adverse impacts. The second is called the plateau parameter, and gives the maximum absolute change of global temperature that can be tolerated (however slowly it occurs). Together the two parameters define a tolerable global temperature change profile over time for each impact sector, as shown in Figure 4.

PAGE assumes that if the change in global temperature stays below this profile, there will be no adverse impacts in this sector, even if no adaptive

[4]Mainstream forecasts, such as those in Houghton *et al.* (1990, p. xxii), give a range of from 2 to 5°C; lower values are implied in Balling (1990); positive feedbacks leading to a higher estimate are contained in the appendix to Legett (1991).

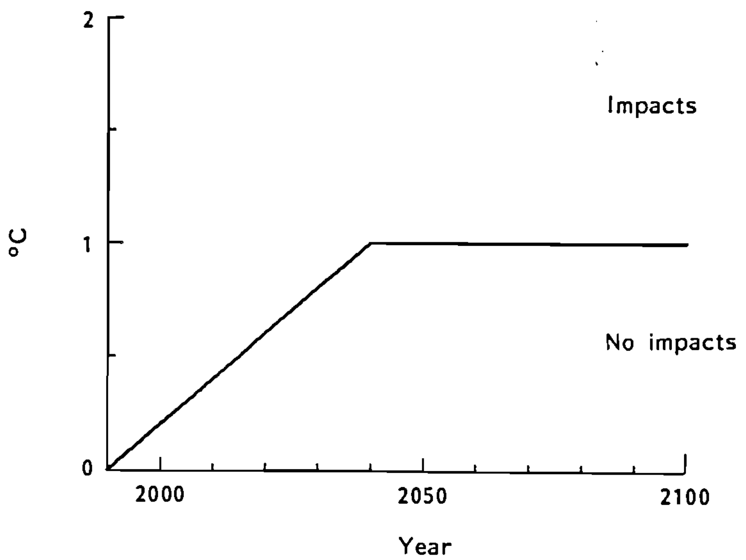


**Figure 4.** The representation of tolerable global temperature change in PAGE.

policy measures are taken. The way in which adaptive policies modify this profile is described under adaptive policies below.[5]

In this study, all tolerable global change parameters are set to zero. Thus any rise in global temperature from 1990 levels is assumed to have some effect, unless adaptive measures are taken, although the size of the effect will be uncertain.

## 3.4. Economic impact weights and damage

A probability distribution for each of the seven economic sectors gives the valuation (in billion ECU per °C)[6] of the impact in that sector in the EC if the global temperature should exceed the tolerable global temperature change profile for that sector. The impact is discounted and aggregated over time by PAGE.

[5]In regions other than the EC, a single uncertain factor multiplies the plateau and slope parameters from the EC to make them applicable to the region in question. Thus a value for this parameter of more than one implies that a region is more tolerant of global temperature changes than the EC, while a value of less than one implies that the region is less tolerant. The same multiplicative factor is used across all impact sectors.

[6]All costs and damage in this study are expressed in European Currency Units at 1990 prices; in late 1992, 1 ECU is approximately equal to US$1.

**Table 2.** Economic impact weight values by sector in the EC (billion ECU/°C).

| Economic sector | Minimum value | Modal value | Maximum value |
|---|---|---|---|
| Tourism | –13 | 4 | 40 |
| Agriculture | –6 | –1 | 11 |
| Mining | 0 | 0 | 1 |
| Manufacture | 6 | 22 | 79 |
| Utilities | 1 | 3 | 10 |
| Transport | 1 | 5 | 17 |
| Services | 5 | 29 | 114 |
| Total | –6 | 62 | 272 |

Source: These figures are taken from CRU (1992a), where their derivation is discussed in detail. The majority of the impact is caused by sea level rise. The values shown apply to 1990; in the study they are increased by 3% per year to represent the greater impact that would be felt as economies grow over time.

Table 2 shows the economic impact weight values used in this study for the damage caused in the economic sectors of the EC. They are applied across all policies. These are very tentative estimates, and the breadth of the ranges in Table 2 reflects this. For tourism and agriculture, it is not even certain whether a global temperature rise would cause damage (represented by a positive value in Table 2), or bring benefits (a negative value in the table).

In the other world regions, a single uncertain factor multiplies the impact weights from the EC to make them applicable to the region in question. Thus a value for this parameter of more than 100% implies that there will be a greater absolute impact in that region than in the EC to a global temperature rise that exceeds the tolerable by 1°C, while a value of less than 100% implies that the absolute impact will be less than in the EC. The same multiplicative factor is used across all sectors. The values used in this study are shown in Table 3.

The implications of the economic impact weight values shown in Tables 2 and 3 are given in Table 4, which shows the global economic impacts under the two policies of "no-action" and "aggressive" prevention. The total rows show the impacts aggregated across all economic sectors and world regions, and for the whole period 1995 to 2100, discounted back to 1990 at 5% per year. The mean results show the "aggressive" measures reducing these impacts by only a little over 10%, from 18.1 to 16.1 trillion ECU. This

**Table 3.** Impact weight values by world region, compared to the EC (percent of EC values per °C).

| World region | Minimum value | Modal value | Maximum value |
|---|---|---|---|
| Rest of the OECD | 80 | 160 | 240 |
| Former USSR and Eastern Europe | 10 | 20 | 30 |
| Rest of the world | 50 | 100 | 150 |

Source: The values are based on estimates of economic activity at risk. Details can be found in Annex A of CRU (1992b).

**Table 4.** Discounted global economic impacts of "no-action" and "aggressive" prevention, by policy and time period (trillion ECU[a]).

| | Low value[b] | Mean value | High value[b] |
|---|---|---|---|
| "No-action" total | 5.6 | 18.1 | 28.1 |
| of which | | | |
| 1995–2010 | 0.3 | 1.1 | 1.7 |
| 2011–2050 | 2.1 | 7.0 | 10.9 |
| 2051–2100 | 3.2 | 10.0 | 15.5 |
| "Aggressive" total | 5.1 | 16.1 | 24.7 |
| of which | | | |
| 1995–2010 | 0.3 | 1.1 | 1.7 |
| 2011–2050 | 2.0 | 6.5 | 9.9 |
| 2051–2100 | 2.8 | 8.5 | 13.1 |

[a]In late 1992, 1 ECU is approximately equal to US$1.
[b]As in all the tables of results in this paper, the low value is the 5% point on the cumulative probability distribution of results, and the high value is the 95% point.

demonstrates just how difficult it will be to deal with the problem of global warming by taking preventive action alone.

For each policy, the impacts are also shown divided into three time periods, and the values in Table 4 reinforce two messages from other studies:

- The major impacts occur after 2050, as the global temperature rises become more marked, and the economies of the world have grown. Under both policies, Table 4 shows that over half of the discounted impact occurs after 2050, even with the relatively high discount rate of 5% per year used in this study.
- The reductions in impact brought about by the "aggressive" policy are even more concentrated in the latter half of the next century. The mean values give a 2 trillion ECU reduction in discounted economic impact (16.1 versus 18.1 trillion ECU); 1.5 trillion ECU of this is obtained after

2050, 0.5 trillion ECU between 2011 and 2050, and much less than 0.1 trillion ECU before 2010.

Whether the "aggressive" policy, which gives a mean reduction in economic impact of the order of 2 trillion ECU, is worth pursuing depends upon three further considerations:

- The extra costs of controlling emissions that would be incurred in following this policy, rather than "no-action".
- The availability and attractiveness of other policies that involve adapting to increased global temperature, either instead of, or as well as, making efforts to prevent the rise in temperature.
- The size of the non-economic impacts, such as environmental degradation and social disruption, that could also follow a rise in global temperatures.

These three considerations are addressed in turn in the next three sections of the paper.

## 3.5. Costs of prevention

A very simple representation of preventive costs is used in PAGE, reflecting the current confused state of knowledge, with results from top-down and bottom-up studies often disagreeing by orders of magnitude.

Even if no measures are taken to combat global warming, emissions of each gas in each region will still change over time because of population change, economic growth, and policy decisions unrelated to the greenhouse effect. For instance, carbon dioxide emissions in the rest of the world will grow with population growth and industrialization, while CFC emissions in the EC will decline because of commitments to protect the ozone layer. This is modeled in PAGE by defining an emission profile for each gas in each region that can be achieved without incurring any costs.

In this study, the zero cost profile is taken to be the 'no-action' preventive policy. Future economic growth rates and other policy measures are not completely known, so a probability distribution is defined for each gas to show the effect of this uncertainty on the profile.

Three probability distributions for each gas express the cost of any reduction below this profile. The first parameter is the annualized unit cost in 1990 ECU per ton of the cheapest control measures, the second gives the range of cutbacks over which these cheap measures can be employed, and the third gives the additional annualized unit costs of any cutbacks larger

**Table 5.** Costs of carbon dioxide control measures in the EC.

| | Minimum value | Modal value | Maximum value |
|---|---|---|---|
| Cost of initial cutbacks[a] (ECU/t of $CO_2$)[b] | 5 | 20 | 40 |
| Extra cost of further cutbacks[a] (ECU/t of $CO_2$)[b] | 20 | 35 | 50 |
| Range of cutbacks for which the lower cost applies[c] (% of 1990 emissions) | 15 | 50 | 80 |

[a]In regions other than the EC, the cost is multipied by between 0.6 and 1.0, with a modal value of 0.8.
[b]In late 1992, 1 ECU is approximately equal to US$1.
[c]In other regions, the range is identical, except for the developing countries of the rest of the world, where it is between 25% and 100% of 1990 emissions, with a modal value of 60%.

than this. The values used for EC carbon dioxide control costs in this study are shown in Table 5.[7]

The modal values from Table 5 show that, for example, with the zero cost profile in 2075 for carbon dioxide being 177% of the 1990 emissions, the first reductions below this would cost 20 ECU/ton, and any reductions below 127% of the 1990 level would cost 55 ECU/ton.[8]

In the other world regions, an additional single probability distribution for each region multiplies the cost parameters for preventive measures in the EC to give the cost parameters in the region in question. A value for this input of more than one implies that the costs of control are higher in this region than in the EC and vice versa. The same factor applies to each pollutant and to both the cheaper and extra costs.

In this study, the unit costs in all other regions are taken to be between 60% and 100% of the unit costs in the EC, with 80% being the most likely value. This reflects the smaller remaining opportunities for low cost conservation given the high energy prices already existing in the EC, and the

[7]No methane control strategies are considered in this study, since the technical potential for control is not yet established. CFC control is included, and the costs are based broadly upon Nordhaus (1991b), but they do not amount to more than a few percent of carbon dioxide control costs in any analysis year.

[8]This range of values is an attempt to incorporate the wide divergence of views expressed in the literature. Top-down macroeconomic models have tended to report high control costs, as in Nordhaus (1991b) and Manne and Richels (1991b). Bottom-up studies such as Mills *et al.* (1991) have found costs much closer to the lower end of the range that we use. The results of Barker *et al.* (1993), which incorporate the effects of recycling carbon tax revenues, and seem to demonstrate very low or even negative preventive costs, came too late to be included in this study.

**Table 6.** Discounted global emission control costs of the "aggressive" preventive policy, by time period[a] (trillion ECU[b]).

| | Low value | Mean value | High value |
|---|---|---|---|
| "Aggressive" total | 0.8 | 2.7 | 5.7 |
| of which | | | |
| 1995–2010 | 0.2 | 0.6 | 1.3 |
| 2011–2050 | 0.5 | 1.6 | 3.3 |
| 2051–2100 | 0.1 | 0.5 | 1.1 |

[a]Emission control costs of the "no-action" preventive policy are essentially zero throughout.
[b]In late 1992, 1 ECU is approximately equal to US$1.

higher costs of construction and civil engineering works in the EC's high wage economy.

Within PAGE, probability distributions are also defined for each pollutant in each region other than the EC describing the percentage range of cutbacks over which the cheaper measures can be employed. The rationale for this is that whereas the costs of the various control measures are unlikely to vary greatly across the world, reflecting only the influence of high local manufacturing costs etc., the range of cutbacks over which cheaper measures can be applied will depend strongly on the particular patterns of industrialization in a region, and so will vary from region to region and gas to gas.

The emission control costs that result from these inputs are shown in Table 6, aggregated across all world regions and discounted back to 1990 at a 5% discount rate. Costs of between 1 and 6 trillion ECU, even when spread over the next 110 years, are not negligible; they are of the same order of magnitude as one year's output from the whole of the EC.[9]

The costs of control are in fact concentrated in the first half of the next century; over half of the discounted control costs come in the period 2011–2050, and over 20% come before 2010. This contrasts with the discounted global economic impacts, shown previously in Table 4, where only about 6% of the total came before 2010, and over half occurred after 2050.

The obvious comparison to make is between the costs of control in Table 6 and the reduction in economic impacts that the "aggressive" preventive policy might bring. Table 7 shows this comparison. At a 5% discount rate, the mean results show the extra costs of control, at 2.7 trillion ECU, just

[9]Gross Domestic Product in the EC in 1987 was 3.7 trillion ECU (Eurostat, 1989).

**Table 7.** Reduction in economic impacts and extra costs of control worldwide: "aggressive" preventive policy versus "no action" (trillion ECU at a 5% discount rate[a]).

| | Low value | Mean value | High value |
|---|---|---|---|
| Reduction in economic impacts | 0.5 | 2.0 | 3.4 |
| Extra costs of control | 0.8 | 2.7 | 5.7 |

[a]In late 1992, 1 ECU is approximately equal to US$1.

outweighing the 2 trillion ECU benefits from the reduction in economic impacts. Only if the costs of control are towards the lower end of the range of estimates, or if a lower discount rate than 5% per year is thought to be appropriate, would the direct economic benefits from the "aggressive" preventive policy outweigh its costs.

It would be possible to pursue this comparison further; it turns out, for example, that in the EC region and the rest of the OECD, even on the mean results and at a 5% discount rate, the costs of the "aggressive" preventive policy are justified by the reduction in direct economic impacts. However, as we commented earlier on the results in Table 4, it would not seem sensible to try to tackle global warming by prevention alone; however draconian the cutbacks in emissions, some warming and consequent economic impacts will occur, and so adaptation to that warming will need to be considered. We turn now to the method of handling adaptive policies in PAGE, and the results obtained from including a package of adaptive measures in the study.

## 3.6. Adaptive Policies

Adaptive policies include measures like the building of sea walls, better management of water resources, land use planning to prevent development in vulnerable areas, and changes in the types of crops grown.

The effect of these measures is modeled in PAGE by defining three single values for each of the economic sectors in each of the world regions in each of the analysis years, describing the three elements of a policy that can be taken in that sector to adapt to climate change.

The first two values increase the speed and absolute amount of global temperature change that can be tolerated in that sector; the third decreases the impact if the global temperature nevertheless exceeds this revised tolerable profile.

The first value defines an increase in the slope of the tolerable profile in an impact sector in a world region, from that analysis year on. For

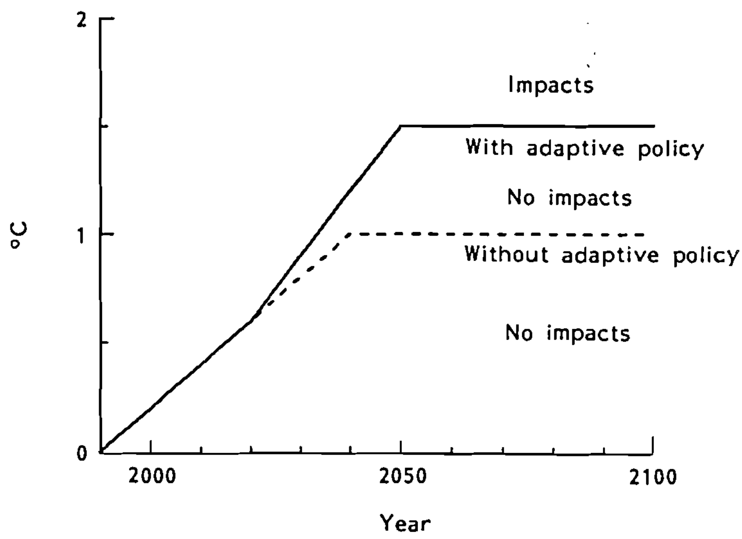


**Figure 5.** The effect of an adaptive policy on tolerable global temperature change.

instance, if the slope parameter without adaptation is 0.2°C per decade, and an adaptive policy provides an extra 0.1°C per decade in 2000, the tolerable climate change profile will have a slope of 0.3°C per decade from 2000 onwards.

The second value describes an increase in the plateau parameter in an impact sector in a world region, from the analysis year in question. The action of the two values together is to alter the tolerable global temperature change profile, as shown in Figure 5.

The third value describes the percentage decrease in impact in an impact sector in a world region, from the analysis year in question, if the change in global temperature exceeds the tolerable global temperature change profile (possibly as modified by the first two values as shown in Figure 5). Thus if the impact weight in an impact sector without an adaptive policy were 5 billion ECU per °C, and the adaptive policy reduced this by 20% from 2010, the actual impact weight used in the calculation would be 5 billion ECU per °C before 2010, and 4 billion ECU per °C from 2010 onwards.

PAGE allows the three elements of an adaptive policy to be phased in over time. The only constraint in the model is that they cannot then be phased out again to recoup their costs, since many of them take the form of massive capital projects, such as sea walls.

As with preventive policies, two adaptive policies are examined in this study with PAGE:

1. A policy representing "no-action" as far as adaptive measures are concerned. Impacts are accepted as and when they occur. This is the adaptive policy that was assumed in the calculations of the global economic impacts from the "no-action" and "aggressive" preventive policies shown in Tables 4 and 7.
2. An "aggressive" package of adaptive measures, based primarily on mitigation of impacts due to water resource changes and sea-level rise.[10] Work is assumed to start on the adaptive policy in the near future, and its effect is to make a global temperature rise of 2°C tolerable in all sectors by 2000. If the global temperature rise exceeds 2°C, land use planning measures are assumed to reduce the economic impacts for each additional °C of temperature rise by up to 90% from those shown in Table 3 by 2050.[11]

As with the "aggressive" preventive policy, the basic comparison is between the costs of "aggressive" adaptation and the reduction in economic impacts that the "aggressive" adaptive policy would bring. Table 8 shows this comparison. At a 5% discount rate, the mean results show that the costs of adaptation, at about half a trillion ECU, are easily justified by the 17.5 trillion ECU benefits from the reduction in economic impacts.

The remaining economic impacts to 2100, if "aggressive" adaptation is introduced, have a mean value of only about 0.3 trillion ECU worldwide at a 5% discount rate. Therefore, adaptation is very effective at reducing the worldwide economic impacts from global warming.

With such a strong excess of benefits over costs at the global level, it is no surprise that the "aggressive" adaptive policy is economically worthwhile in every region. An additional advantage is that all of the benefit from its introduction is captured in the region that incurs the costs. Adaptation is notably different from prevention in this respect.

Despite all the uncertainties, the argument for introducing an aggressive adaptive policy is very strong. Plans should be made to start introducing sea defenses, water resource management, and land use planning measures

[10] The measures include the construction of sea walls, enhanced water resource management, and land use planning to restrict future development in vulnerable areas. They are described in more detail in CRU (1992a).

[11] Except for agriculture in the developing countries, where the pressure of population is assumed to make adaptive measures only 50% effective at all levels of temperature rise.

**Table 8.** Reduction in economic impacts and costs of adaptation worldwide: "aggressive" adaptive policy versus "no action"[a] (trillion ECU at a 5% discount rate[b]).

| | Low value | Mean value | High value |
|---|---|---|---|
| Reduction in economic impacts | 5.5 | 17.5 | 27.0 |
| Costs of adaptation[c] | [d] | 0.5 | 1.0 |

[a]Under the "no-action" preventive policy.
[b]Rounded to the nearest half trillion ECU. In late 1992, 1 ECU is approximately equal to US$1.
[c]The costs of adaptation are modeled in PAGE as follows: Three probability distributions are defined for each of the economic impact sectors. The first gives the annualized cost of an increase in the slope (in million 1990 ECU per °C per decade), and the second gives the annualized cost of an increase in the plateau (in million 1990 ECU per °C) of the tolerable global temperature change profile. The third gives the annualized cost of achieving a one percent drop in the impact weight in the sector. The cost of an adaptive policy in each sector in each year is simply given by the amount of adaptation "purchased" multiplied by these unit costs.
[d]Less than 0.25 trillion ECU.

in all regions. Since they will take several decades to have their full effect, their implementation should start as soon as possible.

Therefore it is against the background of the much smaller worldwide economic damage after "aggressive" adaptation (mean value of 0.3 trillion ECU to 2100), rather than the 18.1 trillion ECU shown in Table 4, that the case for prevention has to be made. It is clear that if "aggressive" prevention cannot be justified by the reduction in worldwide economic impacts with no adaptation, it certainly cannot be justified by pointing to a reduction in the economic impacts of 0.3 trillion ECU that remain after adaptation.

However, relying solely upon adaptation runs the risk of potentially severe and irreversible impacts upon society of a quite different kind from the direct economic impacts that have been considered so far. These impacts are considered next.

## 3.7. Environmental and social impacts

The environmental and social consequences of global warming which do not enter directly into the calculation of economic impacts but which could nevertheless be significant include:

- inundation and permanent loss of coastal locations with particular social, natural, or educational value;

- loss of biodiversity, natural habitats, nature reserves, and areas of special scientific interest, for instance through the inability of ecosystems to migrate sufficiently rapidly in response to shifting climatic zones;
- a lower quality of life through environmental degradation and health effects, for instance from the interaction between climatic extremes and pollution, from the spread of disease with climatic and vegetation shifts, and from the degradation of water resources in less developed regions;
- loss of human life through coastal flooding, natural hazards, health effects, and regional degradation of the socioeconomic resource base;
- the societal, cultural and security implications of large-scale migration;
- local transitional pressures resulting from economic decay in some regions and sectors, and the problems of restructuring to take advantage of new economic opportunities elsewhere.

These impacts cannot easily be estimated, and none of the results reported so far has included them. However, with PAGE we can calculate how such environmental and social impacts would have to be valued in order that a particular combination of preventive and adaptive policies (namely "aggressive" prevention combined with "aggressive" adaptation) would be considered a worthwhile option, both for individual regions and for the world as a whole.[12]

The environmental and social impacts are incorporated into PAGE by designating a new impact sector, and using this to define an impact weight like those described in Table 2 for direct economic impacts. Table 9 shows the weight that needs to be placed upon environmental and social impacts (as a multiple of the modal weight on all economic impacts combined, 62 billion ECU per °C in the EC) for the mean value of a combined strategy of "aggressive" prevention with "aggressive" adaptation to be preferred to adaptation alone.

Because the effect of a preventive policy is to reduce the rise in global temperature, some of its benefits are received outside the region adopting the policy. Two types of motivation are recognized in Table 9 for adopting the combined strategy. If the motivation is selfish, the countries implementing the combined strategy need to see a sufficient reduction in impacts in those countries alone; if the motivation is altruistic, the countries implementing

[12]In this calculation, it is assumed that adaptive measures would be largely ineffective against environmental and social impacts. This may overstate the difficulty of dealing with these impacts, since, for instance, land use planning would prevent some of the loss of life that would otherwise occur with increased flooding in developing countries.

**Table 9.** Valuation of environmental and social impacts to justify a combined strategy, by region and motivation, multiple of direct economic impact.

| Region adopting combined strategy | Selfish motivation | Altruistic motivation |
|---|---|---|
| European Community | 14.8 | 5.1 |
| Whole of the OECD | 3.9 | 2.3 |
| Worldwide | 2.0 | 2.0 |

the strategy need to see a sufficient reduction in impacts in the world as a whole.

The results in Table 9 show how important it would be for the EC to persuade at least its main trading partners in the rest of the OECD to adopt the combined strategy as well.

Environmental and social values would have to be about 15 times the sum of all economic impacts if the EC were to introduce the combined strategy alone, and expect to see a sufficient reduction in impacts just in its own member states. Even with an altruistic motivation, environmental and social impacts would have to be five times direct economic impacts. However, if the whole of the OECD were to introduce the combined strategy, the corresponding valuation of environmental and social impacts would need to be only about four times with selfish direct economic impacts and just over twice with altruistic motivation, respectively. This does not fall much further if the whole world were to adopt a combined strategy; a valuation of environmental and social impacts of twice the sum of direct economic impacts would still be required for adoption of the combined strategy to be justified.[13]

Environmental and social impacts of this sort of magnitude are not unusual in willingness to pay studies; for instance, Randall reports that non-use values such as these are frequently substantial and sometimes exceed current use values, such as our direct economic impacts, by a considerable margin (Randall, 1991).

[13]These multiples are of the valuation of direct economic impacts without adaptation; because the "aggressive" adaptation considered here reduces the direct economic impacts by up to 90% by 2050, environmental and social impacts actually make up the great majority of realised impacts, since adaptive policies are assumed to be ineffective at mitigating them.

**Table 10.** Input parameters having the greatest effect on the costs and impacts of the combined strategy.

| | PRCC |
|---|---|
| *Influence on total cost uncertainty:* Cheaper preventive costs of $CO_2$ | +0.95 |
| No action emissions of $CO_2$ | +0.90 |
| Adaptive cost for altered plateau in services sector | +0.55 |
| Adaptive cost regional factor for rest of the world | +0.50 |
| Range of cheaper $CO_2$ costs in former USSR and Eastern Europe | −0.35 |
| Preventive cost regional factor for former USSR and Eastern Europe | +0.35 |
| Adaptive cost for altered plateau in manufacturing sector | +0.35 |
| *Influence on total impact uncertainty:* | |
| Global temperature sensitivity to doubling of $CO_2$ | +0.95 |
| Half life of global warming response to change in forcing | −0.80 |
| Weight on economic impacts in agricultural sector | +0.75 |
| Weight on economic impacts in service sector | +0.70 |
| Weight on economic impacts in manufacturing sector | +0.55 |
| Proportion of $CO_2$ emitted to air | +0.50 |
| Stimulation of natural emissions of $CO_2$ | +0.40 |
| Weight regional factor for OECD excl. EC | +0.40 |
| Weight on economic impacts in tourism sector | +0.30 |

## 3.8. The treatment of uncertainty

This is about as far as analysis with PAGE can go without some reasonable estimates for actual valuations of environmental and social impacts as opposed to direct economic impacts. The essence of greenhouse policy making is to decide whether the decrease in damage from a more aggressive policy outweighs the increase in preventive or adaptive costs. Given the present state of knowledge, any conclusion must be tentative, and subject to great uncertainty. PAGE offers a final, important means of assistance to the policy maker in the form of a measure of the contribution that the uncertainty in each of the 84 input parameters in the model makes to the uncertainty in the results.

Table 10 shows the input parameters whose uncertainty has the greatest effect on the costs and the impacts of the combined strategy, respectively.[14] The standard measure of the Partial Rank Correlation Coefficient (PRCC) between the input and the result in question is employed in PAGE. PRCC

[14]The costs and impacts do not include environmental and social impacts. These are the inputs whose influence can be declared to be different from zero at the 95% confidence level.

values close to plus or minus 1 show a strong influence; values near to zero show a weak influence.

For costs, all the preventive cost factors refer to $CO_2$, rather than CFCs or HCFCs, as we would expect given the dominance of $CO_2$ costs. The region that has the greatest influence on uncertainty in the total costs is the former USSR and Eastern Europe; no factor for the OECD is significant. Three adaptive cost factors also have a large influence. All the PRCCs are in the direction that would be expected.

For impacts, four factors from the climate part of the model and five concerned with weights show that neither the science nor the economics is dominant in introducing uncertainty about the impacts. All the PRCCs are again in the direction that would be expected.

Overall, it can be seen that important factors come from all four groups of inputs to the model, science, costs of control, costs of adaptation, and valuation of impacts. The ability of PAGE to incorporate all of these uncertainties within a unified framework is one of its greatest advantages over more detailed but partial models.

# 4. Future Uses of PAGE

The PAGE model as it stands is capable of many further applications:

- similar calculations to those reported in this paper, to assist policy makers in world regions other than the EC;
- incorporating improved information on scientific basis, costs of control, costs of adaptation, and valuation of impacts as it becomes available;
- testing out a broader range of adaptive policies which vary both in the effectiveness of the measures taken, and the time scale over which they are introduced;
- varying the growth assumptions and discount rates applied to the valuation of costs, economic, and environmental and social impacts; and
- describing more fully the effects if certain world regions take unilateral action, or refuse to co-operate with policies that are adopted elsewhere.

Refinements to PAGE that are under active consideration include:

- incorporating greater climate change detail, including explicit representations of sea level rise and regional temperature change, which are implicit in the present model; and
- linking the preventive, adaptive, and impact costs back into an explicit model of the economic system.

We would also welcome other suggestions for further applications of, or improvements to, PAGE from the readers of this IIASA Collaborative Paper.

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# MERGE: A Model for Evaluating Regional and Global Effects of GHG Reduction Policies*

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## Abstract

MERGE provides a framework for thinking about climate change management proposals. The model is designed to be sufficiently flexible so that it can be used to explore alternative views on a wide range of contentious issues, e.g., costs, damages, valuation, and discounting.

We begin with a description of the model's individual components and show how they fit together. We then provide an initial application to illustrate how the framework can be used in the assessment of alternative policy options. Four alternative policies are compared with a business-as-usual scenario. In each case, we provide estimates of the costs of abatement and the resulting benefits.

Like all analyses of this type, the results are driven by the inputs. Sensitivity analysis is provided on three key sets of assumptions: the willingness-to-pay to avoid damages, the cost of alternative emission control policies, and the discount rate.

Given the level of uncertainty which pervades the climate debate, it would be unrealistic to expect benefit-cost analysis to lead to consensus on a bottom line - at least any time soon. Rather, models such as MERGE should be viewed as research tools capable of providing insights into which aspects of the debate may be most important. In this way, they can help

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focus the discussion and identify the areas where additional research may have the highest payoff.

## 1. Introduction

To date, much of the greenhouse debate has focused on the costs of emissions abatement. At one end of the spectrum, there are those who believe that substantial reductions can be achieved at negligible costs. All that is needed is to remove energy subsidies, and to dismantle the artificial barriers which limit investment in cost-effective conservation and renewables. If this view is correct, emissions abatement represents an inexpensive hedge against the possibility of unacceptable climate changes.

Toward the other end of the spectrum, there are those who believe that energy markets are already operating efficiently. This group is considerably less sanguine about the costs of greenhouse insurance. Its members find difficulties in believing that economically attractive alternatives currently exist, and are not automatically entering the marketplace. If this view is correct, emission abatement will be far from costless.

As with most policy issues, the answer is apt to lie somewhere between the polar points of view. There are certainly cost-effective opportunities for improving energy efficiency and reducing greenhouse gas emissions. These "no regrets" options would be worthwhile in themselves. But the global abatement targets currently under discussion are likely to entail substantial reductions below a no regrets emissions path. Few believe that this can be accomplished at a negligible cost.

Once we recognize that there are limits to the possibilities for "free lunch", we are forced to make difficult choices. Limited resources must be allocated among competing ends. It then becomes essential to analyze the trade-offs, and to ask what the proposed reductions will buy in terms of reducing the undesirable impacts of global climate change. There are many claimants for scarce resources – e.g., health, education and welfare expenditures. How much of today's limited budget is it worthwhile to spend on the purchase of greenhouse insurance?

Climate benefit–cost analysts face a daunting task. In recent years, considerable attention has been devoted to the economy-wide costs of emission abatement proposals. Although the range of uncertainty is narrowing, we have yet to arrive at a consensus. It is even more difficult to assess what such measures will buy in terms of reduced environmental damages.

Why is it so hard to assess the benefits? To begin with, there remain important gaps in our understanding of the science of global climate change. Increased concentrations of greenhouse gases are likely to lead to global warming. But by how much? Over what time frame? And what will be the impacts on different regions of the globe? Without a better understanding of these issues, it will be difficult to assess the effectiveness of various countermeasures.

There is also the difficult problem of valuation. Critics often complain that economists count what they can count, and not necessarily what counts. It is far easier to value damages to agriculture, energy, and coastal structures than to bio-diversity, environmental quality, and human health. Yet, both categories are important and need to be incorporated into global climate benefit–cost analyses. Unfortunately, there is no widely accepted standard for translating global environmental damages into their dollar equivalents.

And there is the issue of discounting. The greenhouse debate is one of intergenerational trade-offs. Many proposals require substantial near-term costs. Benefits (in terms of reduced damages) do not begin to accrue for half a century. Unless one places a high weight on the welfare of future generations, it will be difficult to justify costly near-term actions. Among policy analysts, there is an enormous range of disagreement as to what constitutes an appropriate discount rate.

This paper will not attempt to resolve these issues: costs, benefits, valuation, and discounting. Rather, our goal is to provide a sufficiently transparent integrating framework so that one can explore the implications of alternative viewpoints. The framework is called MERGE (model for evaluating regional and global effects of GHG reduction policies). It consists of a series of linked modules representing the major processes of interest. These include: (1) the costs of reducing the emissions of radiatively important gases, (2) natural system disposition and reactions to the emissions of these gases, and (3) the reaction of human and natural systems to changes in the atmospheric/climate system.

We begin with a description of the model's individual components and show how they fit together. We then provide an initial application to illustrate how the framework can be used in the assessment of alternative policy options. Four alternative policies are compared with a business-as-usual scenario. In each case, we provide estimates of the costs of abatement and the resulting benefits.

This work builds upon the earlier contributions of a number of researchers. The pioneering effort in this area was done by Nordhaus (1991). Peck and Teisberg (1992) followed up the Nordhaus analysis by showing how

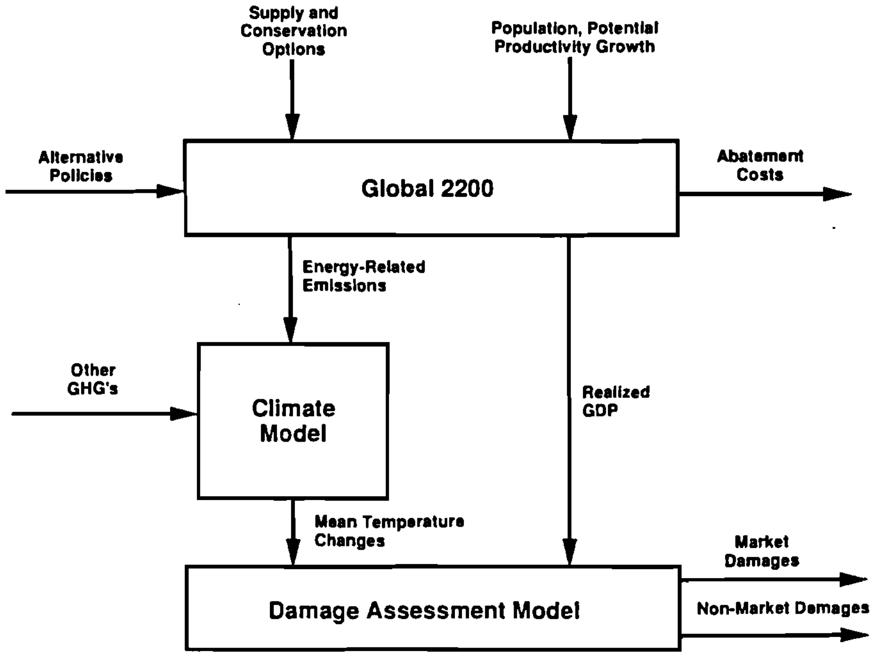


**Figure 1.** An overview of MERGE.

the optimal global emissions path might change under alternative assumptions about economy-wide costs and the nature of the damage function. Falk and Mendelsohn (1993) developed a global model of carbon control which emphasizes the optimal set of carbon taxes over time. Cline (1992) has also conducted analyses at the global level, reporting benefit–cost ratios for a wide range of scenarios. Other researchers have developed regional models for exploring the payoffs from various levels of international cooperation. See, e.g., Eykmans *et al.* (1992), Dowlatabati and Morgan (1993) and Hope *et al.* (1993).

## 2. Global 2200

Figure 1 provides an overview of the principal components of MERGE and highlights the major linkages. There are three major submodels: (1) Global 2200, (2) the climate submodel, and (3) the damage assessment submodel. Each is described in turn.

Global 2200 is used to assess the economy-wide costs of alternative emission constraints at the regional and global level. It is an extension of the Global 2100 model of Manne and Richels (1992). Like its predecessor, Global 2200 divides the world into five major geopolitical regions: the US, other OECD nations (Western Europe, Japan, Canada, Australia and New Zealand), FSU (the former USSR), China and the ROW (rest of world). Unlike Global 2100, Global 2200 is a fully integrated applied general equilibrium model. Each of the regions is viewed as an independent price-taking agent, and is subject to an intertemporal budget constraint. At each point in time, supplies and demands are equilibrated through the prices of the internationally traded commodities: oil, gas, coal, carbon emission rights, and a numeraire good. This numeraire represents a composite of all items produced outside the energy sector. All prices are expressed in terms of US dollars of constant 1990 purchasing power.

The model is benchmarked with energy and economic statistics for 1990. Global 2200 is based upon look-ahead rather than recursive dynamics. This seems particularly important for the evolution of the prices of exhaustible resources such as oil, gas and coal – and for their eventual replacement by backstop technologies.

To facilitate computations, the model employs time intervals of unequal length. There are ten-year time steps from 1990 through 2050, and 25-year steps during the following century and a half. For purposes of current decision-making, it is important to provide details on the near future but sufficient to take a more aggregate view of future events.

## 2.1. Intertemporal optimization

For each region, there is a single representative producer-consumer. Savings decisions are modeled by choosing each region's consumption sequence so as to maximize the sum of the discounted "utility" of consumption. That is,

$$\max \sum_{t=1}^{T} U(c(t))(1+\rho)^{-t} \tag{1}$$

where $U$ is the single period level of utility or social well-being, $c(t)$ is the flow of consumption at time $t$, and $\rho$ is the rate of time preference for utility.

For optimizing the pattern of investment and consumption over successive time periods, we take the special case where the utility function is the logarithm of consumption. That is,

$$\max \sum_{t=1}^{T} \log c(t)(1+\rho)^{-t} \tag{2}$$

This implies that marginal utility is always positive, but is a diminishing function of the aggregate level of consumption. There is a unitary elasticity of substitution between consumption in each time period.

It is important to distinguish between the rate of time preference for utility and the marginal productivity of capital. The former applies to the discounting of the utility of different generations, the latter to the discounting of goods and services. For the logarithmic form of the utility function, the following equation will hold along an optimal steady-state growth path:

$$r = g + \rho \tag{3}$$

where $r$ is the marginal productivity of capital; and g is the annual growth rate. For a proof of this proposition, see Chakravarty (1969, p. 65). Our approach has been to choose a value of $\rho$ so that the marginal productivity of capital will remain close to its current level over the entire planning horizon. E.g., in order to simulate an economy in which the growth rate $g = 2\%$, and $r$ is 5%, we set $\rho$ at 3%.

Note that a lower or a zero rate of utility time preference would not provide a good description of the collective outcome of individual choices. It would also imply an unrealistically rapid increase in the near-term rate of investment and capital formation. See, e.g., the numerical results reported in Manne (this volume). In that report, see also the implications of choosing a more general isoelastic utility function rather than the logarithmic form.

The model is benchmarked and the utility discount rates are chosen so that – when expressed in terms of the international numeraire good – the net real rates of return on capital are identical (5% per year) in all regions. At first glance, this simplification appears unrealistic. For practical purposes, however, this seemed preferable to incorporating the complexities required to define the rate of change of each region's real foreign exchange rate relative to the US dollar.

## 2.2. Production and consumption

In order to focus upon the long-run issues of energy-economy interactions, resource exhaustion and the introduction of new technologies, each region is described in highly aggregated terms. Outside the energy sector, all economic activity is represented in terms of dollars of real purchasing power. Within the energy sector, only two end products are distinguished: electricity and nonelectric energy.

Electric and nonelectric energy are supplied by the energy sector to the rest of the economy. Like the material balance equations of an input-output model, aggregate economic output ($Y$) is allocated between interindustry payments for energy costs ($EC$) and "final demands" for current consumption ($C$) and investment ($I$). Thus:

$$Y = C + I + EC \tag{4}$$

For the economy-wide production function in each region, we assume that gross output ($Y$) depends upon four inputs: $K, L, E, N$ – capital, labor, electric and nonelectric energy. To minimize the number of parameters that require either calibration or econometric estimation, the long-run static production function is described by a nested nonlinear form:

$$Y = \left[a(K^{\alpha}L^{1-\alpha})^{\gamma} + b(E^{\beta}N^{1-\beta})^{\gamma}\right]^{1/\gamma} \tag{5}$$

where $\gamma = (\sigma - 1)/\sigma$ for $\sigma \neq (0, 1, \infty)$.

Equation (5) is based on the following assumptions:

- there are constant returns to scale in terms of these four inputs;
- there is a unit elasticity of substitution between one pair of inputs – capital and labor – with $\alpha$ being the optimal value share of capital within the pair;
- there is a unit elasticity of substitution between the other pair of inputs – electric and nonelectric energy – with $\beta$ being the optimal value share of electricity within the pair;
- there is a constant elasticity of substitution between these two pairs of inputs – the constant being denoted by $\sigma$ (also known as ESUB);
- the scaling factors a and b are determined so that the energy demands in the base year are consistent with the "reference price" for nonelectric energy; and
- there are autonomous energy efficiency improvements (AEEI) that are summarized by the scaling factor b.

## 2.3. Key demand-side parameters

The rate of GDP growth is a key determinant of energy demands. The rate depends on both population and per capita productivity trends. Figure 2 shows our estimates of the projected population. For the twenty-first century, these are taken from Zachariah and Vu (1988). It is supposed that the population will stabilize in all regions during the twenty-second century. At that time, 88% of the world's population will be located in the regions currently described as developing countries: China and the ROW.

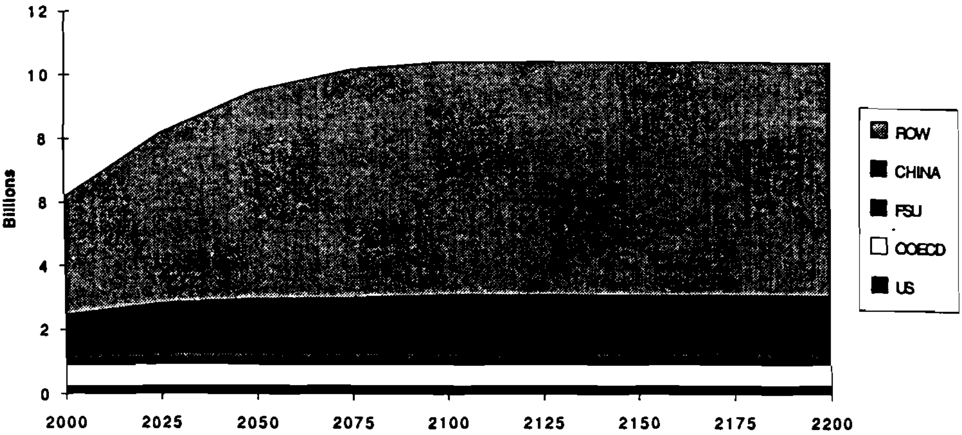


**Figure 2.** Population projections.

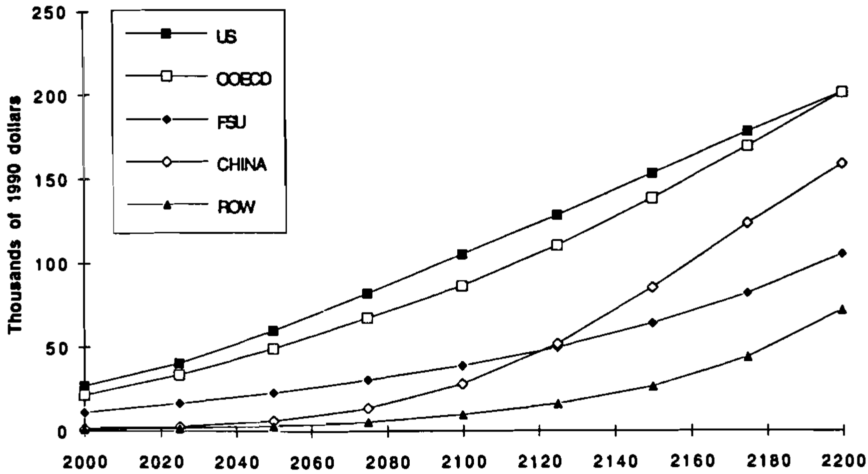


**Figure 3.** Per capita GDP.

Figure 3 presents our per capita GDP projections. These are termed "potential" because they are based upon constant energy prices. Through 2100, these rates represent the average of the higher and lower growth cases adopted by the IPCC's Working Group III (1991). From 2100 onward, it is supposed that per capita growth rates will decline over time, but that the gap between the industrialized countries and the ROW will continue to be substantial. If we follow the IPCC's projections through 2100, it is difficult to believe that the ROW's growth rate will accelerate rapidly enough so that its per capita incomes will converge to those of the other regions between 2100 and 2200.

Because of energy-economy interactions, the potential GDP growth rates do not uniquely determine the realized rates. Energy costs represent just one of the claims on the economy's output. Tighter environmental standards and/or an increase in energy costs will reduce the net amount of output available for meeting current consumption and investment demands. The realized GDP will then fall short of the potential.

Energy consumption need not grow at the same rate as the GDP. Over the long run, they may be decoupled. In Global 2200, these conservation possibilities are summarized through two macroeconomic parameters: ESUB (the elasticity of price-induced substitution) and AEEI (autonomous energy efficiency improvements).

If there is sufficient time for the adaptation of capital stocks, most analysts would agree that there is a good deal of possible substitutability between the inputs of capital, labor, and energy. The degree of substitutability will affect the economic losses from energy scarcities and from price increases. The ease or difficulty of these trade-offs is summarized by the elasticity of price-induced substitution (ESUB). The higher its value, the less expensive it is to decouple energy consumption from GDP growth during a period of rising energy prices.

When energy costs are a small fraction of total output, ESUB is approximately equal to the absolute value of the price elasticity of demand. In Global 2200, this parameter is measured at the point of secondary energy production: electricity at the busbar, crude oil and synthetic fuels at the refinery gate. On the basis of a "backcasting" experiment for the US, the reference case values for ESUB have been set at 0.40 both for the United States and for the other OECD nations. These countries have already demonstrated their ability to use the price mechanism for decoupling energy from GDP growth.

In other regions of the world, price-induced conservation is more problematic. It depends on long-term structural changes in the political and economic system. We have therefore set ESUB at 0.30 for these other three regions.

Along with the reductions in energy demand induced by rising energy prices, there is also the impact of autonomous energy efficiency improvements (AEEI). Non-price efficiency improvements may be brought about by deliberate changes in public policy, e.g., speed limits for automobiles. Energy consumption may also decline as a result of shifts in the basic economic mix away from manufactured goods and toward more services. Thus, the AEEI summarizes all sources of reductions in the economy-wide energy intensity per unit of output.

For most regions and time periods, we have assumed that the AEEI will be 0.5% per year. That is, regardless of whether the GDP growth is 2.5% or 1.0% per year, total primary energy consumption will grow at a rate that is 0.5% lower than that of the GDP.

The numerical value of the AEEI is highly controversial. Clearly, the cost of emissions abatement is sensitive to the value of this parameter. Suppose, for example, that one were quite optimistic and projected the AEEI at 1.5% per year. By the year 2100, the economy would then consume only 20 percent of the amount of energy required with an AEEI of zero. This is entirely apart from the conservation induced by rising energy prices in response to the depletion of conventional oil and gas resources.

In addition to the ESUB and AEEI, one other numerical parameter affects the decoupling between energy consumption and economic growth. The reference price of nonelectric energy, PNREF, is employed in benchmarking the aggregate production function. Its numerical value is chosen so as to allow for differences in the extent to which domestic policies have insulated consumers from international energy price movements.

As a consequence, the economies of some regions may not have completed the long-term adjustment to the oil price shocks of the 1970s. If PNREF is less than the actual 1990 base year oil price of $3.70 per GJ ($22 per barrel), there will be some near-future price-induced conservation in addition to that determined by the AEEI factor. The importance of this effect will depend upon what is assumed with respect to the persistence of tax and subsidy wedges between domestic and international prices.

In calculating these once-for-all efficiency gains, the value of PNREF is taken to be $3.00 per GJ in the United States, $7.70 (including taxes of $4.00) in the other OECD region, $1.00 in the former USSR and $2.00 both in China and the ROW. For purposes of the simulations reported here, domestic taxes are maintained at the 1990 level within the other OECD region, but subsidies are eliminated at a rapid pace elsewhere.

## 2.4. Key supply-side parameters

Table 1 identifies the alternative sources of electricity supply. The first five technologies represent existing sources: hydroelectric and other renewables, gas-, oil- and coal-fired units, and nuclear power plants. The second group of technologies includes the new electricity generation options that are likely to become available during the coming decades. They differ in terms of

**Table 1.** Identification of electricity generation technologies.

| | Identification | Earliest possible introduction date[a] | Estimated US cost[b] (mills/kWh) |
|---|---|---|---|
| *Existing technologies* | | | |
| HYDRO | Hydroelectric, geothermal, and other renewables | | |
| GAS-R | Remaining initial gas fired | | |
| OIL-R | Remaining initial oil fired | | |
| COAL-R | Remaining initial coal fired | | |
| NUC-R | Remaining initial nuclear | | |
| *New technologies* | | | |
| GAS-N | Advanced combined cycle, gas fired | 1995 | 34.3[c] |
| COAL-N | New coal fired | 1990 | 51.0[d] |
| ADV-HC | High-cost carbon free | 2010 | 75.0 |
| ADV-LC | Low-cost carbon free | 2020 | 50.0 |

[a]Estimated year when the technology could provide 0.1 trillion kWh (approximately 20 GW of installed capacity at 60 percent capacity factor). For the other OECD region, we assume that the technology could provide 0.2 trillion kWh by this date.
[b]Based on 1990 dollars.
[c]Based on price of gas in 1990. Gas prices are projected to rise over time.
[d]Estimated costs are assumed to be 10 mills/kWh higher in the other OECD region due to higher fuel costs.

their projected costs, carbon emission rates, and dates of introduction. The introduction date for a new technology is defined as the earliest year in which the technology could provide 0.1 trillion kWh in each region (approximately 20 GW of installed capacity at a 60 percent capacity factor).

ADV-HC and ADV-LC, respectively, refer to advanced high- and low-cost carbon-free electricity generation. Any of a number of technologies could be included in these categories: solar, wind, nuclear, biomass, and others. Given the enormous disagreement as to which of these will ultimately win out in terms of economic attractiveness and public acceptability, we have chosen to refer to them generically.

Table 2 identifies the nine alternative sources of nonelectric energy within Global 2200. In the absence of a carbon constraint or a limit on coal resources, the SYNF technology (coal- or shale-based synthetic liquid fuels) places an upper bound on the future cost of nonelectric energy. Table 2 includes two broad categories of carbon-free alternatives: RNEW (low-cost renewables such as ethanol from biomass) and NE-BAK (high-cost backstops

**Table 2.** Nonelectric energy supplies.

| Technology name | Description | Carbon emission coefficient (tons of carbon per GJ of crude oil equivalent | Unit US cost per GJ of crude oil equivalent (1990 dollars) |
|---|---|---|---|
| OIL-MX | Oil imports or exports | 0.0199 | 3.70 in 1990 rising over time |
| CLDU | Coal, direct uses | 0.0241 | 2.00 |
| OIL-LC | Coil, low cost | 0.0199 | 2.50 |
| GAS-LC | Natural gas, low cost | 0.0137 | 2.75[a] |
| OIL-HC | Oil, high cost | 0.0199 | 3.00 |
| GAS-HC | Natural gas, high cost | 0.0137 | 4.25[a] |
| RNEW | Renewables | 0.0000 | 6.00 |
| SYNF | Synthetic fuels | 0.0400 | 8.33 |
| NE-BAK | Nonelectric backstop | 0.0000 | 16.67 |

[a]To allow for gas distribution costs, $1.25 per GJ is added to the wellhead price.
Note: The source of most of these carbon emission and cost coefficients is *Energy Modeling Forum 12* (1993).

such as hydrogen produced through photovoltaics and electrolysis). The key distinction is that RNEW is in limited supply, but NE-BAK is available in unlimited quantities at a constant but considerably higher cost.

Upper bounds are imposed upon the contribution of each of these supply technologies during each time period. There are also constraints that limit the rate of expansion from one period to the next. As a result of these constraints, there may be an erratic time path for the prices of alternative forms of energy. There may be a temporary phase during which prices overshoot their long-term backstop equilibrium levels.

Oil, gas, and coal are viewed as exhaustible resources. Proved reserves are depleted by current production and augmented by new discoveries out of the remaining stock of undiscovered resources. At any one time, production is a fixed fraction of remaining reserves. New discoveries may not exceed a fixed fraction of the remaining undiscovered resources. Thus, Global 2200 combines some of the desirable economic attributes of Hotelling's model of depletable resources and the geological attributes of Hubbert's model. Under our standard assumptions, it turns out that conventional oil and gas resources are largely depleted by 2050, but that the world's coal supplies could provide for an additional century's worth of synthetic fuels.

Global 2200 is written in the GAMS language. See Brooke *et al.* (1988). In order to solve this computable general equilibrium model, we used the sequential joint maximization technique originated by Rutherford (1992).

**Table 3.** Summary of assumptions regarding key greenhouse gases.

| Trace gas | $CO_2$ | $CH_4$ | $N_2O$ |
|---|---|---|---|
| Atmospheric concentration | | | |
| Pre-industrial (PPMV) | 280 | 0.80 | 288 |
| 1990 (PPMV) | 353 | 1.72 | 310 |
| Energy related emissions | | | |
| 1990 (billion tons) | 6.0 | 0.08 | 0.0001 |
| Growth rate, post-1990 | | (determined endogenously) | |
| Nonenergy related emissions | | | |
| 1990 (billion tons) | 0.2 | 0.454 | 0.0139 |
| Growth rate, post-1990 | 0.0 | 0.800 | 0.2000 |

Sources: IPCC, 1990, 1992.

There are 2800 linear and nonlinear constraints, and there are 3800 variables – many of them subject to individual upper bounds. On an IBM RS/6000-375 work station, the solution time is about half an hour per case.

## 3. Climate Submodel

In MERGE, we focus on three of the most important anthropogenic greenhouse gases: carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$). The concentrations of these gases in the earth's atmosphere have been increasing since the industrial revolution – primarily due to human activities. In this section, we describe the relationship between man-made emissions and atmospheric concentrations and the resulting impact on temperature.

The emissions of each gas are divided into two categories: energy and nonenergy. Global 2200 projects energy-related emissions of $CO_2$, $CH_4$, and $N_2O$ by fuel type for each period through 2200. Emissions from other sources are exogenous inputs into MERGE. Table 3 presents a summary of key assumptions.

Without the withdrawal of carbon from the atmosphere, observed atmospheric concentrations of $CO_2$ would have risen much more rapidly than indicated by the quantity of carbon emissions. In recent history, approximately 50% of the industrial emissions of $CO_2$ appeared to have been absorbed. Most of this absorption is by the oceans but not all of the withdrawals can be explained in this way. We assume that prior to the industrial revolution, natural additions were offset exactly by natural removal. That is, the stock of carbon was in steady state.

Future atmospheric $CO_2$ concentrations are modeled using a reduced-form carbon cycle model developed by Maier-Reimer and Hasselmann (1987). Carbon emissions are divided into five classes, each with different atmospheric lifetimes. Specifically, $G(t)$, the impulse response function to an instantaneous injection of $CO_2$ to the atmosphere, is expressed as a weighted sum of the exponentials

$$G(t) = \sum_{i=1}^{5} a_i \exp(-t/\tau_i) \tag{6}$$

where $a_i$ are scaling factors; $\sum a_i = 1$; and $\tau_i$ are decay constants. The above linear response expression was fitted by least squares to the computed response of a full scale ocean carbon cycle model (Maier-Reimer and Hasselmann, 1982).

For $CH_4$ and $N_2O$, the atmospheric stock in year $t+1$ equals the fraction of the stock in year $t$ remaining in the atmosphere plus new emissions. That is,

$$S_{G,t+1} = k_G * S_{G,t} + E_{G,t} \tag{7}$$

where $S_{G,t}$ is the stock of gas $G$ in year $t$; $k_G$ is the retention factor for gas $G(k_{\mathrm{CH4}} = 0.9$ and $k_{\mathrm{N2O}} = 0.9933)$; and $E_{G,t}$ are the emissions of gas $G$ in year $t$.

The next step is to assess the impact of future concentrations of greenhouse gases on the earth's radiative forcing balance. That is, the balance between the energy absorbed by the earth and that emitted by it in the form of infrared radiation.

According to the IPCC (1990), atmospheric concentrations of $CO_2$, $CH_4$, and $N_2O$ have the following impacts on radiative forcing relative to their 1990 levels (respectively indicated by $\mathrm{CO2}_0$, $\mathrm{CH4}_0$and $\mathrm{N2O}_0$):

$$\Delta F_{\mathrm{CO2}} = 6.3 \ln(\mathrm{CO2}/\mathrm{CO2}_0) \tag{8}$$

$$\Delta F_{\mathrm{CH4}} = .036(\mathrm{CH4}^{.5} - \mathrm{CH4}_0^{.5}) - f(\mathrm{CH4}, \mathrm{N2O}_0) + f(\mathrm{CH4}_0, \mathrm{N2O}_0) \tag{9}$$

$$\Delta F_{\mathrm{N2O}} = .14(\mathrm{N2O}^{.5} - \mathrm{N2O}_0^{.5}) - f(\mathrm{CH4}_0, \mathrm{N2O}) + f(\mathrm{CH4}_0, \mathrm{N2O}_0) \tag{10}$$

where $\Delta F_G$ is the change in net flux ($Wm^{-2}$) corresponding to a volumetric concentration change for gas $G$ relative to the 1990 level and the $CH_4$-$N_2O$

interaction term $f(\mathrm{CH4}, \mathrm{N2O}) = .47 \ln[1 + 2.01 * 10^{-5} * (\mathrm{CH4} * \mathrm{N2O})^{.75} + 5.31 * 10^{-15} * \mathrm{CH4} * (\mathrm{CH4} * \mathrm{N2O})^{1.52}]$.

The aggregate effect is obtained by summing the radiative forcing effect of each gas. Aggregate radiative forcing is assumed to have the following impact on the change in global potential surface temperature, $\Delta PT$:

$$\Delta PT = d * \Delta F \tag{11}$$

where the potential temperature is the long-run temperature which will occur if a specific level of forcing is maintained indefinitely; $\Delta PT$ is measured relative to 1990 temperature; $d = 0.455°\mathrm{C}/Wm^{-2}$; and, $\Delta F = \Delta F_{\mathrm{CO2}} + \Delta F_{\mathrm{CH4}} + \Delta F_{\mathrm{N2O}}$.

Since oceans take a long time to warm up, the actual temperature, $AT$, will lag behind the potential temperature. We model this lag process as follows:

$$\Delta AT_{t+1} - \Delta AT_t = c_1 * (\Delta PT_t - \Delta AT_t) \tag{12}$$

where $c_1 = 0.05$ represents a 20-year mean lag, and $\Delta AT_t$ measures the actual change in temperature in year $t$ relative to 1990.

According to global circulation model analyses, temperatures will increase more rapidly as one moves toward the poles. We assume that the temperature change in temperate countries is the global mean and that the change in tropical countries is half the global mean.

## 4. Damage Assessment Submodel

In a critique of attempts to quantify the impacts of climate change, Grubb (1993) identifies the question that analysts need to address: "What may be the impact of increasing greenhouse gas concentrations on the overall welfare of future generations globally, expressed in terms of present day monetary equivalence?" It is easy to pose this question in qualitative terms, but difficult to arrive at a consensus on the quantitative impacts.

Part of the problem is what to include in the evaluation. It is far easier to quantify effects on goods sold in markets such as food and energy than on services such as bio-diversity, environmental quality, and human health which have no market values. Both categories are important and need to be incorporated into global climate benefit–cost analyses.

Figure 4 (adapted from Fankhauser (1993)) presents a classification of climate change impact categories. Market effects reflect categories that are

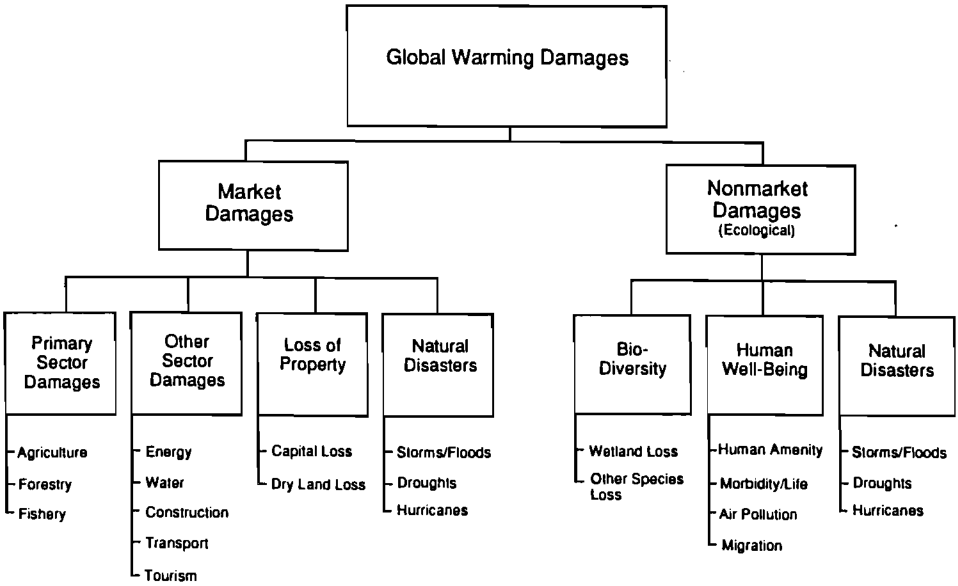


**Figure 4.** Overview on global warming impacts.

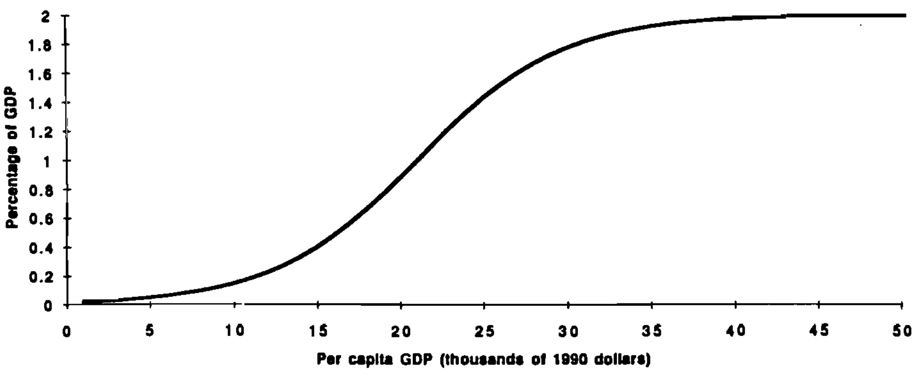


**Figure 5.** Willingness-to-pay to avoid 2.5°C change in temperature: nonmarket (ecological) damages.

included in conventionally measured national income and can be valued using prices and observed demand and supply functions. Nonmarket effects have no observable prices, and so they must be valued using alternative revealed preference or attitudinal methods.

Consistent with Figure 4, we divide damages into two categories: market and non-market. $D_{t,n}$, market damages for period $t$ in region $n$, are defined by the following relationship:

$$D_{t,n} = d_{1,n} * \Delta AT_{t,n}^{d_{2,n}} * \text{GDP}_{t,n} \tag{13}$$

Much of the discussion has focused on damages at a single point in time – when temperature increases by 2.5°C above 1990 levels. It is also important to specify what happens before and after this date. There has been considerable speculation about the shape of the damage function. See, for example, Peck and Teisberg (1992). For the present analysis, we adopt the assumption of Nordhaus (1991) that damages rise quadratically with temperature change. That is, in Equation (13), $d_{2,n} = 2$.

Next, we turn to nonmarket damages. Few issues in the greenhouse debate are more challenging or have engendered more controversy. What value does society place on bio-diversity? Environmental quality? Human health? Many benefit–cost calculations ignore the issue altogether and confine their analyses to economically measurable consequences only. As noted by Dorfman and Dorfman (1976), "there is discretion in declining to attempt the nearly impossible, but there is also danger since effects omitted from the benefit–cost calculation tend to be given insufficient weight in making decisions based upon the calculation."

In this paper, we take an approach based on willingness-to-pay (*WTP*). The issue is framed in the context of how much consumers in each region would be willing to pay to avoid ecological damages. The fraction depends both on temperature change and GDP per capita:

$$WTP_{t,n} = d_{3,n} * \Delta AT_{t,n}^{d_{4,n}} / (1 + 100 * \exp(-.23 * \text{GDP}_{t,n}/\text{POP}_{t,n})) \tag{14}$$

The relationship between *WTP* for nonmarket goods and per capita income is assumed to be S-shaped, and is calibrated so that it does not exceed 100% of GDP. At low incomes, people are not willing to pay much to avoid nonmarket effects. However, as incomes climb, *WTP* increases rapidly and then plateaus at a constant proportion of income. For example, Figure 5 shows the *WTP* function for $d_{3,n} = 0.0032$ and $d_{4,n} = 2$. This means that when per capita incomes approach \$40,000 (about twice the 1990 level in the OECD nations), consumers are willing to pay 2 percent of GDP to avoid a 2.5°C increase in temperature, and 8 percent of GDP to avoid a 5°C increase.

According to Equation (14), each region values ecological damages independently of where such damage occurs. That is, consumers in a particular region place the same value on wetland losses whether they occur within or outside their own boundaries. The same is true for human health and wildlife. The S-shaped function implies, however, that lower income regions will place a lower value on such losses than higher income regions. As a result, nonmarket damages will be higher for developed countries.

Rather than advocate any particular set of numbers, we will explore the implications of alternative valuations. We seek to address the following question: how much must an informed global community be willing to pay to avoid ecological damages in order for a particular policy to make sense?

## 5. Emissions, Concentrations, and Temperature Change Under Five Alternative Policy Scenarios

Numerous proposals have been put forward for controlling greenhouse gas emissions. These have ranged from a modest slowing in the rate of growth to drastic reductions below present levels. To illustrate how MERGE can be used for integrated benefit–cost analysis, we will apply it to a representative menu of policy choices. These include:

1. Business as usual,
2. a tax on carbon emissions starting at \$1/ton in 2000 and increasing at 5%/year,
3. a tax on carbon emissions starting at \$5/ton in 2000 and increasing at 5%/year,
4. stabilizing global $CO_2$ emissions at 1990 levels, and
5. stabilizing concentrations of $CO_2$ in the atmosphere at near current levels.

The difference between the two tax policies is primarily one of timing. The tax beginning at one dollar per ton rises to five dollars per ton by about 2030. If we ignore the relatively small deadweight losses incurred prior to this date, it is equivalent to delaying the imposition of the five dollars per ton tax by thirty years. For short hand, we will refer to this as the delayed tax alternative.

There is no unique formula for achieving stabilization – either of emissions or concentrations. Each involves the difficult issue of the allocation of emission rights among regions. In this paper, we explore one widely discussed proposal, a gradual transition to equal per capita emission rights. We assume that carbon rights are initially distributed among regions in proportion to their 1990 level of emissions. Over time, the shares change gradually.

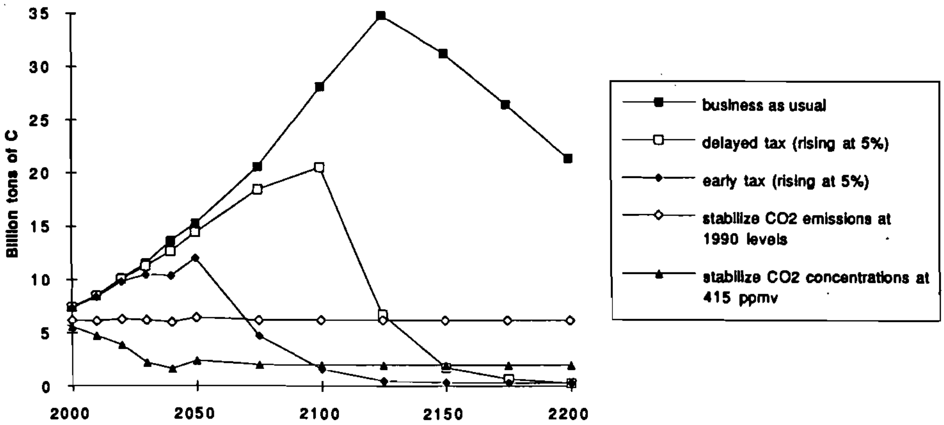


**Figure 6.** Global $CO_2$ emissions.

By 2030, carbon rights are distributed in proportion to 1990 population levels. Note that the 1990 population base penalizes nations that fail to control their rate of population growth.

The IPCC (1990) estimates that emissions would have to be reduced immediately to 30% of 1990 levels in order to keep atmospheric $CO_2$ concentrations constant. Given that fossil fuels provide more than 90% of the world's commercial energy, this seems unrealistic. For our stabilization scenario, we assume that emissions are reduced gradually to 30% of 1990 levels by 2030. This results in stabilization of atmospheric concentrations at 415 ppmv – approximately 50% higher than pre-industrial levels.

Figure 6 compares carbon emissions for the five alternatives. Under business as usual, emissions continue to rise into the twenty-second century. The growth reflects the increasing dependence on coal in the nonelectric sector. With the eventual exhaustion of low-cost oil and gas resources, coal-based synthetic fuels are apt to become the marginal source of nonelectric energy supply. Unfortunately, the synthetics emit twice as much $CO_2$ per unit of energy as conventional oil.

In the longer term, $CO_2$ emissions will begin to decline – even under business as usual. Coal, like other fossil fuels, is in limited supply. As economically recoverable resources are exhausted, coal too will be replaced by other alternatives. Even in the absence of $CO_2$ considerations, the world's dependence on fossil fuels is likely to decline sharply toward the end of the twenty-second century.

The effect of the tax policies is to hasten the end of the synthetic fuels era. When the tax on carbon rises above $200 per ton, the carbon-free

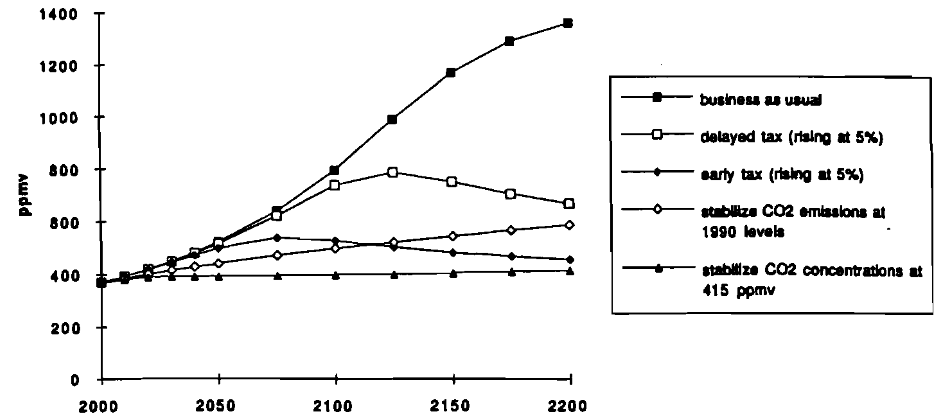


**Figure 7.** $CO_2$ concentrations.

nonelectric backstop becomes the technology of choice. With the delayed tax, this happens shortly after the year 2100. This explains the rapid fall-off in carbon emissions as we move into the twenty-second century. With the early tax, the \$200 threshold is reached thirty years earlier. The synthetic fuels era is shortened accordingly.

Using the carbon cycle model, it is straightforward to convert emissions into atmospheric concentrations. Figure 7 compares results for the five alternatives. Under business as usual concentrations are twice pre-industrial levels in the middle of the next century, and they double again by 2200.

The tax policies initially stabilize concentrations, and eventually lead to their decline. In the case of the delayed tax, concentrations approach 800 ppmv and then return to 650 ppmv. For the early tax policy, they peak at 550 ppmv, then return to 450 ppmv.

By stabilizing emissions at 1990 levels, we do not halt the rise in atmospheric $CO_2$ concentrations. By 2200, concentrations approach 600 ppmv, and they continue to rise. The most stringent policy is designed specifically to achieve stabilization of concentrations. This happens at approximately 415 ppmv.

Figure 8 compares the impact on mean global temperature. Under business as usual, temperature increases by 2.5°C (above the 1990 level) by 2075 and by nearly 6°C by 2200. Not surprisingly, the delayed tax is the least effective in reducing temperature change. It does, however, serve to limit the long-term temperature rise to 4°C.

By accelerating the imposition of the tax, there is a substantial impact on temperature change. The increase is now limited to 2.5°C. Note also that

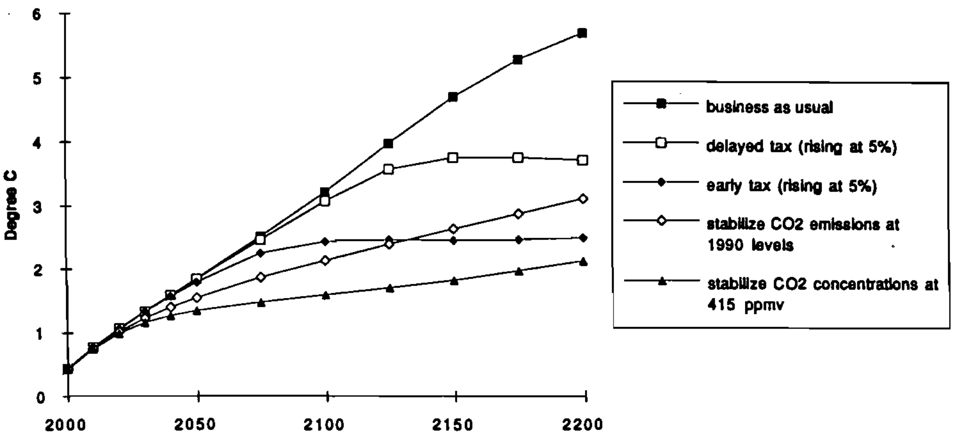


**Figure 8.** Mean global temperature change from 1990.

over the longer term (post-2075), the early tax turns out to be more effective than the emissions stabilization policy (in terms of limiting temperature change).

Through 2200, the policy with the greatest impact on global warming is one in which concentrations would be stabilized near current levels. Note, however, that stabilizing $CO_2$ concentrations does not cap the temperature rise. There are continuing emissions of the other greenhouse gases.

## 6. Benefits and Costs

In the previous section, the effectiveness of the policy options were measured in physical terms – emissions, concentrations and mean temperature change. Although the exercise yielded some useful insights, it is a limited guide to greenhouse decision making. Sensible greenhouse policy requires a careful balancing of both benefits and costs. The next step in an integrated assessment is to translate temperature changes into market and nonmarket damages. To do this, we must first calibrate the regional damage functions.

In his original work on the impacts of climate change, Nordhaus (1991) focused primarily on market damages to the US from a doubling of atmospheric $CO_2$ levels ($2\times CO_2$). Noting that only 3% of US national output originates in climate sensitive sectors and another 10% in sectors that are modestly sensitive to climate change, he estimated that the net economic damages from a $2\times CO_2$ scenario are likely to be of the order of 0.25% of national income.

Nordhaus acknowledged, however, that many valuable goods and services are excluded from conventional national income accounts. Correcting for these omissions and extending to the world, his best guess of the of the costs imposed by a doubling in atmospheric $CO_2$ concentrations was one percent of global GDP, with a range of 0.25–2%.

Subsequent studies have attempted more comprehensive analyses for the US with surprisingly similar results. Cline (1992) and Fankhauser (1993) estimate losses of the order of 1.1% and 1.3%, respectively, for a $2\times CO_2$ scenario. When Cline adjusts for output composition in different countries, he projects total losses to the global economy of 1.3%. Similarly, Fankhauser suggests that the damage related to a doubling of atmospheric concentration may be of the order of 1-1.5% of GDP worldwide.

Although there appears to be some convergence in the GDP estimates, it is important to note that climate impact assessment is still in a rudimentary stage. Investigators are quick to stress the preliminary nature of their findings and the need for additional work. The present analysis makes no attempt to narrow the range of uncertainty surrounding damages, nor do we endorse a particular set of estimates. Rather, our goal is to demonstrate how damage projections should fit into the overall assessment of climate change. In doing so, we hope to shed some light on the sensitivity of greenhouse policy to alternative assumptions about the shape and nature of the damage function.

With these caveats in mind, we now describe the assumptions used to estimate the regional loss functions. If damages change quadratically with temperature, the calibration requires only a single point on each function.

For developed regions, we assume that a 2.5°C increase in temperature (above 1990 levels) would result in market damages of 0.25% of GDP. This is consistent with Nordhaus' estimates of market losses to the US for a $2\times CO_2$ scenario.

For other regions, the assessment is more difficult. Relatively little attention has been devoted to estimating market damages outside of the OECD. Developing countries tend to have a larger share of their economies concentrated in climate-sensitive sectors, particularly in agriculture. This vulnerability, however is apt to shrink over time as these countries take on more of the characteristics of their industrialized counterparts. Moreover, they are more likely to be in equatorial regions where temperature changes are less severe than in polar latitudes. Nevertheless, many believe that market damages are apt to be a higher percentage of GDP for developing countries. For the present analysis, we assume a multiple of two.

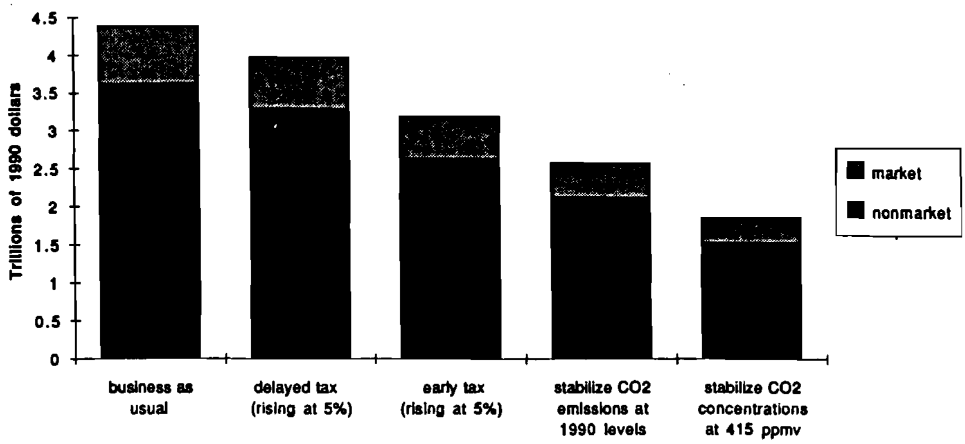


**Figure 9.** Global damages discounted to 1990 at 5%.

For nonmarket damages, we begin with the willingness-to-pay function described in Figure 5. It is based on the assumption that consumers in high income countries would be willing to pay 2% of GDP to avoid the ecological damages associated with a 2.5°C increase in temperature. As a point of reference, the US currently devotes approximately 2% of its gross domestic product to all forms of environmental protection. This compares with 2.7% for research and development and 5.5% for national defense (Council of Economic Advisors, 1993). Because of the highly subjective nature of the willingness-to-pay assumption, we will subject it to extensive sensitivity analysis.

We are now ready to conduct the next step in an integrated assessment – the estimation of market and nonmarket damages. Figure 9 summarizes the results in present value terms. For the business-as-usual alternative, the losses approach \$4.4 trillions (discounted to 1990 at 5% per year). Consistent with the earlier studies, the bulk of the damages are in nonmarket categories.

As a point of comparison, the projected losses for a 2.5°C change in temperature amount to 1.4% of discounted worldwide GDP. This is also well within the range of the earlier estimates.

The economic benefits of an alternative policy may be measured in terms of the reduction in damages relative to business as usual. Total damages are reduced the most when $CO_2$ concentrations are stabilized at 415 ppmv. In this case, the benefits are nearly \$2.5 trillions. By contrast, the benefits from the delayed tax policy are less than \$.5 trillions.

The desirability of a policy depends upon both benefits and costs. Using Global 2200, we calculate the economy-wide costs of each abatement

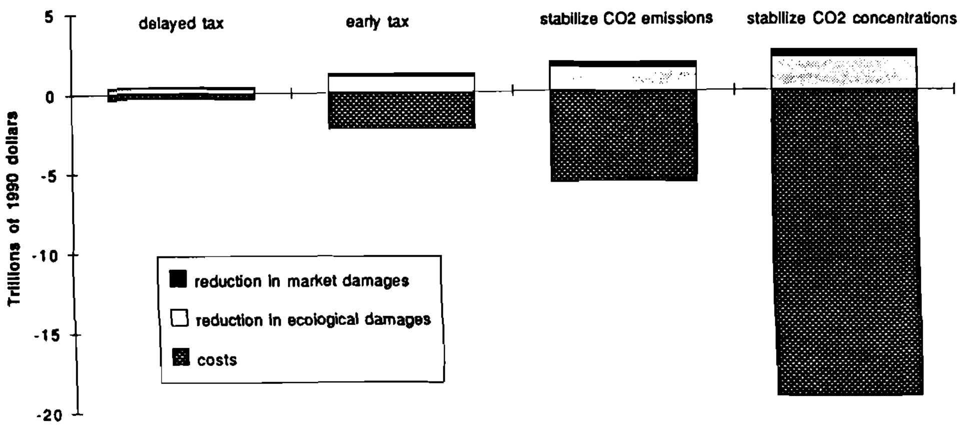


**Figure 10.** Global benefits and costs discounted to 1990 at 5%.

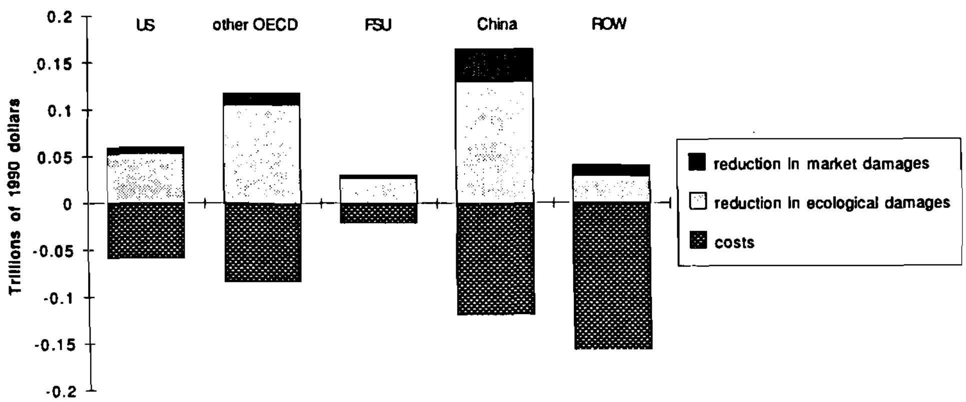


**Figure 11.** Regional benefits and costs from delayed tax policy (discounted to 1990 at 5%).

alternative. The results are summarized in Figure 10. Although stabilizing concentrations buys the most – in terms of reduced market and nonmarket damages – it also carries the highest price tag. Costs outweigh benefits by almost eight to one. From a purely benefit–cost perspective, the only policy that appears attractive is the delayed tax. Both benefits and costs are of the order of \$.4 trillions.

MERGE also allows us to examine the distribution of benefits and costs across regions. Figure 11 shows such a breakdown for the delayed tax policy. Note that all regions are winners except ROW. There are two reasons for this. First, the temperature increase for the tropics is half of the global

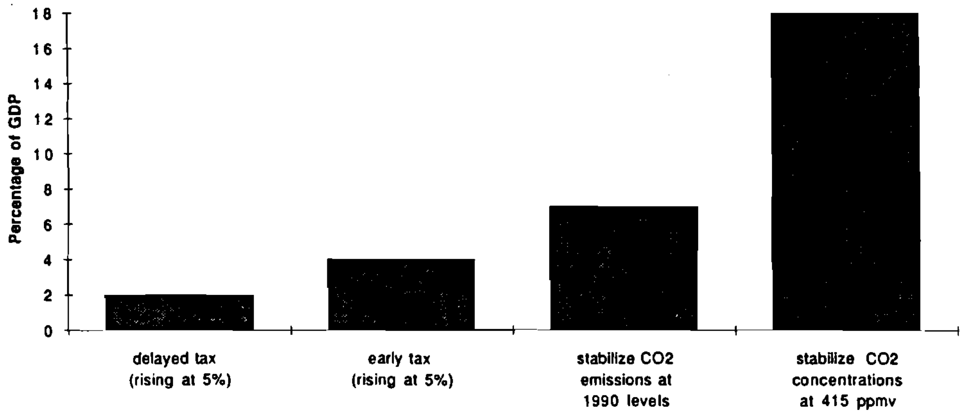


**Figure 12.** Break-even willingness-to-pay: 5% rate of return on capital.

mean increase and most of ROW is in the tropics. Hence, it experiences less damage than the other regions. Secondly, because of its relatively low per capita income, it values nonmarket damages less than its more wealthy counterparts. In order to induce ROW to join into an agreement with the other four regions, there would have to be additional side payments.

## 7. Some Sensitivity Analyses

Like all quantitative analyses, the results are driven by the numerical inputs. In this section, we explore the sensitivity of the results to three key sets of assumptions: the willingness-to-pay to avoid ecological damages, the cost of alternative emission control policies, and the discount rate.

Given the highly subjective nature of the willingness-to-pay function, limited insight is gained from any particular set of estimates. It is more instructive to ask how much consumers must be willing to pay to avoid ecological damages in order for a particular policy to make sense from an economic benefit–cost perspective.

Figure 12 shows the break-even points for our four alternatives to business as usual. The delayed tax is justified when high-income consumers are willing to pay 2 percent of GDP to avoid a 2.5°C increase in temperature. For a stringent emissions policy to be attractive, there must be a high willingness-to-pay. For the most costly policy (stabilization of emissions at 415 ppmv), high-income consumers must be willing to pay approximately 17 percent of GDP to avoid a 2.5°C increase in temperature. This is the point at which the benefits just break even with the costs.

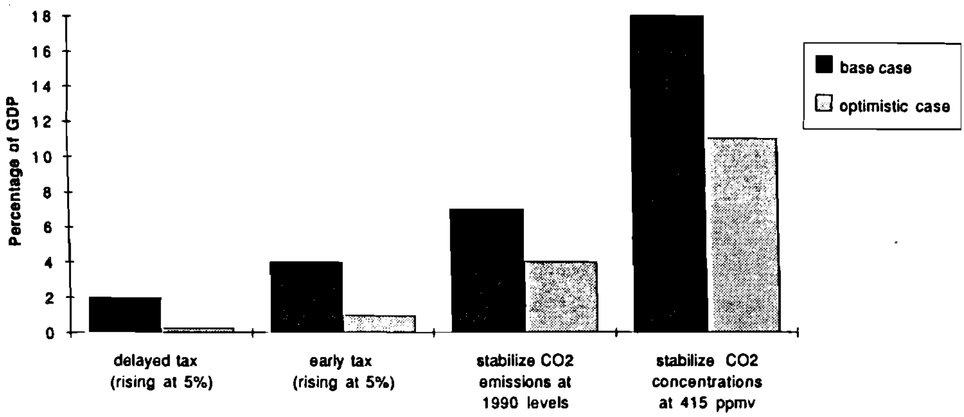


**Figure 13.** Break-even willingness-to-pay: sensitivity to abatement costs.

Next, we look at how the break-even willingness-to-pay depends upon the costs of the emission control policies. Our reference case Global 2200 assumptions were described in Section 2. We now adopt more optimistic assumptions regarding two critical parameters: the elasticity of price-induced conservation and the cost of the carbon-free nonelectric backstop (NE-BAK).

The degree of substitutability between the inputs of capital, labor, and energy will affect the economic losses from energy price increases. Our earlier substitution elasticities were based on a backcasting exercise, and they best explain the US historical record (Manne and Richels, 1992). For the sensitivity analysis, we assume that the elasticities are 50% higher.

Similarly, we adopt considerably more optimistic assumptions about the cost of the nonelectric backstop. For the sensitivity analysis, we assume that NE-BAK is only slightly more expensive than coal-based synthetic fuels – \$55 versus \$50 per barrel.

Figure 13 shows the impact of these optimistic abatement cost assumptions on the break-even willingness-to-pay. The effect is to lower the cost of the policy. This automatically lowers the value we must assign to ecological damages for control policies to be economically justifiable.

Finally, we turn to the issue of the discount rate – i.e., the rate at which we discount goods and services from the future to the present. Costs and benefits are both discounted at the same rate as investment opportunities elsewhere in the economy.

From Equation (3), recall that in an economy growing at 2% per year, a 5% marginal productivity of capital is consistent with a 3% pure rate of utility time preference. If one adopts a prescriptive rather than a descriptive

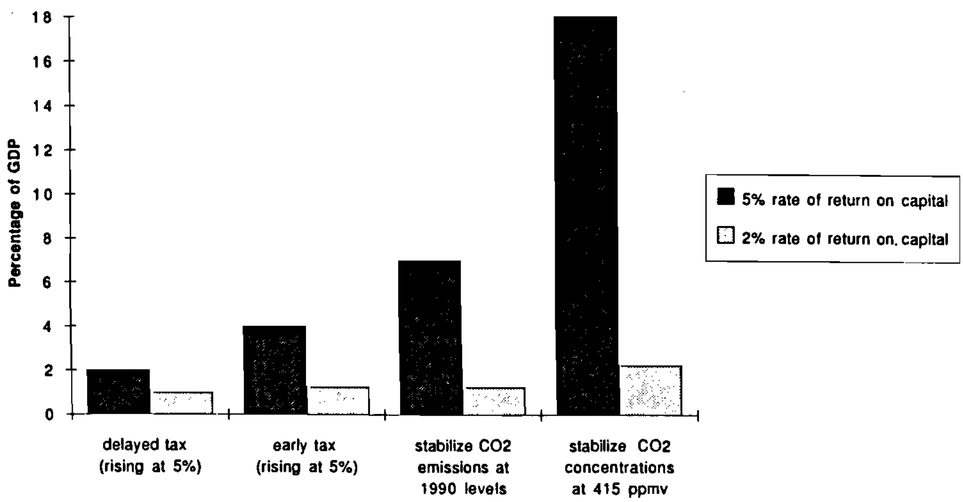


**Figure 14.** Break-even willingness-to-pay: 5% versus 2% rate of return on capital.

approach, one might assume a lower rate of utility time preference. This is a logically consistent scenario, but would require an unrealistically rapid increase in investment in the early years. The result would be to drive down the marginal productivity of capital to some much lower value than its current level of 5%. For example, Cline (1992) suggests that the appropriate number is closer to 2%. MERGE is designed so that such differences in viewpoints can be incorporated easily and their significance assessed.

Figure 14 shows the impact of the lower discount rate on the break-even willingness-to-pay. Increased weight is placed on future impacts. Hence, damages do not have to be as high in the future in order to justify action. As a result, the break-even point is lower.

## 8. Some Final Comments

MERGE provides a framework for thinking about climate change policy proposals. The model is designed to be sufficiently flexible and transparent so that it can be used to explore alternative views on a wide range of contentious issues, e.g., costs, damages, nonmarket valuation, and discounting.

Given the level of uncertainty which pervades the climate debate, it would be unrealistic to expect benefit–cost analysis to lead to consensus on a bottom line – at least any time soon. Rather, models such as MERGE should be viewed as research tools capable of providing insights into which aspects of the debate may be most important. In this way, they can help focus the discussion and identify the areas where additional research may have the highest payoff.

The present analysis has indeed identified a number of issues for further investigation. The evaluation of damages – particularly ecological damages –deserves a great deal more attention. The conventional wisdom, that losses will be higher for developing countries, needs to be reexamined. True, developing countries tend to derive a larger share of their economic output from climate sensitive sectors. But market damages may turn out to be a relatively minor part of the story.

The more important issue may be how we allocate and value ecological losses. Unfortunately, the accounting is far from straightforward. For the present analysis, we assumed that inhabitants of a particular region place the same value on global ecological losses regardless of their geographical location. The losses are then evaluated in terms of willingness-to-pay. This means that low income countries have lower ability to pay, and therefore lower losses than high income countries.

Given the importance of ecological factors to the overall climate benefit–cost calculus, more attention needs to be devoted to their valuation. "Non" market damages do not lend themselves easily to monetary valuation. Yet, there is little alternative but to try. The best course of action may be to frame the issue in terms of a "break-even" willingness-to-pay. The various parties can then debate whether the benefits of a policy outweigh the costs.

The analytical framework itself needs further attention. Perhaps the most serious limitation is the treatment of uncertainty. The climate issue entails high stakes. Waiting leads to the risk of irreversible damages. Immediate action leads to the risk that large costs will be incurred in the near future, and there is considerable disagreement on how these actions will eventually affect the world's climate. Policy makers need help in identifying hedging strategies which balance the costs of delay against those of premature action.

To be a more effective policy tool, MERGE needs to deal more explicitly with critical climate-related risks. We need to provide the capability to replace point estimates with probability distributions reflecting the full range of possible outcomes. Much of the greenhouse debate centers around low probability but high consequence events. These concerns must be included in the analytical process.

We must also do a better job of capturing the true nature of policy making. Greenhouse decision making is apt to be a sequential process with many opportunities for learning and midcourse corrections. The issue is not deciding what to do about greenhouse emissions over the next century. It is deciding what to do over the next decade in the light of alternative consequences over the next century.

Policy frameworks are needed which reflect this "act – then learn" character of the decision process. With the help of such tools, we will be better able to address two central issues: Which of the many climate-related uncertainties are most important to today's decisions? And which strategies provide the best hedge against greenhouse-related risks.

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# The Impact of Potential Abrupt Climate Changes on Near-Term Policy Choices*

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## Abstract

We investigate an important scientific uncertainty facing climate-change policymakers, namely, the impact of potential abrupt climatic change. We examine sequential decision strategies for abating climate change where near-term policies are viewed as the first of a series of decisions which adapt over the years to improving scientific information. We compare two illustrative near-term (1992–2002) policies – moderate and aggressive emission reductions – followed by a subsequent long-term policy chosen to limit global-mean temperature change to a specified "climate target." We calculate the global-mean surface temperature change using a simple climate/ocean model and simple models of greenhouse-gas concentrations. We alter model parameters to examine the impact of abrupt changes in the sinks of carbon dioxide, the sources of methane, the circulation of the oceans, and the climate sensitivity, $\Delta T_{2x}$. Although the abrupt changes increase the long-term costs

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of responding to climate change, they do not significantly affect the comparatively small cost difference between near-term strategies. Except for an abrupt increase in $\Delta T_{2x}$, the investigated abrupt climate changes do not significantly alter the values of the climate target for which each near-term strategy is preferred. In contrast, innovations that reduce the cost of limiting greenhouse-gas emissions offer the potential for substantial abatement cost savings, regardless of which level of near-term abatement is selected.

## 1. Introduction

A key challenge for climate-change policy is to balance the extensive scientific uncertainty about the dangers of climate change – which suggests postponing costly action until more is known – against the risk that delay may constrain future options. To address this issue we have examined sequential-decision strategies for abating climate change (Hammitt *et al.*, 1992; Hammitt and Lempert, 1992; summarized by Schlesinger, 1992, 1993). Instead of viewing the policy response as a decision to be made once and for all, we explicitly considered near-term policy as the first of a series of decisions which adapt over the years to improving scientific information. In particular, we simulated the abatement costs associated with two illustrative near-term policies, moderate and aggressive emission reductions, assuming that the goal of policymakers is to minimize the costs of limiting climatic change, indexed by the increase in global-mean surface temperature, to a specified "climate target," or maximum realized increase in global-mean surface temperature.

We concluded from our earlier studies that: (1) there is only a small difference in the long-term cost implications of moderate and aggressive near-term emission-reduction policies; (2) the long-term costs of the aggressive policy are less than those of the moderate policy only when the climate target, $\Delta T^*$, is less than a critical value which depends on the climate sensitivity, $\Delta T_{2x}$; (3) the long-term abatement costs are significantly more sensitive to the revealed characteristics of the climate system than to the choice between the two near-term policies; (4) if the damages due to climate change are revealed to be severe, then the optimum climate target will be low and the global consumption of fossil fuels will need to be sharply reduced much earlier than if the climate change damages are less severe, this regardless of which near-term policy is chosen; and (5) if the optimum climate target is found to be low, our ability to achieve this target will depend less on which near-term policy is chosen than on the rate at which the switch from fossil-fuel-consuming facilities to non-fossil-fuel-consuming facilities can be achieved.

The relatively small cost difference between the aggressive and moderate policies indicates that even if the damages due to climate change are revealed to be large, the penalty for waiting ten years to begin emission reductions beyond those inexpensively available – for example, through energy conservation – may be a small fraction of the overall abatement costs. The cost penalty for beginning aggressive reductions which subsequently prove unwarranted may be a larger fraction of the smaller overall abatement costs. Furthermore, if we subsequently discover climate change to be a serious problem, even aggressive near-term emissions reductions in excess of those currently proposed by any government do not provide much relief. However, our current study suggests that near-term technology research and development, designed to reduce future abatement costs, could yield significant benefits if climate change is severe.

The above findings, however, are based on the presumption that greenhouse-gas-induced climatic change will not be abrupt. This presumption is reflected in our use of the simple climate/ocean model of Schlesinger and Jiang (1991a), whose simulations do not exhibit spontaneous climate changes. This fact has been noted by Risbey *et al.* (1991) and led them to express the following concern:

> "The simple climate model on which Schlesinger and Jiang base their conclusion does not allow for abrupt changes or surprises in the climate response. For nonlinear responses to climate forcing and climate surprises, thresholds may be important at which the climate response changes abruptly at a particular point in time in response to a certain amount of forcing (Broecker, 1987). Some potential sources of nonlinear response not included in the model are changes in deep ocean circulation, melting of polar ice caps, changes in cloud type and distribution, and release of methane from clathrates. By delaying action, the likelihood that more-abrupt climate changes will occur sooner, rather than later or not at all, might be increased."

Accordingly, we examine here the potential impact of such abrupt climate changes on the choice between the moderate and aggressive abatement policies.

In the following, we present in Section 2 an expanded description of both the sequential decision strategy and the methods we use to analyze it. In Section 3 we present results, similar to those of Hammitt *et al.* (1992) and Hammitt and Lempert (1992), obtained under the presumption that climate change is non-abrupt. We also explore in Section 3 the impacts of near-term research-and-development policies. In Section 4 we examine three types of abrupt climate change, namely, those involving the sources and sinks of greenhouse gases, the ocean circulation, and the feedbacks and sensitivity of the climate system. In Section 5 we discuss these results and present our conclusions.

## 2. Sequential Decision Strategy

We consider a sequential decision strategy to explore the long-term ramifications of near-term policy choices about climate change. The analysis described here is similar to that of Hammitt *et al.* (1992), but with changes in the treatment of individual greenhouse gases (GHGs) to enable the investigation of abrupt changes described in Section 4.

### 2.1. Strategy and assumptions

We assume that policymakers, operating with the currently available information, select a near-term (1992-2002) abatement strategy of either moderate emission reductions, modeled as energy conservation only, or aggressive emission reductions, modeled as energy conservation coupled with switching to non-carbon-emitting fuels. We assume that in 2002 the scientific uncertainties about climate change and its effects are sufficiently reduced to allow policymakers to select a long-term, least-cost abatement policy to limit global-mean temperature change to an optimal target, $\Delta T^*$. We compare the long-term costs to society of meeting any given climate target as a function of: (1) the choice of near-term policy and (2) the revealed behavior of the climate system.

To perform this analysis we make four key assumptions. First, we assume that the aggregate damages from climate change can be reasonably characterized by the increase in global-average surface temperature, $\Delta T(t)$. Of course, the actual damages will be due to an amalgamation of numerous regional effects, none of which can now be predicted with any confidence. However, these regional effects are likely to be well-correlated with increases in the global-average temperature (Schlesinger and Jiang, 1991b). We further assume that damages are equal for temperature trajectories that achieve the same maximum value of $\Delta T$, denoted $\Delta T_{\text{max}}$, and that damages increase monotonically, though not necessarily linearly, with $\Delta T_{\text{max}}$.

Second, we aggregate all the uncertainties about climate change and its consequences into two parameters. The climate target, $\Delta T^*$, contains all the uncertainty about damages due to climate change. We use $\Delta T^*$ to index the "optimal" level of climate change to accept, defined implicitly as the level which equalizes the marginal costs of more-stringent abatement and the marginal costs of damages from greater change, after accounting for benefits and costs of efficient adaptation. We do not estimate damage costs in this study. Rather, we report the long-term cost implications of near-term policy choices as a function of the ultimate choice of climate target. The climate sensitivity, $\Delta T_{2x}$, indexes the magnitude of climate change as a function of GHG concentrations. $\Delta T_{2x}$ is defined as the equilibrium $\Delta T$ resulting from an atmospheric concentration of carbon dioxide twice its pre-industrial level.

Third, we assume that the scientific uncertainties are sufficiently resolved in ten years to allow policymakers to choose optimal policies based on their understanding of $\Delta T_{2x}$ and $\Delta T^*$. The assumption of perfect knowledge a decade hence is almost certainly an overestimate. However, the costs of the long-term policy can be interpreted as approximating the expected value of a policy of sequential decision-making continued past 2002, conditional on the choice of near-term policy (Hammitt, 1990).

Fourth, we use a heuristic model, based on the link between energy-use and GHG releases, to simulate the cost of policies to reduce the anthropogenic emissions of carbon dioxide and methane, and thus their associated radiative forcings.

## 2.2. Greenhouse-gas concentrations and radiative forcing

Below we consider separately the radiative forcing of carbon dioxide, methane, and other GHGs.

*Carbon dioxide*

For carbon dioxide, the radiative forcing is given by (Shine *et al.*, 1990; hereinafter IPCC/90)

$$\Delta R_{CO2}(t) = 6.3 \ln[C_{CO2}(t)/C_{CO2}(1765)], \quad Wm^{-2} \quad , \tag{1}$$

where $C_{CO2}$ is the atmospheric concentration of carbon dioxide in year $t$ and $C_{CO2}(1765) = 279$ ppmv is the pre-industrial concentration. For the period 1765 to 1990, we use the concentration reported by IPCC/90. For the period after 1990, the atmospheric concentration is given by the linear impulse-response function (Maier-Reimer and Hasselmann, 1987),

$$C_{CO2}(t) \quad = \quad C_{CO2}(1765) +$$

$$\int_{1765}^{t} k_{CO2} F_{CO2}(\tau) \left\{ \alpha_1 + \sum_{i=2}^{5} \alpha_i \exp[(\tau - t)/\lambda_i] \right\} d\tau \quad , \quad (2)$$

where $F_{CO2}(t)$ [GtC/yr] is the annual anthropogenic emissions of carbon dioxide in year $t$, and the conversion factor $k_{CO2} = 0.476$ ppmv/GtC. The weighting parameters $\alpha_{1-5} = 0.13, 0.20, 0.32, 0.25$, and $0.10$ and lifetimes $\lambda_{2-5} = 363, 74, 17, 2$ years were obtained by Maier-Reimer and Hasselmann (1987) from a fit to a coupled ocean-atmosphere model, and include the effects of the primary ocean sinks, but not of the biota or any modification of the carbon cycle accompanying climate change.

*Methane*

The direct radiative forcing due to methane is given by IPCC/90 as,

$$\begin{aligned} \Delta R_{CH4}(t) \;&=\; 0.08894 + 0.036 \left[\sqrt{C_{CH4}(t)} - \sqrt{C_{CH4}(1765)}\right] - \\ & 0.47 \ln \{ 1 + 1.39 \times 10^{-3} [C_{CH4}(t)]^{0.75} + \\ & 2.86 \times 10^{-11} [C_{CH4}(t)]^{2.52} \} \quad , \qquad (3) \end{aligned}$$

where $C_{CH4}(t)$ is the atmospheric concentration of methane in year $t$ and $C_{CH4}(1765) = 790$ ppbv is the pre-industrial concentration. We include the additional indirect forcing due to the effect of methane on stratospheric water vapor, given by

$$\Delta R(t) = 0.011 \left| \sqrt{C_{CH4}(t)} - \sqrt{C_{CH4}(1765)} \right| \quad . \qquad (4)$$

For the period 1765 to 1990, we use the methane concentrations reported by IPCC/90. For the period after 1990, we use the first-order difference equation,

$$C_{CH4}(t) = (1 - \mu\Delta t) C_{CH4}(t-1) + k_{CH4} \left[ F_{CH4}(t) + F^{nat}(t) \right] \Delta t \quad , \qquad (5)$$

where $F_{CH4}(t)$ is the annual anthropogenic methane emission in year $t$, the conversion factor $k_{CH4} = 376$ ppbv/Gt $CH_4$, $F^{nat}(t) = 0.165$ Gt $CH_4$/yr is the natural annual methane emission (Rotmans, 1990), and $\Delta t = 1$ yr. The decay rate, $\mu = 0.0968$ yr$^{-1}$, is chosen to reproduce the IPCC/90 Scenario-A methane-concentration projections from the IPCC/90 Scenario-A projections for methane emission. This decay rate represents a lifetime of 10.3 years, which is consistent with other estimates.

*Other Greenhouse Gases*

Carbon dioxide and methane currently constitute roughly 80% of the radiative forcing due to anthropogenic GHGs. To treat the contribution of the remaining GHGs, we use the IPCC/90 Scenario-C radiative forcing due to nitrous oxide, CFCs, and CFC substitutes for 1990 < t < 2100. For t > 2100 we hold the radiative forcing due to these gases constant at the 2100 level. IPCC/90 Scenario C assumes CFCs are phased out at an accelerated rate according to the Montreal Protocol and that steps are taken to limit agricultural emissions of nitrous oxide. We choose Scenario C for these gases, rather than Scenario A, to reflect our expectation that emission-reduction policies for carbon dioxide and methane would likely be complemented by emission-reduction policies for these other GHGs.

## 2.3. GHG emissions

Below we consider emissions of carbon dioxide and methane, both without and with emission-reduction policies. Anthropogenic $CO_2$ and $CH_4$ emissions are heuristically modeled as if both were produced solely through the energy sector.

*Carbon Dioxide*

We model the worldwide, anthropogenic emissions of carbon dioxide as

$$F_{CO2}(t) = B_{CO2}(t) I_{CO2}(t) E_{CO2}(t) \quad , \tag{6}$$

where $B_{CO2}(t)$ is the Base Case emission trajectory, and $I_{CO2}(t)$ and $E_{CO2}(t)$ respectively represent policy-induced shifts in primary energy consumption per unit economic product and in carbon dioxide emissions per unit energy. For $t$ = 1990 and 1991, and for all $t$ in the Base Case scenario, $I_{CO2}(t) = E_{CO2}(t) = 1$ (Table 1). We choose $B_{CO2}(t)$ for $1765 \leq t < 1990$ so that Equation (2) approximates the observed IPCC/90 $CO_2$ concentrations, $B_{CO2}(1990) = 6.8$ GtC/yr to be consistent with the IPCC/90 Scenario-A projections, and a smoothly varying $B_{CO2}(t)$ for $1990 < t < 2100$ so that Equation (2) reproduces the IPCC/90 Scenario-A projections for the atmospheric concentration of carbon dioxide. For $t > 2100$, we linearly extrapolate $B_{CO2}(t)$ based on the 2075–2100 emissions. Figure 1a, curve Base Case, shows $B_{CO2}(t)$ for $1990 < t < 2140$.

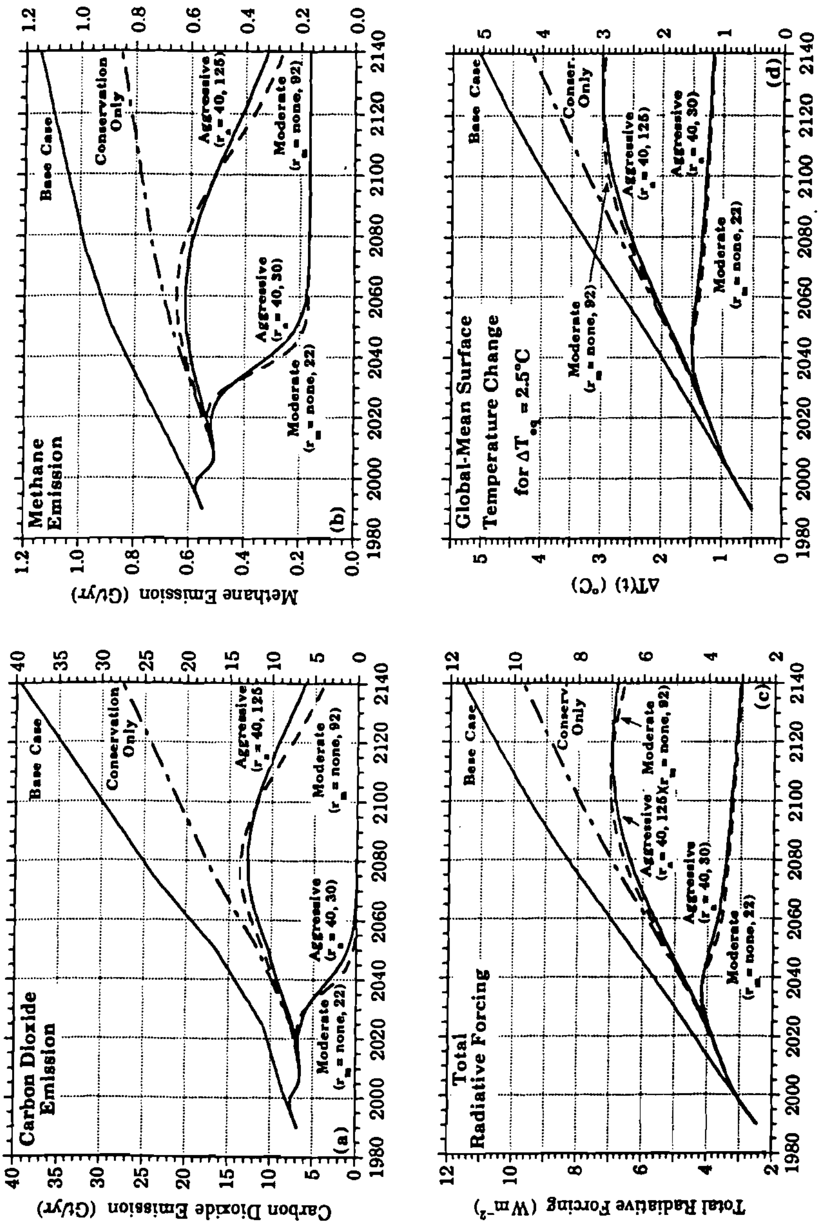



**Figure 1.** Time evolution of carbon dioxide emissions (a), methane emissions (b), total radiative forcing (c), and increase in global-mean surface temperature for $\Delta T_{2x} = 2.5°C$ (d) for our base-case and conservation-only policies, and moderate and aggressive abatement policies for $\Delta T^{*} = 1.5$ and 3°C.

**Table 1.** Primary energy consumption per unit economic product relative to its value in 1992, $I(t)$, and carbon dioxide and methane emissions per unit energy, $E(t)$, relative to their respective values in 1992, for four scenarios. The function $\Psi(t; t_c, r) = 0.7 + \frac{0.3}{1-\varepsilon}\frac{1}{1+\exp[\rho(t-t_c-r)]}$, where $t_0$ is the initial time, $r$ is the transition half-life, $\varepsilon = 0.01$ and $\rho = -(1/r)\ln[\varepsilon/(1-\varepsilon)]$ so that $\Psi(t_c; t_c, r) = 1$. The function $\Phi(t; t_{fs}, r) = \frac{1}{1-\varepsilon}\frac{1}{1+\exp[\rho(t-t_{fs}-r)]}$, where $\varepsilon = 0.01$. For the moderate policy, $\rho = -(1/r_m)\ln[\varepsilon/(1-\varepsilon)]$ so that $\Phi(t_{fs}; t_{fs}, r_m) = 1$. For the aggressive policy, $\rho = -(1/r_a)\ln[\varepsilon/(1-\varepsilon)]$ for $2002 \leq t < 2012$ so that $\Phi(t_{fs}; t_{fs}, r_a) = 1$, and $\rho = -(1/r_a*)\ln[\varepsilon/(1-\varepsilon)]$ for $t \geq 2012$.

| | Base case | Conservation only | Moderate reduction | Aggressive reduction |
|---|---|---|---|---|
| $I(t)$ | | | | |
| $t < 1992$ | 1 | 1 | 1 | 1 |
| $t \geq 1992$ | 1 | $\Psi(t; 1992, 10)$ | $\Psi(t; 1992, 10)$ | $\Psi(t; 1992, 10)$ |
| $E(t)$ | | | | |
| $1765 \leq t < 2002$ | 1 | 1 | 1 | 1 |
| $2002 \leq t < 2012$ | 1 | 1 | 1 | $\Phi(t; 2002, r_a = 40)$ |
| $t \geq 2012$ | 1 | 1 | $\Phi(t; 2012, r_m)$ | $\Phi(t; 2012 - \frac{r_a*}{4}, r_a*)$ |

*Methane*

We model anthropogenic methane emissions as

$$F_{CH4}(t) = B_{CH4}(t) I_{CH4}(t) E_{CH4}(t) \quad , \tag{7}$$

where $B_{CH4}(t)$ is the Scenario-A (Business-as-Usual) emission trajectory of IPCC/90, and $I_{CH4}(t)$ and $E_{CH4}(t)$ represent, similarly to the carbon dioxide case, policy-induced shifts in primary energy consumption per unit economic product and in methane emissions per unit energy, respectively. For $1990 < t < 2100$, $B_{CH4}(t)$ is given by the IPCC/90 Scenario-A methane emission and, for $t > 2100$, we linearly extrapolate $B_{CH4}(t)$ based on the 2075–2100 emissions. Figure 1b, curve Base Case, shows $B_{CH4}(t)$. We assume that $I_{CH4}(t) = I_{CO2}(t) = I(t)$ and $E_{CH4}(t) = E_{CO2}(t) = E(t)$. Since much methane comes from shorter-lived capital stock than carbon dioxide, this assumption slightly biases our results toward favoring aggressive near-term action.

*Emissions Reduction*

Emissions of carbon dioxide and methane can be reduced by various means which vary in cost effectiveness and speed of implementation. We consider two stylized options, energy conservation and fuel switching. Here we characterize our emission-reduction policies. In Section 2.5 we discuss the cost of these abatement policies. We are particularly interested in characterizing the rate at which these policies can be implemented, so we constrain $I(t)$ and $E(t)$ to follow the logistic curves which are characteristic of technology diffusion (Mansfield, 1961; Fisher and Pry, 1971; Häfele, 1981).

Energy conservation represents a set of low-cost, quickly implemented policies. We assume that if conservation is initiated at time $t_c$, the energy intensity relative to 1992, $I(t)$, thereafter falls 30% over 20 years following

$$I(t) = \Psi(t; t_c, 10) \quad , \tag{8}$$

where

$$\Psi(t; t_c, r) = 0.7 + \frac{0.3}{1-\varepsilon} \frac{1}{1 + \exp[\rho(t - t_c - r)]} \quad , \tag{9}$$

with $r = 10$ years the transition half-life. To satisfy $I(t_c) = 1$, $\rho = -(1/r)\ln[\varepsilon/(1-\varepsilon)]$, and we choose $\varepsilon = 0.01$ to obtain reasonable slopes at $t_c + r$ (Häfele, 1981). This amount of conservation is an intermediate estimate of what can be accomplished at low cost in the United States (NAS, 1985; OTA, 1991; Fickett *et al.*, 1990). As such, it is probably an optimistic estimate for low-cost conservation available worldwide.

Fuel switching represents a set of high-cost, slowly implemented emission-reduction technologies. Its cost and effectiveness are simulated by assuming that all emissions are produced by long-lived capital equipment using either emitting (fossil fuel) or non-emitting (e.g., nuclear, solar, biomass) technologies. For both technologies the construction period is ten years and the operating period is thirty years. We assume that the first non-emitting equipment begins operations at time $t_{fs}$ with transition half-life $r$, so that the emission per unit energy relative to 1992 thereafter follows

$$E(t) = \Phi(t; t_{fs}, r) \quad , \tag{10}$$

where

$$\Phi(t; t_{fs}, r) = \frac{1}{1-\varepsilon} \frac{1}{1 + \exp[\rho(t - t_{fs} - r)]} \quad , \tag{11}$$

with $\varepsilon = 0.01$ and $\rho$ defined above.

## 2.4. Policies

We consider three emission-reduction policies – Conservation Only, Moderate Reduction, and Aggressive Reduction – together with a Base Case policy. Each policy is summarized in Table 1 and is described below.

*Base Case*

This reference policy is identical to IPCC/90 Scenario A for carbon dioxide and methane (Figures 1a and 1b), and to IPCC/90 Scenario C for nitrous oxide, CFCs, and CFC substitutes. For this policy there is no conservation and no fuel switching, hence $I(t) = E(t) = 1$ in Equations (6) and (7). The total radiative forcing is shown in Figure 1c.

*Conservation Only*

In this policy, conservation for both carbon dioxide and methane is initiated in 1992 such that the energy intensity thereafter falls 30% over 20 years. Thus $I(t)$ in Equations (6) and (7) is given by Equation (8) with $t_c = 1992$, and $E(t) = 1$ for all $t$ (Figures 1a and 1b). The radiative forcing for the other GHGs is that of IPCC/90 Scenario C. The total radiative forcing is presented in Figure 1c. This policy is close to the middle estimate of the Wigley and Raper (1992) scenarios.

*Moderate Reduction*

Under the moderate reduction policy, only conservation is undertaken during the first period, 1992 to 2002, again such that $I(t)$ falls 30% over 20 years. This policy is consistent with those proposed by several European governments, but is more stringent than US policy through 1992 (Morrisette and Plantinga, 1991). At the beginning of the second period, 2002, the values of $\Delta T_{2x}$ and $\Delta T^*$ are assumed to become known and fuel switching is begun. Because of the ten-year construction period, initiation of fuel switching in 2002 cannot affect $E(t)$ until a decade later – consequently, $t_{fs} = 2012$. The transition half-life, $r_m$, is the decision variable. It is chosen such that $\Delta T(t)$ peaks at $\Delta T^*$ for the revealed $\Delta T_{2x}$. The resulting emissions of carbon dioxide and methane, and the total radiative forcing are presented in Figures 1a, 1b, and 1c for targets $\Delta T^* = 1.5°C$ and $3.0°C$.

*Aggressive Reduction*

Under the aggressive reduction policy, both conservation and fuel-switching options are adopted in 1992, the latter with transition half-life $r_a = 40$ years. Because of the ten-year construction period, $E(t) = 1$ for $1992 \leq t \leq 2002$, $t_{fs} = 2002$, and $r_a = 40$ years during 2002 to 2012. At the beginning of the second period, 2002, the rate of fuel switching is adjusted to $r_a*$ to yield the desired $\Delta T^*$ for the revealed $\Delta T_{2x}$. Thus, for $t \geq 2012$, $r_a = r_a*$ and $t_{fs} = 2012 - r_a * /4$, the latter so that $E(t)$ is continuous at $t = 2012$. The resulting emissions of carbon dioxide and methane are shown in Figures 1a and 1b, and the total radiative forcing in Figure 1c, each for targets $\Delta T^*$ = 1.5°C and 3.0°C. Note that under both moderate and aggressive policies, as $F_{CO2}(t)$ and $F_{CH4}(t)$ decrease, the radiative forcing peaks and begins to fall. The decline in radiative forcing is sensitive to the modeling of the atmospheric carbon dioxide and methane concentrations (Equations 2 and 5); the dynamics of the removal of GHGs from the atmosphere could be important in choosing long-term emission levels.

## 2.5. Costs and constraints

We calculate the abatement costs associated with each of our emission reduction policies as described below. We also examine cost reductions due to research and development in order to compare the impacts of aggressive and moderate near-term R&D policies.

*Costs of Emission Reduction Policies*

The incremental cost of conservation is taken as \$5 per ton (carbon weight) of carbon dioxide emissions avoided. The incremental annual cost of fuel-switching in billions of 1990 dollars is

$$K(t) = C(t) + O(t) \quad , \tag{12}$$

where

$$C(t) = \sum_{j=0}^{2} \kappa_j \sum_{i=0}^{-9} n_{j,i}(t) \quad , \tag{13}$$

is the total cost in year $t$ of having under construction $n_{j,i}$ plants scheduled for completion in year $t - i$ having emitting ($j = 0$), low-cost non-emitting ($j = 1$) and high-cost non-emitting ($j = 2$) equipment, and

**Table 2.** Total-capital and annual-operating costs of emitting, low-cost non-emitting, and high-cost non-emitting equipment.

| $j$ | Type of equipment | Annual operating cost $\sigma_j$ (\$/kWh) | Total capital cost $10\kappa_j$ (\$/kWh) |
|---|---|---|---|
| 0 | Emitting | 0.025 | 0.152 |
| 1 | Low-cost non-emitting | 0.028 | 0.170 |
| 2 | High-cost non-emitting | 0.037 | 0.220 |

$$O(t) = \sum_{j=0}^{2} \sigma_j \sum_{i=1}^{30} n_{j,i}(t) \quad , \tag{14}$$

is the total operating cost in year $t$ of $n_{j,i}$ plants having age $i$ in year $t$. The construction and operating costs for each type of equipment, $\kappa_j$ and $\sigma_j$, are shown in Table 2. In this table the costs for low-cost and high-cost non-emitting equipment are equivalent to $50 and $200 per ton of carbon avoided (Manne and Richels, 1991; Nordhaus, 1991a). By setting $E_{CH4}(t) = E_{CO2}(t) = E(t)$ in Equations (6) and (7), we have assumed that methane emissions are reduced together with carbon dioxide emissions at no additional cost. This simplification restricts our ability to compare policies that reduce methane and carbon dioxide independently, but does not affect our study of the impact of abrupt changes on the policies described in Section 2.4.

The values of the $n_{j,-9}(t)$ for $t \geq 1990$ are determined subject to a demand constraint,

$$\sum_{i=-9}^{20} \sum_{j=0}^{2} n_{j,i}(t) = Q_0 B(t+10) I(t+10) \quad , \tag{15}$$

an emission constraint,

$$\sum_{i=-9}^{20} n_{0,i}(t) = Q_0 B(t+10) I(t+10) E(t+10) \quad , \tag{16}$$

and a constraint on the applicability of low-cost non-emitting equipment,

$$\sum_{i=-9}^{20} n_{1,i}(t) \leq \frac{1}{2} Q_0 B(t+10) I(t+10) \quad , \tag{17}$$

where $Q_0$ is the magnitude of the energy-using sector in 1990 determined as 1990 world $CO_2$ emissions (6.8 GtC) divided by the 1990 ratio of industrial $CO_2$ emissions to commercial energy use, 7.2 tons of carbon per $10^5$ kWh. For $-8 \leq i \leq 30$ and all $j, n_{j,i}(t+1) = n_{j,i-1}(t)$. For $t < 1990$ and all $i, n_{1,i}(t) = n_{2,i}(t) = 0$ and $n_{0,i}(t)$ are chosen to reproduce the pre-1990 $CO_2$ fluxes. Unless Equation (17) binds, $n_{2,-9}(t) = 0$. If $n_{0,-9}(t) = 0$ is insufficient to satisfy Equation (16), emitting equipment of ages $i \leq 20$ is scheduled for early retirement, oldest first.

*Cost Reductions Due to R&D Policy*

It is difficult to quantify the impacts of near-term research and development on future long-term abatement costs. Nevertheless, it is instructive to consider the effects of policies which might make the fruits of R&D available sooner rather than later. Thus, we postulate an unspecified research and development program which will reduce the cost difference between non-emitting and emitting equipment by $d$ percent per year. If these cost reductions begin in the year $t_{\mathrm{R\&D}}$, the incremental capital and operating costs of fuel-switching for $t > t_{\mathrm{R\&D}}$ are given by Equations (13) and (14) with the coefficients $\kappa_j$ and $\sigma_j$ replaced by the time-dependent functions,

$$\begin{aligned} \kappa_j(t) &= \kappa_0 + (\kappa_j - \kappa_0)(1-d)^{t-t_{\mathrm{R\&D}}} \text{ for } t \geq t_{\mathrm{R\&D}}, j = 1,2 \;, \\ \sigma_j(t) &= \sigma_0 + (\sigma_j - \sigma_0)(1-d)^{t-t_{\mathrm{R\&D}}} \text{ for } t \geq t_{\mathrm{R\&D}}, j = 1,2 \;, \end{aligned} \tag{18}$$

We compare an aggressive near-term research-and-development policy having $t_{\mathrm{R\&D}} = 2002$ to a moderate research-and-development policy having $t_{\mathrm{R\&D}} = 2012$. We arbitrarily assume that $d = 2\%$ and that the annualized global cost of the moderate and aggressive R&D policies are small compared with global abatement costs.

## 3. Non-abrupt Climate Changes

The transition half-life for the second period of our two-period sequential-decision strategy is determined such that, for each first-period policy (moderate and aggressive) and specified climate sensitivity ($\Delta T_{2x}$), the resulting temperature increase peaks at the specified climate target ($\Delta T^*$). As in Hammitt *et al.* (1992), we use the energy-balance climate/upwelling-diffusion ocean model of Schlesinger and Jiang (1991a) to simulate the increase in global-average surface temperature resulting from our radiative-forcing scenarios (Figure 1c). The resulting $\Delta T(t)$ trajectories for $\Delta T_{2x} = 2.5°C$ are presented in Figure 1d. For $\Delta T^* = 3.0°C$ (1.5°C) the temperature trajectories for the moderate and aggressive near-term policies, with respective second-period transition half-lives of 92 (22) and 125 (30) years, each peak at $\Delta T(t) = 3°C$ (1.5°C). The temperature trajectory peaks earlier for the moderate near-term policy than for the aggressive near-term policy, 2121 (2040) compared to 2135 (2044), because the emission-reduction rate for the moderate policy is less rapid during the first period, and more rapid during the second period, than for the aggressive policy.

We assume that the temperature trajectories for the moderate and aggressive pair, each of which peaks at the same climate target, cause the same damage due to climate change. We report abatement costs as annualized values, defined as the constant annual rate that has the same present value over the period 1992–2100, using a 5% discount rate, as the stream of capital and operating costs associated with each emission-reduction scenario. The incremental long-term (1992–2100) annualized costs for the moderate and aggressive abatement policies are presented in Figure 2 as a function of the climate target, $\Delta T^*$, for four values of the climate sensitivity, $\Delta T_{2x} =$ 0.5, 1.5, 2.5, and 4.5°C.

Consider a case where the near-term moderate policy is chosen today with uncertain information about the climate sensitivity and climate target, and that in ten years we learn that the climate sensitivity is $\Delta T_{2x} =$ 2.5°C and that the damages due to climate change are such that the optimum climate target is $\Delta T^* = 3°C$. As shown in Figure 1d, achieving this climate target for the moderate near-term policy and climate sensitivity of 2.5°C requires a second-period policy in which emissions are reduced with a transition half-life of 92 years. Figure 2 shows that the annualized global-abatement cost for the moderate near-term policy and its subsequent tailored long-term abatement is $13 billion/year. If the near-term aggressive policy were chosen instead, Figure 1d shows that a second-period policy in which emissions are reduced with a transition half-life of 125 years would be required. The annualized global-abatement cost for the aggressive near-term policy and its subsequent tailored long-term abatement is $22 billion/year, that is, $9 billion/year greater than the abatement costs for the moderate near-term policy (Figure 2). On the other hand, if we learn in ten years that the climate target is 1.5°C, with a climate sensitivity of 2.5°C, the moderate and aggressive near-term policies would have to be followed by second-period emission-transition half-lives of 22 and 30 years, respectively. In this case, as shown in Figure 2, the annualized global-abatement costs for the aggressive near-term policy would be $227 billion/year, while those for the moderate policy would be $23 billion/year greater, that is, $249 billion/year.

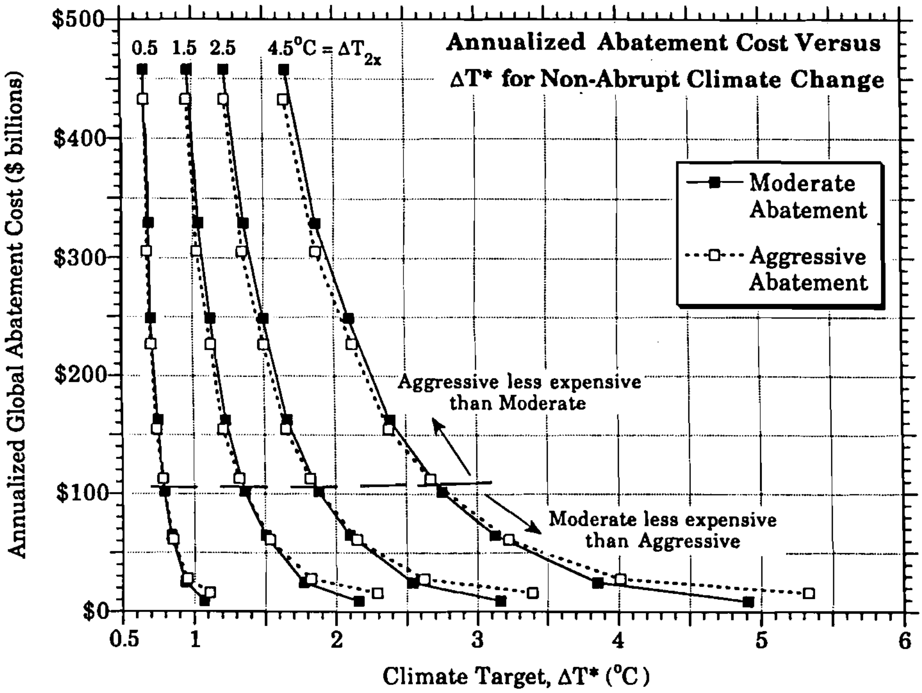



**Figure 2.** Annualized costs (1992–2100, 5% discount rate) of moderate and aggressive abatement policies versus climate target $\Delta T^*$ for non-abrupt climate change for $\Delta T_{2x}$ = 0.5, 1.5, 2.5, and 4.5°C.

The most salient feature of Figure 2 is that the long-term abatement cost is significantly less sensitive to the choice between the two near-term policies than it is to the revealed characteristics of the climate system, $\Delta T^*$ and $\Delta T_{2x}$. The costs for both the moderate and aggressive near-term policies rise sharply with decreasing climate target and increasing climate sensitivities, since these conditions require relatively rapid emission reductions. These rapid emission reductions result in higher costs because for them: (i) non-emitting capital must begin operation earlier, which increases the present-value cost; and (ii) some emitting capital must be discarded and replaced before it has served its full life.

For any given climate target and climate sensitivity, the first-period cost is always greater for the aggressive policy than for the moderate policy, while the second-period cost is always greater for the moderate policy than for the aggressive policy. The annualized long-term (first period plus second period) cost is less for the aggressive abatement policy than for the moderate-abatement policy only when the climate target is less than 2.7, 1.9, 1.4, and 0.8°C for climate sensitivities 4.5, 2.5, 1.5, and 0.5°C, respectively. These cross-over values are smaller than those quoted in Hammitt *et al.* (1992) – 2.9, 2.1, 1.5, and 0.9°C. The costs in the present study also differ from those of Hammitt *et al.* (1992). In the present study, baseline emissions for $N_2O$ and the CFCs are lower, requiring smaller reductions in $CO_2$ and $CH_4$ emissions to achieve any specified climate target; $CH_4$ emissions are reduced in tandem with $CO_2$ emissions at no additional cost; and $N_2O$ and CFC emissions are not altered from their respective baselines. The net effect of these differences is to reduce abatement costs and cross-over values below those of Hammitt *et al.* (1992).

The small difference between the costs of the aggressive and moderate policies for any given climate target and climate sensitivity is due to the long time scale of the response of the climate system to changes in radiative forcing and the fact that yearly anthropogenic greenhouse-gas emissions cause only small changes in radiative forcing. The small difference between the costs of aggressive and moderate policies is insensitive to the assumed discount rate (varied between 0% and 10%), the duration of the first period (5 to 20 years), and the ratio of high-cost capital to low-cost capital (1 to 10). While the cross-over values are only moderately sensitive ($\leq 30\%$ variation) to the choice of these parameters, the total abatement cost is highly sensitive to their values.

The relatively small cost difference between the aggressive and moderate abatement policies at low climate targets suggests that the penalty for waiting ten years to begin emissions reductions, beyond those inexpensively available through conservation, may be a small fraction of the overall abatement costs. Similarly, the costs of adopting the aggressive near-term policy, if it subsequently proves unwarranted, may be small relative to the world economy (Schneider, 1993). For both near-term policies, the large costs at low climate targets relative to the costs at high climate targets suggests that even the aggressive policy, with its near-term emissions reductions in excess of those currently proposed by any government, does not provide much relief if we subsequently discover climate change to be a serious problem.

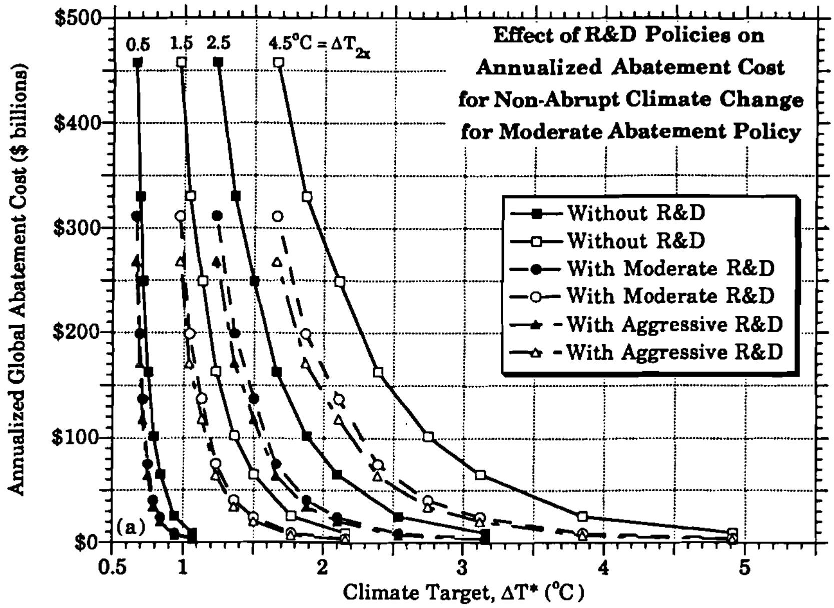
At present there is little definitive information available to judge what the value of $\Delta T^*$ should be. Rijsberman and Swart (1990) argue that the global-mean temperature rise should be limited to 1°C and that an increase above 2°C would cause grave and unacceptable damage to ecosystems. Nordhaus (1991b) estimates steady-state damages as a function of Gross Global Product for $\Delta T$ = 3°C. A crude extrapolation, which estimates a marginal damage function from Nordhaus' point estimate (Hammitt and Lempert, 1992), suggests a climate target of 1.5°C to 2°C for the $\Delta T_{2x} = 2.5°C$ curve in Figure 2. This span of uncertainty in $\Delta T^*$, from 1°C to 2°C, implies an order of magnitude uncertainty in the abatement costs, regardless of which near-term abatement policy is chosen.

The long-term cost implications of the aggressive and moderate R&D policies described in Section 2.5 are shown in Figure 3. Combining the moderate R&D policy with either the moderate or aggressive abatement policies from Figure 2 reduces the overall costs of each abatement policy by roughly a factor of two. The R&D does not significantly affect the relatively small cost difference between the abatement policies or the cross-over points. In regions of low $\Delta T^*$, the aggressive R&D policy reduces the overall abatement costs beyond those of the moderate R&D policy by about 15%. A low climate target requires rapid construction of non-emitting capital early in the second period regardless of whether the aggressive or moderate-abatement policy is chosen in the first period. In such cases the aggressive R&D policy has more opportunity than the moderate R&D policy to reduce the costs of this construction surge. These results are admittedly preliminary, but suggest that if we subsequently discover climate change to be a serious problem, the marginal near-term dollar spent on climate change abatement could yield significantly greater long-term benefit if it were spent on an aggressive near-term R&D policy rather than on an aggressive near-term abatement policy.

## 4. Abrupt Climate Changes

As stated in the Introduction, our conclusions above are based on the presumption that GHG-induced climatic change will not be abrupt. Here we abandon this presumption and examine the potential impact of abrupt climate change on the choice between the moderate and aggressive abatement policies. In particular, we examine below the effects of abrupt changes in: (1) the sinks of $CO_2$ and the sources of $CH_4$, (2) the circulation of the ocean, and (3) the climate sensitivity, $\Delta T_{2x}$.

We perform this analysis using the simple climate/ocean model of Schlesinger and Jiang (1991a) by prescribing a threshold global warming, $\Delta T_{ac}$, at which each of the abrupt changes occurs. For this study we assume that $\Delta T_{ac} = 1.5°C$ and that the nature and magnitude of the abrupt change are sufficiently well known at the beginning of the second period that policy makers can choose a policy to limit climatic change to the target $\Delta T^*$.



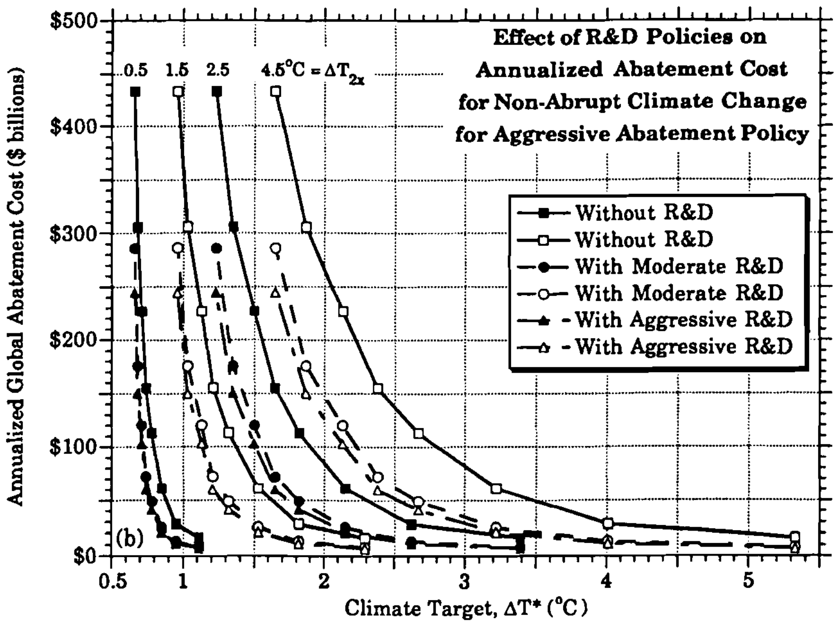




**Figure 3.** Annualized costs (1992–2100, 5% discount rate) of moderate and aggressive abatement policies with and without moderate and aggressive R&D policies as a function of climate target $\Delta T^*$ for non-abrupt climate change for $\Delta T_{2x}$ = 0.5, 1.5, 2.5, and 4.5°C.

This value conveniently places one of the pairs of curves in Figure 2 ($\Delta T_{2x}$ = 4.5°C) completely above $\Delta T_{ac}$ and one pair ($\Delta T_{2x}$ = 0.5°C) completely below the abrupt change. The two remaining pairs of curves intersect $\Delta T_{ac}$, one pair ($\Delta T_{2x}$ = 2.5°C) where the $\Delta T^*$ values at which the costs of the moderate and aggressive abatement policies are equal (the cross-over value of $\Delta T^*$) lies above the abrupt change and the other pair ($\Delta T_{2x}$ = 1.5°C) where the cross-over value lies below $\Delta T_{ac}$. Thus our choice of $\Delta T_{ac}$ allows us to evaluate the impact of any combination of values of $\Delta T_{ac}$ and $\Delta T^*$.

## 4.1. Abrupt changes in the sinks of $CO_2$ and the sources of $CH_4$

*Carbon Dioxide*

Human activities are known to be responsible for carbon-dioxide emissions of 7.6 ± 1.5 GtC/yr in 1989 and 1990, with the large uncertainty primarily due to uncertainty in the contribution by deforestation, ± 1.0 GtC/yr (Watson *et al.*, 1992). Of these emissions, 3.2 ± 0.1 GtC/yr remain in the atmosphere, 2.0 ± 0.8 GtC/yr are estimated to be absorbed by the oceans, and 2.4 ± 0.6 GtC/yr are absorbed by an undetermined sink or sinks (Watson *et al.*, 1990, 1992).

The dominant oceanic carbon-dioxide sink is thought to be weakly dependent on temperature and other climate conditions, such as wind stirring the ocean surface (Lashof, 1989). Ocean biota play a key role in transferring mixed-layer carbon to the deep oceans, and it is possible that changes in ocean chemistry, ecosystem balance, temperature, and circulation could significantly affect the absorption of carbon dioxide by the oceans. At least a portion of the missing carbon-dioxide sink is thought to be due to absorption by terrestrial biota, primarily forests, which could be affected by climate change (Watson *et al.*, 1992).

We consider the impacts of two abrupt changes in the carbon cycle. In the first, the unknown sink is assumed to saturate permanently in the year $t_{ac}$ that the global-average temperature exceeds the threshold value, $\Delta T(t_{ac}) > \Delta T_{ac} = 1.5°C$. For $t \geq t_{ac}$, the $CO_2$ formerly absorbed by this sink remains instead in the atmosphere. In the second and more severe abrupt change, we assume that all sinks for anthropogenic carbon saturate almost entirely when the global-average temperature exceeds $\Delta T_{ac}$, such that the average atmospheric residence time of anthropogenic $CO_2$, $\tau_{CO2}$, increases from its present value of 230 years to 1000 years. The latter value was chosen to be significantly larger than the present residence time, but constrained such that the atmospheric carbon dioxide concentration would fall fast enough in the years of declining emissions that $\Delta T(t)$ would not exceed $\Delta T^*$.

We model these abrupt changes by replacing Equation (2) for $t \geq t_{ac}$ by

$$C_{CO2}(t) = \left[1 - \frac{k_{CO2}(s+r)\Delta t}{C_{CO2}(1990)}\right] C_{CO2}(t-1) + k_{CO2}F_{CO2}(t)\Delta t \quad , \qquad (19)$$

where $C_{CO2}(1990) = 354.1$ ppmv and $\Delta t = 1$ yr. The term $s = 2.0$ GtC/yr is the best-guess estimate of the ocean sinks and choosing $r = 1.8$ GtC/yr gives the best fit to the IPCC/90 Scenario-A $CO_2$ concentration (within 1%) given the IPCC/90 Scenario-A $CO_2$ emissions. For the Base-Case emissions, Equation (19) reproduces the results of Equation (2) to within 10% for all $t$. We model the abrupt saturation of the missing sink by setting $r = 0$ for $t \geq t_{ac}$. We model the abrupt increase in carbon-dioxide residence time by setting $k_{CO2}(s+r)/C_{CO2}(1990) = 0.001$ yr$^{-1}$.

The GHG-induced temperature change as a function of time, $\Delta T(t)$, is presented in Figure 4 for the abrupt increase of $\tau_{CO2}$ to 1000 years at $\Delta T_{ac} =$ 1.5°C, as well as for the other abrupt climate changes to be discussed below, together with $\Delta T(t)$ from Figure 1d for the non-abrupt change, each for the conservation-only policy and $\Delta T_{2x} = 2.5$°C. Figure 4 shows that $t_{ac} = 2033$ and thereafter the GHG-induced warming for each abrupt climate change shown exceeds that for the non-abrupt change. For the abrupt increase of $\tau_{CO2}$ to 1000 years, this difference in GHG-induced warming is 0.6°C in 2100 and 1.0°C in 2140. (For the abrupt saturation of only the missing sink, which is not shown, the difference is about half as large.) Thus, not surprisingly, an abrupt change which sharply reduces the sinks for carbon dioxide by 80% makes a significant difference in the temperature trajectory.

Figure 5 shows the impact of the abrupt increase of $\tau_{CO2}$ to 1000 years on the annualized abatement costs for the moderate and aggressive abatement policies. As expected, the cost curves are identical to the corresponding curves in Figure 2 for $\Delta T^* < 1.5$°C. For $\Delta T^* > 1.5$°C, the cost curves are shifted to the right, by an amount that increases with decreasing cost. The cross-over values of $\Delta T^*$ are unchanged for climate sensitivities $\Delta T_{2x}$ = 0.5 and 1.5, and increase by 0.2°C and 0.4°C for $\Delta T_{2x} = 2.5$ and 4.5°C, respectively, as shown in Figure 6.

The abrupt increase of $\tau_{CO2}$ to 1000 years increases the cost of reaching any climate target above 1.5°C. For example, for $\Delta T_{2x} = 2.5$°C and $\Delta T^* =$ 3°C, the abrupt change increases the cost of the moderate-abatement policy from \$13 billion per year to \$31 billion per year. However, this abrupt

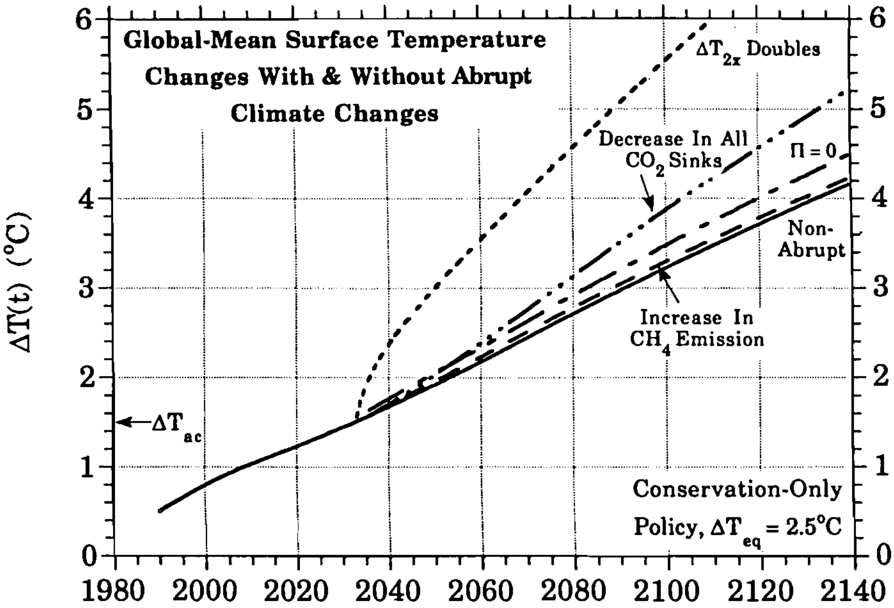



**Figure 4.** Annual global-mean surface temperature change, $\Delta T(t)$, for conservation-only policy and $\Delta T_{2x} = 2.5°\text{C}$ for: (a) non-abrupt climate change, and (b) for abrupt change at $\Delta T(t) = 1.5°\text{C}$ consisting of: (i) decrease in all $CO_2$ sinks; (ii) increase in $CH_4$ sources; (iii) decrease in ocean polar heat transport parameter, $\Pi$; or (iv) doubling of climate sensitivity to $\Delta T_{2x} = 5.0°\text{C}$.

change has only a small effect on the difference between the abatement costs required by the aggressive and moderate abatement policies to achieve a given climate target above the threshold, $\Delta T_{ac}$. For the above example, the aggressive minus-moderate cost difference decreases from $9 billion per year to $7 billion per year. Of course, the abrupt change has no effect on the cost difference between the polices for climate targets less than $\Delta T_{ac}$.

*Methane*

Two potentially important positive feedbacks for methane are that: (1) increased ocean temperatures could cause significant amounts of methane hydrates to outgas from continental-slope sediments (Lashof, 1989), and (2) increased polar air temperatures could cause increased methane emissions from the decomposition of organic materials in anaerobic sediments in northern wetlands. Estimates of these two effects are highly uncertain.

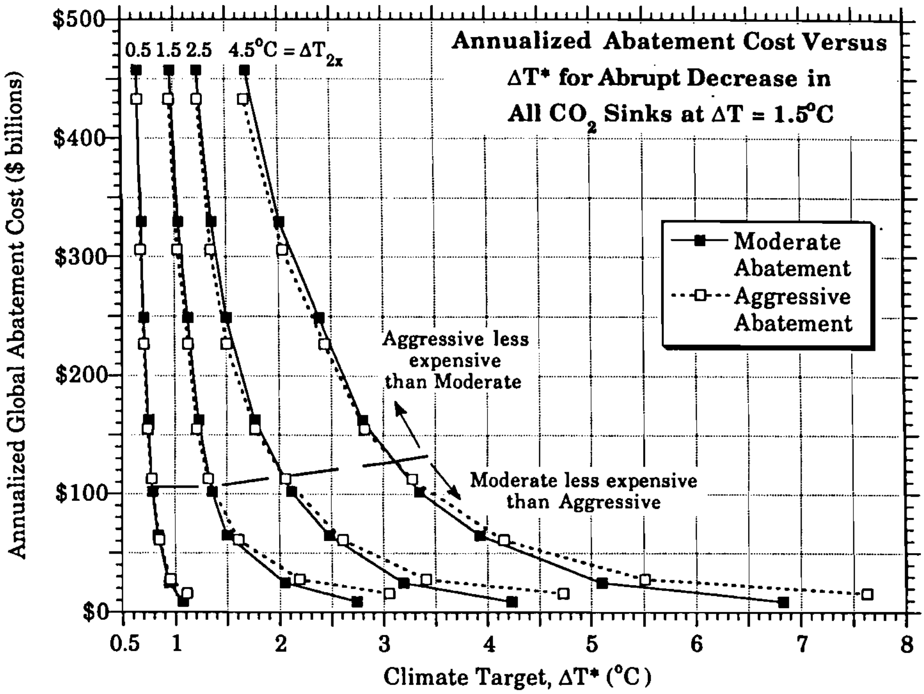



**Figure 5.** Annualized costs (1992-2100, 5% discount rate) of moderate and aggressive abatement policies versus $\Delta T^*$ for abrupt decrease in all $CO_2$ sinks at $\Delta T(t) = 1.5°C$ for $\Delta T_{2x} = 0.5, 1.5, 2.5$, and $4.5°C$.

Kvenvolden (1988) gives an upper bound of 120 Mt $CH_4$/yr for increased emissions from offshore permafrost and other parts of the continental shelf. Moraes and Khalil (1993) argue that the permafrost itself could contribute no more than 10 Mt $CH_4$/yr, but that warming-induced changes in arctic ecosystems could increase emissions by 80 Mt $CH_4$/yr. Accordingly, we consider an abrupt change in which methane emissions instantaneously increase by 100 Mt $CH_4$/yr for $t = t_{ac}$ when $\Delta T(t) > \Delta T_{ac} = 1.5°C$. We model this in Equation (5) by

$$F^{nat}(t) = 0.165 + 0.100\ U(t - t_{ac}),\quad Gt\ CH_4/yr\ , \tag{20}$$

where $U$ is the unit step function.

Figure 4 shows the influence on the GHG-induced temperature change of an abrupt increase in methane emissions at $\Delta T = 1.5°C$ for the conservation-only policy and $\Delta T_{2x} = 2.5°C$. By 2100, the abrupt temperature trajectory increases over the non-abrupt temperature trajectory by only 0.07°C, this

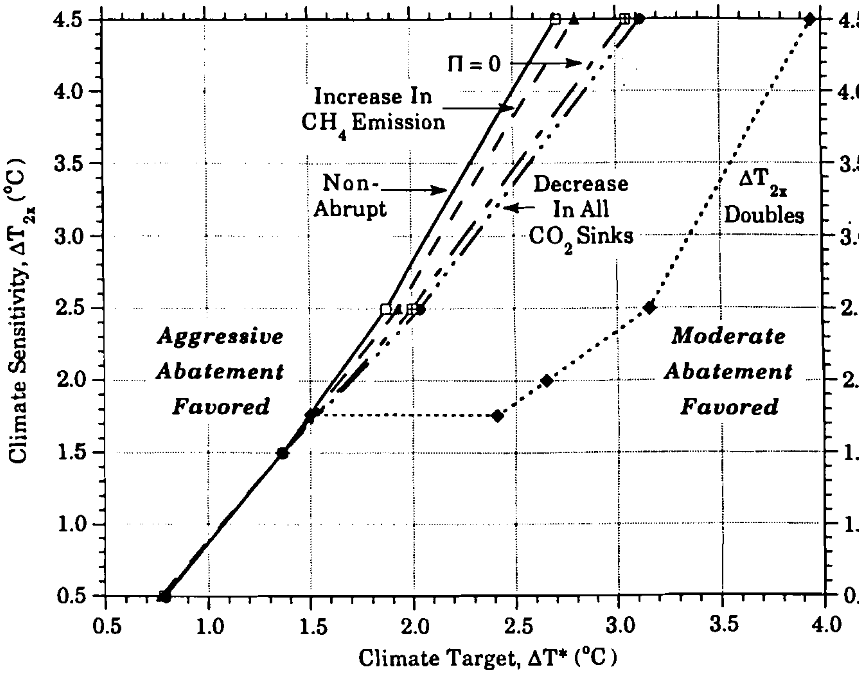



**Figure 6.** Domain of $\Delta T^*$ and $\Delta T_{2x}$ where the abatement cost of the aggressive (moderate) abatement is less than the cost of moderate (aggressive) abatement for: (a) non-abrupt climate change, and (b) for abrupt change at $\Delta T(t) = 1.5°C$ consisting of: (i) decrease in all $CO_2$ sinks; (ii) increase in $CH_4$ sources; (iii) decrease in ocean polar heat transport parameter, Π; or (iv) doubling of climate sensitivity to $\Delta T_{2x} = 5.0°C$.

as a result of both the short atmospheric lifetime of methane, 10.3 years, and the relatively small percentage of the total radiative forcing contributed by methane (14% in 2100). As shown by Figure 6, the cross-over value of $\Delta T^*$, where the cost of the aggressive-abatement policy equals the cost of the moderate-abatement policy, increases slightly for climate sensitivity $\Delta T_{2x}$ greater than 1.5°C.

The abrupt increase in methane emissions slightly increases the long-term costs of responding to climate change. For example, for $\Delta T_{2x} = 2.5°C$ and $\Delta T^* = 3°C$, the abrupt change increases the cost of the moderate-abatement policy from $13 billion per year to $15 billion per year. The abrupt increase in methane emissions has an even smaller effect on the difference between the abatement costs of the aggressive and moderate abatement policies than does the abrupt decrease in $CO_2$ sinks. For the above example, the aggressive minus-moderate cost difference decreases from the \$9 billion per year to \$8 billion per year.

## 4.2. Abrupt changes in the circulation of the ocean

The time scale for the response of the climate system to increasing GHGs is determined by the rate at which the enhanced heating is transported downward into the ocean. If there were little or no downward heat transport, the effective heat capacity of the ocean would be similar to the heat capacity of the continents, and the climate system would respond to the enhanced greenhouse heating within months. But, the ocean can transport considerable heat into its interior as a result of its thermohaline circulation – the vertical circulation of water generated by the sinking of dense water. This sinking or downwelling of water occurs only at particular locations, predominantly, in the Greenland-Norwegian Sea, where North-Atlantic-Deep-Water is formed, and in the Weddell Sea, where Antarctic-Bottom-Water is formed. Elsewhere, a compensating upwelling of water occurs, and the downwelling and upwelling branches are connected by horizontal conduits of flowing sea water. One such circulation system is the "conveyor belt" described by Broecker (1987) which travels at depth from the Atlantic through the Indian to the Pacific Ocean. As a result of the thermohaline circulation, the characteristic response time of the climate system is considerably lengthened, one estimate of which – based on an atmosphere-ocean general circulation model – is $50 \pm 10$ years (Schlesinger and Jiang, 1990).

If the ocean's thermohaline circulation were abruptly diminished by GHG-induced climate change, the heat that would have been transported to the deep ocean would instead be retained at the ocean's surface, thereby enhancing the rate of global warming. The possibility of this occurring was raised by Broecker (1987) who suggested that increased glacier melting and higher precipitation might lower the salinity of the North Atlantic water sufficiently to halt its density-driven downwelling. Broecker asked, "... what is the likelihood that increases in $CO_2$ and other greenhouse gases will jolt the ocean-atmosphere system out of its current mode into one more suitable to the coming conditions?" Broecker (1987) concluded that: "Unfortunately, we have little basis for answering this critical question."

We examine the potential impacts of abrupt changes in ocean circulation on near-term policy choices in two ways. In the first, we decrease the upwelling velocity in the simple climate/ocean model from $W = 4$ m/yr to $W = 0$ for all $t \geq t_{ac}$ after $\Delta T$ reaches the threshold, $\Delta T_{ac} = 1.5°C$. This simulates the extreme case wherein the thermohaline circulation completely shuts down, with the result that all vertical oceanic heat transport occurs by diffusion only. In the second, we decrease the polar parameter of the model from $\Pi = 0.4$ to $\Pi = 0$ for all $t \geq t_{ac}$. This simulates the case wherein the thermohaline circulation does not decrease, but heat ceases to be transported downward from the surface to the abyss by bottom-water formation in polar latitudes.

As shown in Figure 4, the abrupt decrease in $\Pi$ from 0.4 to 0 increases $\Delta T(t)$ by 0.25°C in 2100 and 0.33°C in 2140 relative to the non-abrupt temperature trajectory. This abrupt decrease in $\Pi$ increases the cross-over values of $\Delta T^*$ for $\Delta T_{2x}$ greater than 1.5°C (Figure 6), slightly increases the long-term costs of achieving any particular climate target – for example, from $13 billion per year to $19 billion per year for the moderate-abatement policy for $\Delta T_{2x} = 2.5°C$ and $\Delta T^* = 3°C$, and slightly decreases the difference between the abatement costs of the aggressive and moderate abatement polices – from $9 billion per year to $7 billion per year for the example above.

The results for the abrupt shutdown of the thermohaline circulation, that is, for the abrupt decrease from $W = 4$ m/yr to $W = 0$, are not presented in Figure 4 because they are virtually indistinguishable from the non-abrupt results. In particular, $\Delta T(t)$ for this abrupt change first decreases below that for the non-abrupt change, by a maximum of 0.061°C in 2038, then increases to intersect the non-abrupt curve in 2109, and continues to rise above the latter to a positive difference of 0.014°C in 2140. This complex behavior occurs because $W$ has two effects for $\Pi < 1$. First, positive $W$ acts to warm the mixed layer by upwelling heat from below. Second, $W > 0$ acts to cool all layers below the mixed layer, other than the bottom layer, by transporting upwards more heat from a layer than into it, this by virtue of the decrease in GHG-induced temperature change with increasing depth. Consequently, abruptly setting $W = 0$ first acts to cool the mixed layer by turning off the heating by upwelling heat from below. Thereafter, the ocean beneath the mixed layer warms relative to the non-abrupt, $W = 4$ case. This eventually reduces the downward heat transport from the mixed layer by diffusion, which leads to a slight warming of the mixed layer relative to the non-abrupt case.

It is important to note that while neither of these abrupt changes in ocean circulation has a large effect on global-average temperature, they could have important regional consequences. For instance, an abrupt change in the Gulf Stream could lead to significant cooling in Europe. Thus the most important effect of this abrupt change could be to increase the damages associated with a particular value of $\Delta T_{\max}$, which would imply that a smaller climate target would be appropriate. Such a change in the target could make the aggressive policy preferred. This change would not, however, affect the similarity of costs between the aggressive and moderate strategies.

### 4.3. Abrupt changes in climate sensitivity, $\Delta T_{2x}$

The sensitivity of the climate system to increasing GHG concentrations, $\Delta T_{2x}$, is determined by a number of feedback processes, the most important of which are thought to be those involving water vapor, clouds, and albedo changes from ice and snow cover. Many of the feedback processes are not well understood. As a result, general circulation models predict a range of climate sensitivities, from $\Delta T_{2x} = 1.5°\text{C}$ to 4.5°C (Houghton *et al.*, 1990), and much of this variation is due to uncertainties in the formation and behavior of clouds (Cess *et al.*, 1989, 1990). It is not implausible that the strength of one or more of the feedback processes is a function of the GHG-induced climate change itself.

We examine the potential impact of an abrupt increase in climate feedback by abruptly doubling the climate sensitivity when $\Delta T(t) > \Delta T_{ac} = 1.5°\text{C}$. Figure 4 shows the temperature trajectory for the case where $\Delta T_{2x}$ doubles from 2.5°C to 5.0°C. The difference between the temperature trajectories for this abrupt change and for the non-abrupt change is larger than the differences for the previously considered abrupt changes.

Figure 7 shows the impact of this abrupt increase in climate sensitivity on the annualized abatement costs for the moderate and aggressive abatement policies. While the curves are identical to those in Figure 2 for $\Delta T^* < 1.5°\text{C}$, the abrupt change produces a nearly flat transition region for $\Delta T^* > 1.5°\text{C}$, wherein the cost curves for $\Delta T_{2x} = 1.5$, 2.5, and 4.5°C are spliced respectively to the post-abrupt-change cost curves for $\Delta T_{2x} =$ 3.0, 5.0, and 9.0°C. Even this rather extreme abrupt change reinforces the general results of our previous cases, namely, the abrupt change increases the total long-term costs of responding to climate change, but does not alter the small cost difference between the aggressive and moderate abatement policies.

This result must be interpreted with some caution, however, due to the rapid increase in $\Delta T(t)$ seen in Figure 4, which causes the pronounced stretching of the cost curves in Figure 7. The actual damages are expected to be sensitive to the rate, as well as to the magnitude, of the climatic change, so the most important impact of this abrupt increase in climate feedback could

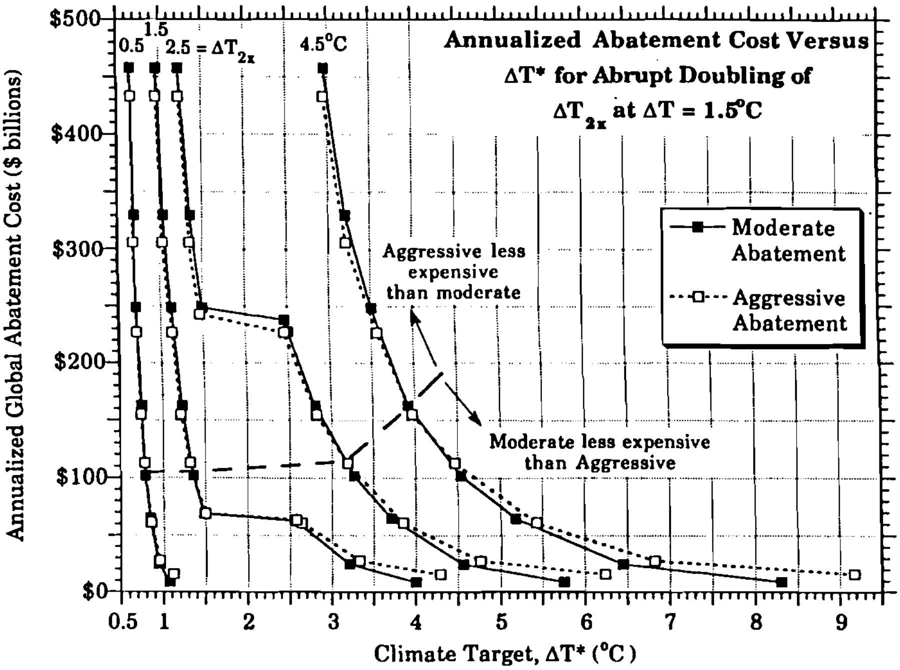



**Figure 7.** Annualized costs (1992–2100, 5% discount rate) of moderate and aggressive abatement policies versus $\Delta T^*$ for abrupt doubling of $\Delta T_{2x}$ at $\Delta T(t) = 1.5°\mathrm{C}$ from $\Delta T_{2x} = 0.5$, 1.5, 2.5, and 4.5°C to $\Delta T_{2x} = 1$, 3, 5, and 9°C, respectively.

be to increase the damages significantly. Similarly to the case of abrupt changes in ocean circulation, we would expect that the climate target could be smaller if the abrupt change were to occur, and that the most significant effect of this particular abrupt change could be to push $\Delta T^*$ toward the region where the aggressive strategy is preferred.

## 5. Discussion and Conclusions

We have shown above that although abrupt changes – in the sinks of carbon dioxide, the sources of methane, the ocean's thermohaline circulation, and the climate sensitivity – increase the long-term costs of responding to climate change, they do not significantly affect the lack of sensitivity of these costs to the choice between near-term moderate and aggressive abatement policies.

Our analysis is not exhaustive, however, because we have not considered several important factors which might increase the desirability of the near-term aggressive-abatement policy. In particular, we have not explicitly considered abrupt changes that would affect the damages due to climate change – for example, by causing unfavorable shifts in the habitats of disease-carrying insects, or the destruction of cherished ecosystems. Such abrupt changes could greatly increase the damages expected from climate change beyond current estimates, such as those in Nordhaus (1991b). Furthermore, as suggested by our discussion of abrupt changes in climate sensitivity, abrupt changes affecting damages could shift the revealed climate target toward lower values where the aggressive-abatement policy is favored. If such abrupt changes were perceived to be likely, policymakers would have greater reason to choose the aggressive-abatement policy.

Our analysis also assumes that policymakers will have improved information about climate change in ten years. In fact, knowledge may not be significantly better in ten years, and it is possible that we may never be able to confidently predict an abrupt change before it manifests itself. The less policymakers believe we can predict abrupt changes before they occur, the more they should be inclined to follow an aggressive near-term abatement strategy in order to delay the start of an abrupt change or to make the response to it easier. In addition, a variety of factors not considered in our cost model, such as shortages of necessary personnel or capital to support rapid technology diffusion, could increase the cost difference between the aggressive and moderate abatement strategies in cases where rapid abatement is necessary.

The above caveats notwithstanding, our analysis predicts small differences between the costs of the aggressive and moderate near-term abatement strategies, even with abrupt changes, because of the long response time scale of the climate system and the fact that yearly GHG emissions are only a small fraction of the atmospheric concentration. These factors are independent of the damages, our assumed rate of learning, and our cost model. Conversely, near-term policies designed to reduce the cost of future abatement and/or increase the rate of future technology diffusion have the potential to change important system parameters more quickly than do policies designed to reduce current emissions, and thus could make an important impact if climate change is severe.

Consequently, even with the risk of abrupt changes, the long-term costs of abating climate change are not sensitive to whether emission reductions (beyond those available at very low cost) begin soon or are delayed ten years. Development and diffusion of less-costly measures for reducing emissions of greenhouse gases hold the potential for much larger reductions in abatement costs.

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# Mitigating Climate Change Impacts: The Conflicting Effects of Irreversibilities in $CO_2$ Accumulation and Emission Control Investment

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## Abstract

This paper investigates the fundamental problem of mitigating the impacts of climate change in an environment of uncertainty and learning. In particular, the paper uses a stochastic version of Nordhaus' DICE model to show that the irreversibility of investment capital has a stronger effect than irreversibilities in climate change (other than catastrophic effects). The implications are that (1) if abatement decisions are irreversible, there should be less emission control today than would be optimal without taking into account learning and (2) policy makers should pursue control policies that are costlessly reversible – a variant on the "no-regrets" strategy.

## 1. Introduction

This paper focuses on two critical features of climate change and the control of its precursors. One is that there is a great deal of uncertainty involved in the problem and some of that uncertainty is slowly being resolved over time. This, of course, is true of many environmental problems. The second feature of climate change, a feature more unique to climate change, is the stock nature of the externality and the long time frame for decisions and effects. Once carbon or other greenhouse gases are emitted into the atmosphere, they stay resident for a very long time, only slowly decaying. Furthermore,

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the lags in the system are such that it takes some time to feel the effects of a unit of greenhouse gases emitted today.

The stock effect and the presence of uncertainty with learning have been major factors in the debate over the control of greenhouse gases. In fact, the US Bush Administration's "go-slow" approach to greenhouse gas control can generously be attributed to the perception that we were learning so much about the problem that it is optimal for society to wait to invest in costly controls until we do know more. In contrast, the position of US Vice-President Al Gore (1992) and many environmentalists has been that the stock nature of the externality means that it will be difficult if not impossible to "undo" the pollution being emitted into the atmosphere today, should we discover in ten or twenty years that climate change is indeed a very serious problem.

There are actually several effects and processes wrapped up in the policy debate. One concerns risk aversion. If it is a possibility that environmental effects will be very severe (e.g., triggering another ice age), then one might wish to be cautious today, erring toward over-control relative to the risk-neutral position. Although it is well-known that governments should generally be largely risk neutral when it comes to public investments, an ice age over North America is probably a significant enough event, affecting a large enough portion of the US and world population in the same manner, that even the US government would be risk averse. In contrast, the risk of over-investment in $CO_2$ control is probably not significant enough to warrant a deviation from risk neutrality on the part of government decision makers.

A second aspect of the climate change problem has nothing to do with risk aversion but rather the quasi-option value of waiting to take irreversible actions (Arrow and Fisher, 1974). The idea here is that if one can choose to take an irreversible action in an environment of uncertainty and learning, then there is a value to postponing the decision until more information is acquired. Of course, without irreversibilities, an action that turns out to be suboptimal later can be undone and thus the irreversibility effect goes away. Also, if there is no learning, then today's decision will be as good as tomorrow's so there is no call to postpone the decision.

It can be argued that this irreversibility effect is foremost in the minds of both sides of the climate change debate. Both sides of the debate acknowledge that society is learning rapidly about climate change. Those leaning toward the Bush Administration's position would argue that there are significant investments that must be made to control $CO_2$ and that once made, these investments cannot be undone. Thus there is a capital investment irreversibility that should lead to caution in applying controls. Those leaning toward the environmentalist position would argue that once $CO_2$ goes into the atmosphere, it cannot be removed, except naturally, and thus we should try to control as much as possible today. If tomorrow the problem turns out to be less severe, we can always increase emissions. If tomorrow the problem turns out to be very significant, we will be glad we erred today on the side of the environment.

In this paper, we focus on the irreversibility problem. In other words, leaving aside the issue of risk aversion, we ask what effect the capital and environmental irreversibilities in climate change should have on decisions today (1990) to control greenhouse gases. Others have looked at the gains or losses from delaying control until more information is acquired (Manne and Richels, 1992; Peck and Teisberg, 1993; Schlesinger and Jiang, 1991). This paper explores the issue using one of the most widely used models for climate change policy analysis, Nordhaus' DICE model (Nordhaus, 1993). We will use a variant of the DICE model for which a stochastic structure with passive learning has been included. The results reported here represent an extension of earlier work, reported elsewhere (Kolstad, 1993).

In the next section, we will review what is known about decisions with irreversibilities and interpret this in the context of climate change. In the subsequent section, we introduce our stochastic version of DICE and discuss the differences between it and the deterministic DICE. We will then present and discuss the results of our analysis, followed by conclusions.

The major conclusion of the paper is that the capital irreversibility appears to be stronger than the environmental irreversibility. An immediate reaction would be that George Bush was right. While he may have been, that is not the correct interpretation of our results. First of all, the optimal response to capital irreversibility is to reduce the $CO_2$ control level from what it should be ignoring irreversibilities, but not reduce the control level to zero. Perhaps more important, however, irreversibilities associated with control capital are significant and thus $CO_2$ control policies which do not involve irreversible investment should be pursued. Thus a temporary but significant $CO_2$ tax (e.g., five to ten years) that would modify behavior but not lead to long-term investments in control capital are more desirable than policies that require such investments, such as a permanent $CO_2$ tax.

## 2. Irreversibilities

The question of how to make sequential decisions when there is uncertainty and learning is not a new one. Before looking at what is known, we characterize the generic problem. Consider a two period model. We can take actions, $a_1$ and $a_2$ in either period. We must make decisions in an environment of uncertainty but that environment changes between period 1 and 2. At the simplest level, suppose that $s$ is a random variable in period 1 and becomes known in period 2. Furthermore, the actions taken in time period 1 may constrain actions taken in time period 2. This problem can be written

$$\max_{a_1, a_2(s)} U[a_1] + \mathcal{E}_s\{V[a_1, a_2(s), s]\} \tag{1}$$

$$\text{such that } a_2(s) \varepsilon C(a_1) \tag{2}$$

where $C$ represents a constraint set. Notice in the problem that the choice of $a_2$ is conditioned on $s$. Denote the optimal choice of $a_1$ in the above problem as $A1_L$. The "no-learning" case is identical to the above except that $a_2$ cannot be conditioned on $s$ and is treated as independent of $s$, just as is $a_1$. Denote the optimal choice of $a_1$ in the "no-learning" case as $A1_{NL}$. The basic question we ask is how does $A1_L$ differ from $A1_{NL}$? How does the fact that we will learn tomorrow, affect today's decision?

The first results in the literature concern the problem without the constraint (2) – no irreversibility. In this case, Simon (1956) has shown that with quadratic utility and normally distributed errors, there is no effect of learning; i.e., $A1_L = A1_{NL}$. Malinvaud (1969) extended this, also focusing on the unconstrained problem. He demonstrated that if uncertainty is "small," then regardless of the functional forms (although with some regularity conditions), there is no effect of learning. In fact, in both of these problems, the extent of the uncertainty itself plays no role. Malinvaud's result is termed first-order certainty equivalence. It is important to realize that if uncertainty is not small, we have not precluded learning having an effect on today's actions. In fact, that would generally be expected, even without irreversibilities.

Freixas and Laffont (1984) treat the constrained problem (1-2) although with a very specific form of (2): $a_1 \leq a_2(s)$ and $V$ independent of $a_1$. The choice of $a_1$ constrains the possibilities for $a_2$. They demonstrate that learning causes a downward bias in the choice of $a_1$: $A1_L \leq A1_{NL}$. Unfortunately, the problem they treat is very specific, not easily applied in general.

In summary, the existing literature is helpful but far from complete in helping answer our original empirical question about the effect of learning on $CO_2$ control. We turn to an empirical model in the next section to help answer this question.

## 3. A Stochastic DICE Model

Prof. William Nordhaus has been studying climate change policy for nearly two decades. Recently, he introduced a simple policy model of climate change based on a single-sector Ramsey model of optimal growth, coupled with a two-box (ocean/atmosphere) model of the earth's climate. This model, termed the DICE model, is widely known (Nordhaus, 1992, 1993) and has been the basis for a number of debates over climate change policy.

Although the model is described in detail in Nordhaus (1993), it is useful to summarize it here since it constitutes the basis for the stochastic growth model used here. The DICE model maximizes the net present value of logarithmic per capita utility multiplied by the population size (which grows over time). The time horizon is several hundred years. Utility is a function of consumption which is the residual from production, after netting out investment and climate change damage. Production depends on the stock of capital, the labor force, time (technical change), and the level of emissions control, more control implying less output. Climate damage depends quadratically on the global temperature increase, pegged at 1.3% of world GDP annually for a 3°C temperature rise. The evolution of the climate is tracked by a $CO_2$ accumulation equation, an atmospheric temperature equation, and an ocean temperature equation, with heat transfer across the ocean-atmosphere interface.

An earlier paper (Kolstad, 1993) reported on modifying the DICE model to include a stochastic structure with learning. In essence, climate damage is considered uncertain, with two states of nature possible. One state (*a priori* with a 20% probability) is that damage is five times as great as assumed by Nordhaus; the other state (*a priori* 80% likely) is that there is no climate change damage. This yields an expected damage equal to that of Nordhaus. I termed these two possible states of nature B and L for climate change being a "big problem" or a "little problem." Finally, in Kolstad (1993), learning occurs over three decade-long time periods. The prior on B is a probability of 0.8 but learning can change that over time. The rate of learning is characterized by a single parameter that takes values between 0

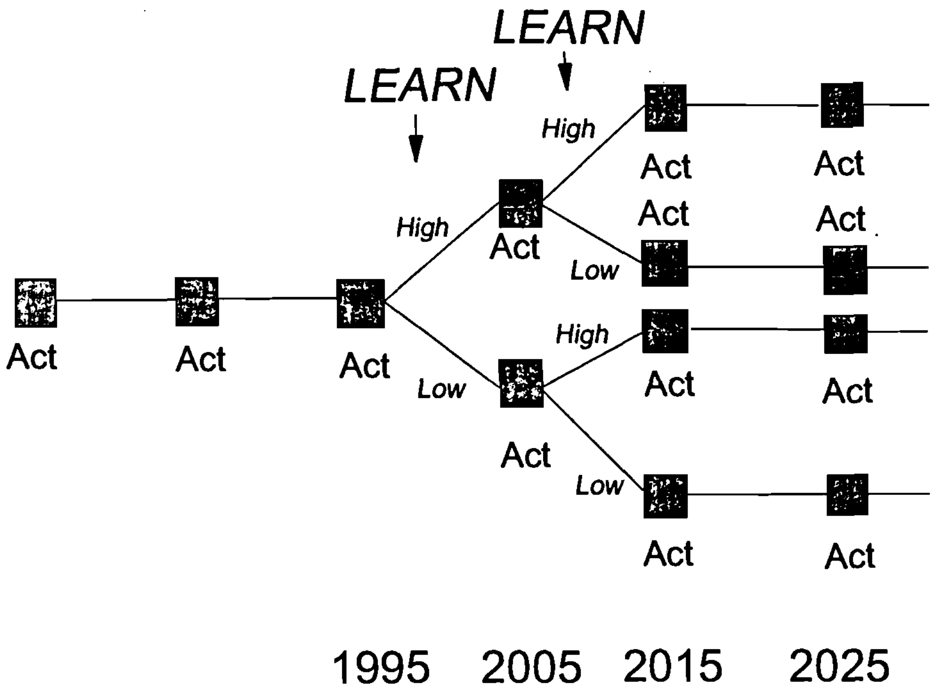


**Figure 1.** Structure of learning in stochastic DICE model.

and 1. A rate of learning of 0 means no learning and a rate of learning of 1 means total resolution of uncertainty within one time period.

The model used in this paper is the same as the earlier version with two important exceptions. One is that learning occurs over two decidual periods only. Figure 1 shows a tree structure of the learning process. Shown in the figure are two periods of learning where learning can either proceed "high" or "low". "High" means that learning has resulted in an increase in the probability of state of nature "B." Thus "high" learning reinforces the view that climate change is a big problem. After two periods of learning, no further learning occurs but not all uncertainty has been resolved. In fact, there will then be four possible values for the probability of states {B,L}, corresponding to different learning in the two periods.

The second difference from the previously reported stochastic version of DICE is that we introduce an emission control investment constraint that relates abated emissions today ($AE_t$) to abated emissions in the previous period ($AE_{t-1}$): $AE_t \geq (1 - \delta_E)AE_{t-1}$. Using the notation in Kolstad (1993), this becomes

$$\sigma(t)Y(t)\mu(t) \geq (1-\delta_E)\sigma(t-1)Y(t-1)\mu(t-1) \ . \quad (3)$$

The $\delta_E$ represents the depreciation rate of the abatement capital stock. If $\delta_E = 0$ (no depreciation), then the amount of pollution abated in period $t-1$ is a lower bound on how much is abated in period $t$, reflecting the fact that emissions control capital installed in period $t-1$ would still be operating in period $t$. If $\delta_E = 1$ (complete one period depreciation), then equation (3) disappears. Thus by varying $\delta_E$ we can simulate the extent of the abatement capital irreversibility.

## 4. Results

In running the stochastic DICE, we are primarily interested in one variable: 1995 $CO_2$ control rates. Obviously, learning will change control levels in future years. Our interest is in our decision today: the current $CO_2$ control level. Figure 2 shows the optimal 1995 control rate as a function of the learning rate (0 = no learning; 1 = complete resolution of uncertainty in one period).[1] Three curves are shown, corresponding to different values of $\delta_E$, the abatement capital depreciation rate. The first thing to note is that the capital irreversibility is real and has an effect on current control decisions. With no learning, there is no difference in the optimal decisions for the three $\delta_E$ values. However, with more rapid learning, it makes sense to reduce control levels when abatement capital investment is irreversible. When abatement capital is perfectly reversible, then learning has virtually no effect on the optimal control level. In other words, the environmental irreversibility does not appear.

It could be that this failure to find an environmental irreversibility is due to discounting the future at 3% per annum – a small rate but one which adds up over 100 years. Figure 3 shows the results of exercising the stochastic DICE with a pure rate of time preference of 1% per annum.[2] Certainly, the desirable level of control increases – from 7% to 15% for the case of no learning. However, the same pattern as found in Figure 2 persists. Irreversible control capital has a significant influence on optimal levels of control in 1995 but an effect of the environmental irreversibility just does not materialize.

[1] Refer to Kolstad (1993) for additional explanation of the learning rate parameter.

[2] The pure rate of time preference is not the same as the discount rate, which is generally higher.

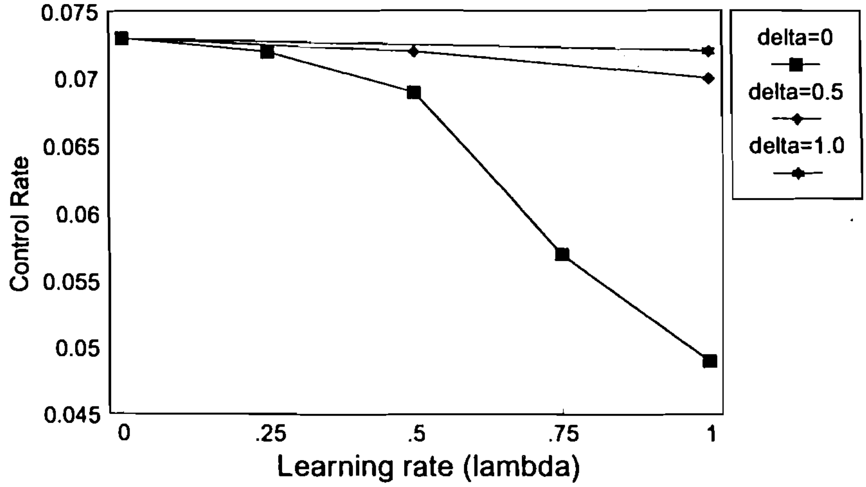


**Figure 2.** 1995 $CO_2$ control rate vs. learning rate (rate of time preference = 3%).

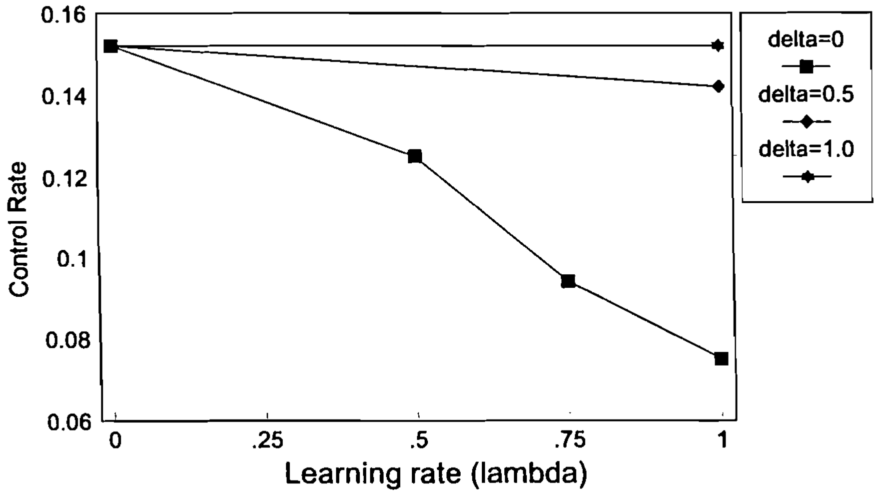


**Figure 3.** 1995 $CO_2$ control rate vs. learning rate (rate of time preference = 1%).

Stepping back to the theoretical results discussed earlier, the lack of an effect of an environmental irreversibility would appear to be an application of Malinvaud's first-order certainty equivalence. An irreversibility only exists if under some future state of nature it is desirable to negatively emit and one is constrained from doing that. Since under no scenario does it turn out to be desirable to negatively emit $CO_2$, the appropriate model is equation (1) and not equation (1-2). Uncertainty appears to be small enough in the context of the overall model to invoke Malinvaud's result and demonstrate that learning has no effect. In fact, uncertainty has no effect. On the other hand, there are states of nature under which it may be desirable to uninvest in control capital. Under state of nature "L", climate change is no problem at all so it is desirable to pursue zero abatement, a possibility which may be precluded for $\delta_E < 1$. Thus the appropriate theoretical model is equation (1-2) to which Malinvaud's result cannot be applied.[3] In this case, something like the Freixas and Laffont model should be applied which indicates that learning does have an effect.

Thus if it is unlikely that the nonnegativity constraint on emissions will be binding but possible that the nonnegativity constraint on abatement investment will be binding, it is not surprising that the result embodied in Figures 2 and 3 emerge.

## 5. Interpretation

To understand further why the results of the previous section emerge, we can examine the deterministic DICE (essentially the same as used by Nordhaus) and its response to suboptimal levels of emissions. In particular, consider three cases. In one case, the base case, an optimal trajectory of emission control is computed (7.3% in 1995). In the second case, the "Overcontrol" case, emission control is held at 15% in 1995 and 2005 and then allowed to re-equilibrate to an optimal level. In the third case, the "Undercontrol" case, emission control is held at 0% during 1995 and 2005 and then allowed to seek an optimal level.

Figure 4 shows the optimal emission control rate over the coming century for these three cases. End-effects are causing the control rate to peak and then decline. Note that there is very little residual effect from the major perturbations involved in the Over- and Undercontrol cases. This can be understood from Figure 5 where the temperature changes resulting from these excursions are shown. Clearly, substantial divergence from optimality in 1995 and 2005 does not make much of a difference in the long-term development of the climate. Since the temperature change is very similar under the three cases, so too is the marginal damage from pollution in 2015. Thus,

[3] Malinvaud's result cannot be applied if there is a positive probability that constraint (2) will be binding.

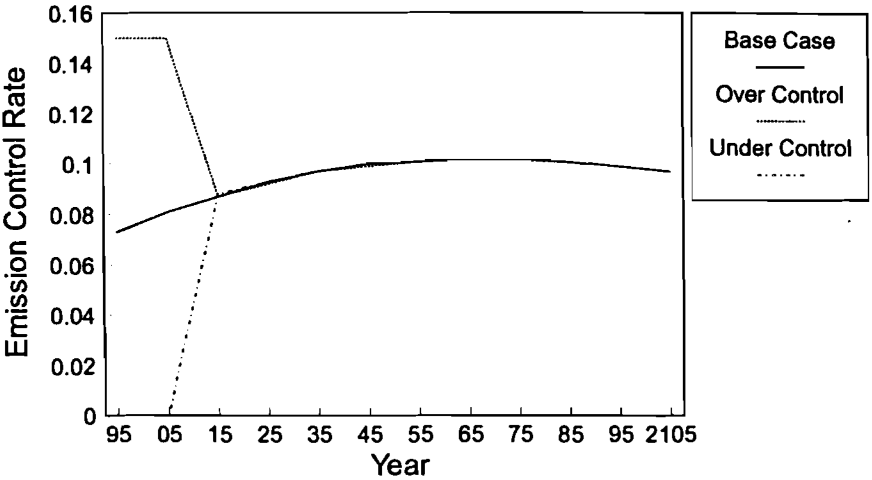


**Figure 4.** Emission control rate with 1995, 2005 suboptimal control (rate of time preference = 3%).

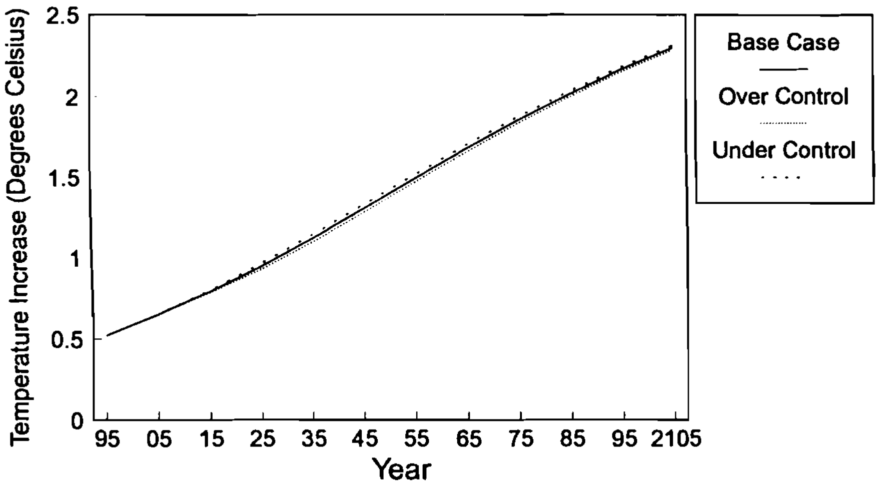


**Figure 5.** Temperature increase with 1995, 2005 suboptimal control (rate of time preference = 3%).

it is not surprising that control levels from 2015 on are very similar for the three cases.

A less "black-boxy" explanation can also be developed. Figure 6 shows the losses in terms of present value of utility from increased $CO_2$ levels in

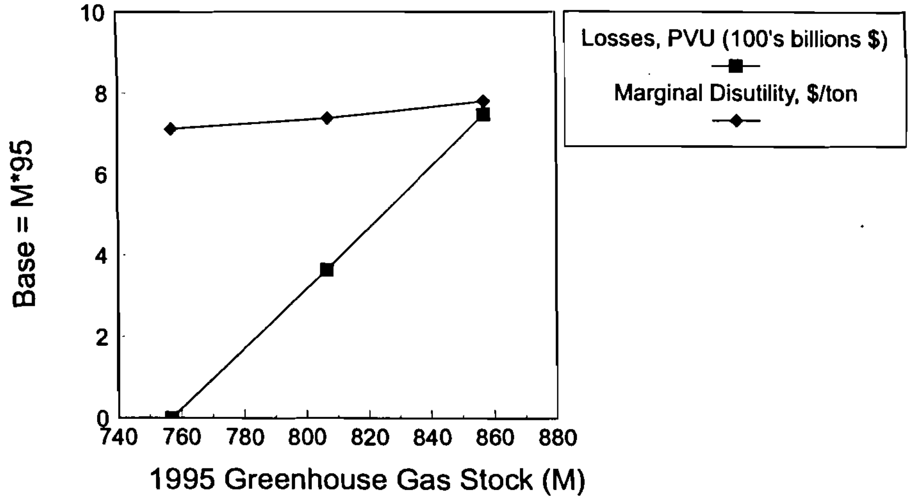


**Figure 6.** Marginal and total disutility as function of $CO_2$ stock.

1995.[4] A level of 757 is associated with the base case. The monetary value for utility is computed using the marginal utility of consumption. As we vary 1995 base $CO_2$ levels, damage occurs as is indicated in the figure. However, the marginal damage is almost constant over the range shown (emissions in the decade centered on 1995 add approximately 50 to the $CO_2$ stock). Figure 7 shows the marginal control cost and marginal damage associated with various levels of 1995 $CO_2$ control. The marginal damage is taken directly from Figure 6, with an appropriate change of variables. It is very nearly constant over the range shown. The marginal cost of control is the marginal one period utility from an increase in the $CO_2$ control level, excluding climate damage.

The reason for the observed behavior becomes obvious from inspection of these figures. Substantial over- or under-emissions of $CO_2$ in 1995 will change the marginal damage from $CO_2$ very little. Considering the steepness of the marginal control cost function, subsequent control levels are largely unchanged from earlier suboptimal control levels. Thus, the sheer persistence of the stock externality makes today's actions only a modest drop in the bucket of a century-long build-up of greenhouse gases.

[4]These values were obtained by incrementing the stock of $CO_2$ in 1995 by either 50 or 100 and then executing the model. Thus the control variables are able to compensate to a certain extent for the increment in concentrations. This does not seem to happen to any extent.

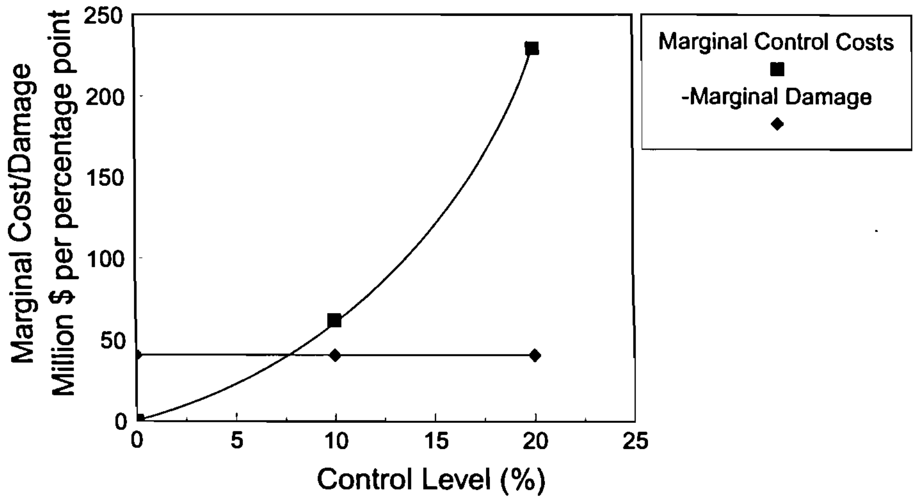


**Figure 7.** Marginal cost, marginal damage vs. 1995 $CO_2$ control rate.

Another conclusion that emerges from Figures 6 and 7 is that if costs and damages had a different shape, then different results might emerge. For instance, if marginal control costs were much flatter and damages exhibited more of a threshold effect, then it would appear that these results would change.

## 6. Conclusions

In this paper, we have explored the apparently conflicting irreversibilities associated with the accumulation of greenhouse gases in the atmosphere and the accumulation of abatement equipment to control the emissions of greenhouse gases. *A priori*, it is not clear which of these irreversibilities is stronger and thus whether today's emission control decisions should be biased upwards or downwards to reflect the learning that is going on with respect to climate change.

We have explored this issue using a stochastic version of Nordhaus' DICE model. In the context of the DICE model, it appears that the control capital irreversibility exists and is substantial whereas the environmental irreversibility does not exist or at least has no effect on current policy decisions. For instance, with a 1% rate of time preference, the optimal 1995 $CO_2$ control level of 15% should be reduced to 7% if learning is proceeding very rapidly and control capital is infinitely lived. With some depreciation of abatement capital, this result is greatly reduced.

There are two ways to interpret this result. One is that learning (which certainly is occurring) should cause us to "go-slow" on $CO_2$ control. This is a correct interpretation if, in fact, abatement capital is long lived, non-fungible, and cannot be uninvested once invested. Of course, the result is not that there should be no control, only that the otherwise optimal control level should be reduced somewhat.

Perhaps a more useful and intriguing result is that the fungibility of control capital is very important. The results suggest that we should be looking very carefully at the reversibility of actions taken to control $CO_2$. Those actions that are reversible should be more desirable than those that are not. For example, behavioral changes are presumably easily reversed whereas capital equipment investments are less easily reversed.

How does one induce reversible investment as opposed to irreversible investment? One way is to use incentives rather than technological controls and stress the tentative nature of those incentives. For example, a \$20/ton carbon tax for five or ten years which may or may not be renewed probably sends a better signal than a smaller permanent carbon tax. Focusing thinking on the reversible nature of control decisions may be the most useful result to emerge from this paper.

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# Summary of Optimal $CO_2$ Emissions Control with Partial and Full World-wide Cooperation: An Analysis Using CETA*

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## 1. Introduction

In this paper, we use the Carbon Emissions Trajectory Assessment Model (CETA) to take a first look at the implications of alternative assumptions about the degree of world-wide cooperation in controlling $CO_2$ emissions. The CETA model represents world-wide economic growth, energy consumption, energy technology choice, global warming, and global warming costs over a time horizon of more than 200 years. To analyze the implications of world-wide cooperation in controlling $CO_2$ emissions, we disaggregate the CETA model into two regions. One of the regions (which we refer to as "Region 1") is assumed to take the initiative in adopting and promoting $CO_2$ control policies, while the other ("Region 2") does not control emissions unless it is compensated for income losses associated with participation in a control agreement. We then explore the implications of alternative assumptions about membership in Region 1 and the control policies that Region 1 pursues.

We consider two possible regional divisions of the world. In our base case, Region 1 is the OECD alone. In our sensitivity case, Region 1 also includes the former Soviet bloc. In both cases, Region 2 is simply the rest of the world. This summary only discusses results for the base case in which Region 1 is the OECD.

When Region 1 is the OECD, it is initially about twice the size of Region 2, as measured by gross output. However, Region 2 grows faster than Region 1; thus, by 2080 it is bigger, and by the year 2200, it is roughly twice the size of the OECD. As measured by carbon emissions, the OECD and Region

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2 are roughly the same size initially, while the relative growth of Region 2 causes its emissions to become roughly four times as large by early in the twenty-second century.

We consider three hypothetical control policies that Region 1 might pursue. In our "Selfish" case, Region 1 controls its own emissions optimally given its own warming costs. In our "Altruistic" case, Region 1 controls its emissions optimally given *world-wide* warming costs. Finally, in our "Optimal" case, Region 1 pays Region 2 to participate in an optimal world-wide emissions control policy.

## 2. Analytical Approach

Warming costs borne by each region are assumed to be a cubic function of the amount of temperature change relative to the pre-industrial temperature:

$$D_t = \alpha \cdot L_t \cdot (T_t^A)^3 \tag{1}$$

where $D_t$ is annual warming cost, time $t$; $\alpha$ is a scaling constant; $L_t$ is labor input index, time $t$ ($L_1 = 1.0$); and $T_t^A$ is temperature rise (above pre-industrial).

The scaling constant, $\alpha$, is set for each region of the disaggregated CETA model so that warming cost at 3°C would be 2% of regional gross production as of 1990 ($t = 1$). Since we assume the damage function power is 3, warming cost rises non-linearly with increasing temperature; for example, at a 6°C temperature rise, cost would be 16% of gross production. We choose a power of 3 so that significant emission control will be optimal. Finally, we assume that the warming cost function above is scaled by the index of labor input (in efficiency units), $L_t$; thus the costs of warming grow as population and output per capita grow.

In the Selfish and Altruistic cases, the CETA model representing the OECD is solved assuming that costs of warming are either those directly borne by the OECD (the Selfish case) or the sum of those borne by the OECD and those borne by Region 2 (the Altruistic case). In both of these cases, the CETA model representing Region 2 is solved assuming that damage costs are zero.

In the Optimal case, a world-wide CETA model is first solved to determine the world-wide optimal carbon tax. Then the CETA models for the OECD and for Region 2 are solved with this optimal carbon tax imposed in each of the regions. This produces the carbon emissions for the two regions under the Optimal policy.

# 3. Carbon Tax Results

Carbon taxes provide a measure of the intensity of control efforts (at the margin) within the region or regions which exercise control over emissions. In the Altruistic and Selfish cases, these taxes apply only in the OECD; in the Optimal case they apply both in the OECD and in Region 2.

In the CETA model, there is a critical level of the carbon tax at \$208/ton; at this level, the carbon-free backstop technology becomes competitive with carbon-intensive coal-based synthetic fuels. This threshold must be crossed before really significant reductions in carbon emissions occur in the CETA model.

Initially, carbon taxes are in the \$5–10 range for all three possible policies that the OECD might follow. However, carbon taxes rise over time, and the rise is fastest in the Altruistic case, next fastest in the Optimal case, and slowest in the Selfish case. Thus, carbon taxes reach the critical \$208/ton level in 2080, 2110, and never for the Altruistic, Optimal, and Selfish cases, respectively.

# 4. Carbon Emissions Results

In the Selfish case, world-wide carbon emissions are not much different than they would be in the no control case. This is because Region 2 does not control emissions at all, and the level of control in the OECD is quite small – in the OECD, the carbon tax never even reaches the critical \$208/ton threshold at which large scale substitution of the carbon-free backstop for carbon-intensive synthetic fuels would occur.

There is little OECD control in the Selfish case because the OECD considers only the warming costs it directly bears in setting its carbon tax. Since warming costs are assumed to be proportional to gross output, the OECD's share of total warming costs falls as its share of gross output falls. By 2080, therefore, the warming cost considered by the OECD is less than half of the world-wide total cost.

In the Altruistic case, there is a noticeable reduction in world-wide emissions relative to the no control case. While Region 2 still does not control in this case, control in the OECD is very tight starting in 2080 (when the tax reaches the \$208/ton level). However, because Region 2 is large relative to the OECD after 2080, even this very stringent control in the OECD has a relatively modest effect on total world-wide emissions.

In the Optimal case, there is a further significant reduction in worldwide emissions relative to the Altruistic case. This reduction occurs in spite of the fact that OECD emissions are actually higher in this case than they are in the Altruistic case. This is possible because Region 2's participation in the control policy causes a reduction in Region 2 emissions that is more than sufficient to offset the increase in emissions from the OECD.

## 5. Welfare Implications

To compare the welfare effects of the alternative policies that the OECD might pursue, we calculate the present value of income losses from controlling emissions, and the present value of warming cost reductions that arise from emission control, both relative to the no control case. Present values are calculated using the discount rates implied by the CETA model – these are roughly 5% per year.

In the Selfish case, the OECD sustains an income loss and obtains a warming cost reduction that are both small and about equal in magnitude; thus there is little net benefit to the OECD in this case. Region 2, however, is a free-rider in this case; it obtains a small reduction in warming cost, while bearing no income loss from emissions control.

In the Altruistic case, the OECD incurs large income losses due to the extreme level of control it undertakes in this case. Although about a third of these income losses are offset by a reduction in warming costs, the OECD remains a big loser under this policy, with a present value net loss of about $800 billion. Region 2 is again a free-rider in this case, and it obtains a warming cost reduction of $800 billion, while bearing no costs of control.

Finally, in the Optimal case, Region 2 sustains an income loss of about $500 billion as a result of its participation in the Optimal policy regime. Thus the OECD pays this amount to Region 2 as compensation for its participation. Since this payment exactly offsets Region 2's income loss, Region 2 is left with a net gain of about $1000 billion, which is due to reduced warming costs. The OECD, on the other hand, bears an income loss of $500 billion in addition to having to make the payment of $500 billion to Region 2. It receives a partially offsetting benefit of $500 billion in the form of reduced warming costs. Thus the OECD's net cost under this policy is $500 billion.

## 6. Conclusions

When the OECD adopts a Selfish emissions control policy, we find that there is very little world-wide emissions control. This is because control in the OECD is modest, while there is no control in Region 2.

When the OECD adopts an Altruistic emissions control policy, we find that there is noticeable world-wide emissions control. However, this control is achieved by draconian emission reductions in the OECD while Region 2 continues its uncontrolled emissions.

When an Optimal policy is adopted, there is further significant emissions control relative to the Altruistic case. In this case, however, the control comes in a more balanced way from both the OECD and Region 2. In fact, the OECD's emissions are substantially higher in this case than they are in the Altruistic case.

We find that the net benefits to both the OECD and Region 2 are small in the Selfish case. In the Altruistic case, the OECD incurs high net costs, while Region 2 has significant net benefits of reduced warming. Finally, in the Optimal case, the OECD still bears a net cost, but it is lower than in the Altruistic case, while Region 2 has a higher net benefit than it does in the Altruistic case. Thus if the OECD were willing to adopt the Altruistic policy, it should be even more willing to make the side payments we assume are required to obtain the participation of Region 2 in an Optimal policy. However, Region 1 may not be willing to incur even the net costs of the Optimal policy; in this case, something like the Selfish case is the likely result.

# The Shadow Price of Greenhouse Gases and Aerosols

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## Abstract

This paper describes a model which integrates economic growth and GHG emissions assumptions with a model of the global climate. Given an abatement cost function for carbon emissions and a temperature dependent damage function culled from the literature, the model may be used to determine the optimal reduction in GHG emissions and the implied shadow price of GHG emissions. The shadow prices are important for determining the cost effectiveness of projects aiming to reduce GHG emissions. The paper hence calculates the marginal rate at which different GHG emissions can be traded while holding the present value of damages constant.

The paper also deals with sulfate aerosols which are thought to backscatter incoming solar radiation and help to mask the onset of climate change. In some perverse sense, sulfur emissions possess an economic value in their ability to fend off global warming. Large scale desulfurization measures could accelerate global climate change.

Using exogenous input assumptions based on the IPCC's best guess scenario and parameter assumptions which have found support in the literature, the paper calculates the impact of business as usual emissions on global GNP. These are compared with the impacts experienced under an optimal control solution and to what GNP would have been in the absence of a greenhouse effect. What emerges is that the greenhouse effect does little to reduce economic growth and that virtually nothing can be done to retrieve these losses anyway even by following the optimal abatement strategy. Furthermore, protocols involving the stabilization of emissions or concentrations at current levels are all much worse than doing nothing.

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# 1. Introduction

This paper introduces a simple model which was built to examine how different assumptions regarding the costs of abating GHG emissions and the damage from global temperature rise translate into different policy recommendations. The extent to which different models of the carbon cycle and different assumptions regarding the thermal lag and climate sensitivity matter can also be assessed. The model is used to evaluate different protocols covering the emission of GHGs and to locate the "optimal" strategy in the sense outlined below.

Whatever protocol the model is asked to evaluate, a set of shadow prices for GHG emissions emerge representing the marginal rate at which different GHG emissions can be traded while holding the present value of damages constant. In general, this rate will be different from that suggested by considering the global warming potential (GWP) of the various gases. Knowing the rates at which the different gases may be traded off against one another could provide a country with some flexibility in meeting aggregate emissions reductions targets. The shadow prices could also form the basis for evaluating the cost effectiveness of projects to reduce GHG emissions in less developed countries since the exogenous input assumptions and the parameter assumptions are not without support in the literature.

The salient features of the model are as follows: the model takes baseline economic output and future GHG emissions as given. GHG emissions accumulate in the atmosphere and are removed only slowly depending on their atmospheric lifetimes. Using equations reported by the IPCC, it is possible to calculate the increase in radiative forcing attributable to each GHG including any indirect effects and overlap effects. This increase in radiative forcing is partially offset by the presence of sulfate aerosols causing a backscattering of solar radiation.

Equilibrium warming is proportional to the change in radiative forcing and actual warming adjusts to equilibrium warming via a process of lagged adjustment. Temperature rise is taken as an index of global environmental change leading to a reduction in "green" GNP (GGNP) beneath conventionally measured economic output. This occurs through the need to divert economic resources into combatting the physical effects of global environmental change or providing compensation for the loss of environmental amenities. Such economic losses are quantified in terms of a damage function. The optimal control of global warming involves explicitly maximizing the sum of discounted GGNP through time by allocating resources between GHG abatement and immediate gratification. The abatement cost function for carbon is an equation linking proportionate reductions in carbon emissions with a proportionate cost in terms of GNP.

A number of other cost–benefit analyses of the global warming problem have been undertaken in the literature, for example with the CETA model of Peck and Teisberg (1992). In a separate cost–benefit analysis of arresting climate change, Cline (1992) considers the economic desirability of a 4 Gt C emissions ceiling compared with business as usual. Recently, Nordhaus (1992) has developed an elegant optimal control model of GHG abatement entitled DICE. This model is based around a Ramsey type model of economic growth in which all climate damage has a market impact cutting income and reducing emissions. This aspect of the DICE model conflicts with the view of many who see climate change as having mainly a non-market impact. In contrast to the DICE model, the analysis offered below calculates the optimal tax rates on a whole range of GHGs and not just $CO_2$. Recently, Fankhauser (1994) has calculated the marginal damage from GHG emissions using a model similar to the one outlined here. But the marginal damage figures presented by Fankhauser are conceptually quite different from the optimal tax rates discussed here.

The remainder of the paper is organized as follows: in Section 2 the model is described in greater detail. The basis for the abatement and damage cost estimates is discussed and the carbon cycle model and temperature change equation explained. Section 3 describes the input assumptions underlying baseline economic growth and emissions. These track the IPCC's best guess scenario fairly closely. Section 4 describes the results of the model when it is run using these assumptions. These results illustrate the impact on GGNP of continuing with BAU and the optimal percentage reduction of GHG emissions. The optimal tax rates necessary to secure the optimal reduction in emissions are computed and contrasted with the marginal damage estimates. Apart from the optimal strategy, a variety of other GHG protocols are assessed. Section 5 concludes with a discussion of the role of uncertainty.

## 2. The Model

The model has the form of a dynamic non-linear program and takes baseline global GNP and GHG emissions as exogenous. The objective of the model is to maximize the sum of GGNP up to the year 2200. Green GNP is the same as conventional GNP but with expenditures on pollution abatement costs and the value of environmental damage subtracted. A constant rate

Table 1. The estimated cost of $CO_2$ abatement with emissions trading.

| Percentage cutback | Percentage cost in terms of GNP 2000 | 2020 | 2050 | 2100 | 2150 | 2200 |
|---|---|---|---|---|---|---|
| 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 25 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 |
| 50 | 1.3 | 1.2 | 1.1 | 0.9 | 0.8 | 0.6 |
| 75 | 4.3 | 4.1 | 3.7 | 3.1 | 2.5 | ·1.9 |
| 100 | 10.3 | 9.7 | 8.9 | 7.4 | 6.0 | 4.6 |

Source: See text.

of discount equal to 5% is applied over all time periods. The control variable in this model is the percentage reduction in carbon emissions in each time period. Increasing abatement reduces income but also reduces future GHG concentrations reducing warming and avoiding climate change related damage.

The extent to which reducing carbon emissions reduces GNP is determined by the abatement cost function. The cost estimates used to generate this equation are from the GREEN model (Burniaux *et al.*, 1992) and the Edmonds and Barnes (1991) model. Both models assume that emissions trading occurs, so costs are kept to a minimum. The technique used to condense the information contained in these models is to take the published results regarding a percentage reduction in emissions, the associated reduction in GNP and the time at which the cutback occurs. Treating these results as data points, summary regression analysis is used to fit an abatement cost curve. This method is a convenient way of summarizing the available information on abatement costs since the results from more than one model may be incorporated. A cubic abatement cost curve through the origin appears to provide the best fit to abatement cost estimates after experimentation with more generalized functional forms. The coefficient on the percentage cutback term appears to be time variant and indicates that abatement costs fall modestly over time.

It is important to understand that the estimated equation has no particular statistical significance. Adding results from many different models does not obviously result in a better cost curve. The abatement cost estimates generated by the equation are displayed in Table 1. These estimates, of course, refer to the costs of reducing emissions of $CO_2$ from the consumption of fossil fuel but there has also been considerable discussion about the potential for afforestation to sequester carbon form the atmosphere as an alternative to such reductions. Although some progress has been made in identifying the potential scope for afforestation and the different management options which might be appropriate much less is known regarding the price of land and how this might change in response to large-scale afforestation. This makes it difficult to assess the cost effectiveness of such measures. At this stage, it seems best to omit the potential for afforestation from the calculations. In fact, the results of the analysis seem to suggest that measures which involve the slow absorption of carbon over a number of decades have a low value at least for the scenario dealt with.

There has been surprisingly little discussion regarding the cost of reducing emissions of $CH_4$ and $N_2O$. Adams *et al.* (1992) have analyzed, with the aid of a linear programming model, deliberate policies to reduce methane emissions from the agricultural sector using market mechanisms. The findings of this study suggest that the marginal cost of abating one ton of methane commence at $1,166. Michaelis (1992) argues that to reduce emissions of $N_2O$ by one ton through restricting the use of fertilizer costs $6,500. The model presented here assumes that it is impossible to abate methane or nitrous oxide emissions.

The damage function takes temperature rise as an index of global environmental change and converts it into a proportionate reduction in GNP. The results of a survey of expert opinion conducted by Nordhaus (1994) suggest a loss of 3.6% of GNP for a 3°C temperature rise. A taxonomy of the impacts of climate change by Cline (1992) points to much smaller losses of 1.1% for a 2.5°C rise and damage increasing by a power of 1.3 with temperature rise. Fankhauser (1993) arrives at an estimate of 1.5%. Titus (1993) uses an estimate of 2.5% of GNP for a 4°C rise in temperature. None of these papers indicate the extent to which damage depends upon the rate of warming. The model follows Fankhauser (1993) in assuming a loss of 1.5% for a 2.5°C temperature rise and a takes damage function exponent of 2.

The model deals with the five main GHGs: $CO_2$, $CH_4$, $N_2O$, CFC-11 and CFC-12. The baseline emissions of these gases is an exogenous input to the model. The purpose of including so many different GHGs is that their shadow values may be directly inferred from the analysis. The model also considers the influence of aerosol particles on the Earth's radiative balance. These particles are thought to mask the onset of global warming by scattering and absorbing solar radiation. According to Charlson *et al.* (1992), the effect of current emission loads corresponds to a negative radiative forcing of 1 $Wm^{-2}$ averaged over the northern hemisphere compared with 2.5 $Wm^{-2}$ from anthropogenic GHG emissions. This implies that the change in radiative forcing over the Northern hemisphere might have been substantially less than was previously believed to be the case. Aerosols, unlike the GHGs, do not mix perfectly and have an atmospheric lifetime measured in terms of weeks. Perversely, attempts to reduce fossil fuel emissions could precipitate global warming depending upon the character of the changes in fossil fuel use and whether they affect the sulfur load (see Wigley, 1991). Large scale desulfurization measures could also conceivably have an important impact. Given their ability to mask the effects of global warming, sulfate aerosols possess an economic value in this model.

The end of period change in the atmospheric concentrations of the non-carbon GHGs depends only upon their current atmospheric concentration, the average residence times of the different gases, and the quantity of each gas released during that period. The average residency times of the gases are the latest estimates contained in the IPCC (1992) document. The dynamics of $CO_2$ in the atmosphere are governed by the carbon cycle. The model of the carbon cycle used here is that of Maier-Reimer and Hasselmann (1987) although simpler models of the carbon cycle tend to leave the results unchanged. The 1985 concentrations of all these gases as reported in Boden *et al.*, (1991) define the initial state of the system.

In order to determine the change in global temperature brought about by an elevated concentration of GHGs in the atmosphere, it is necessary to calculate the change in radiative forcing relative to pre-industrial levels attributable to each gas. Radiative forcing rises less than linearly with concentrations since some spectral bands become effectively saturated. The functional form and parameters of the equations linking radiative forcing to changes in GHG concentrations are those cited by IPCC (1990). Both the direct and indirect forcing from $CH_4$ emissions are included as are the negative indirect effects of CFCs on stratospheric ozone (itself a potent GHG). The indirect effect of CFCs may reduce their potency as GHGs by up to 80% (Ramaswamy *et al.*, 1992). A function is taken from IPCC (1990) to represent an overlap term between $CH_4$ and $N_2O$. The changes in radiative forcing attributable to each of the different gases along with sulfate aerosols are summed to find total change in radiative forcing relative to pre-industrial levels.

In order to calculate the equilibrium temperature rise, it is necessary to multiply the change in radiative forcing by a parameter representing the sensitivity of the climate to changes in forcing (measured in $KW^{-1}m^2$). Given the IPCC's estimate of a 2.5°C temperature increase for a doubling of $CO_2$ concentrations, it is possible to deduce that this parameter takes the value of 0.572 $KW^{-1}m^2$.[1] Given that the climate sensitivity parameter is widely agreed to be 0.3 $KW^{-1}m^2$, the feedback parameter is 1.91 but it could easily be as high as 3.4 or as low as 1.1. Actual temperature adjusts to equilibrium temperature via a simple partial adjustment process exhibiting an e-fold time[2] of 19 years. The observed global temperature record provide the boundary conditions for this equation.

This concludes the specification of the model which is subsequently solved in ten year time intervals using the GAMS software (see Brooke *et al.*, 1992). Further details regarding the structure and parameterization of the model are available from the author on request.

## 3. Input Assumptions

This section describes the construction of the input assumptions which drive the model. The assumptions deliberately reflect key aspects of the IPCC best guess scenario IS92a. Obviously, the results contained in the following section correspond to these assumptions.

Conventional GNP output tracks population growth and population is determined by the cumulative logistic function. The parameters of this function are chosen such that the curve passes through the current population of 5.25 billion and the IPCC estimate of 8.41 billion for 2025 and 11.31 billion for 2100. It is assumed that labour productivity continues to grow at an annual rate of 1.6% per annum. This figure matches the average growth in GNP per capita assumed in IS92a.

The emission of GHGs is determined by the growth in income and exogenous GHG intensities. The annual growth rates used for the GHG intensity of output are all implicit in IS92a and point to a uniform decrease in the GHG intensity of output. Given an average rate of economic growth of 2.3%, the decline in output intensities is insufficient to prevent an increase in total emissions at least over the first half of the next century. In the "no-controls" scenario, emissions of carbon increase rapidly in the early part of the next century reaching 10.7 Gt C annually by the year 2025. Towards the end of the 21st century, however, the rate of increase slows such that by the

[1]Dividing the expected temperature change by the equation for the change in direct forcing from $CO_2$ doubling gives:

$$\lambda = \frac{2.5}{6.3\log(2)} = 0.572$$

[2]The e-fold time corresponds to the time required to close the gap between actual and committed warming by a proportion 1-$e^{-1}$ (about 63%).

**Table 2.** Business as usual annual GHG and aerosol emissions assumptions.

| Year | C (Gt) | $CH_4$ (Tg) | N (TgN) | CFC-11 (kt) | CFC-12 (kt) | S (Tg) |
|---|---|---|---|---|---|---|
| 1995 | 6.7 | 544 | 13.7 | 248 | 290 | 106 |
| 2005 | 8.0 | 620 | 15.2 | 170 | 183 | 120 |
| 2015 | 9.4 | 688 | 16.4 | 113 | 113 | 133 |
| 2025 | 10.7 | 743 | 17.2 | 74 | 68 | 143 |
| 2035 | 12.0 | 785 | 17.7 | 47 | 40 | 150 |
| 2045 | 13.1 | 813 | 17.8 | 29 | 23 | 155 |
| 2055 | 14.1 | 830 | 17.7 | 18 | 13 | 158 |
| 2065 | 15.1 | 837 | 17.4 | 11 | 7 | 158 |
| 2075 | 15.9 | 836 | 16.9 | 7 | 4 | 156 |
| 2085 | 16.7 | 830 | 16.3 | 4 | 2 | 153 |
| 2095 | 17.4 | 819 | 15.6 | 2 | 1 | 150 |

Source: See text.

year 2095 annual emissions reach 17.4 Gt C per annum. Beyond that point, the decline in the carbon intensity almost matches the increase in economic output such that the growth in carbon emissions stabilizes. In contrast, methane, nitrogen, and sulfur emissions reach a maximum half way through the 21st century and then turn down modestly as the decline in their output intensities outstrips economic growth. The IPCC has assumed that, with the Montreal Protocol and the amendment to it signed in London, the output intensities of the CFC gases will decline extremely rapidly. CFC-11 intensity falls at 6.85% annually while CFC-12 intensity falls by 7.66% annually. These negative growth rates nevertheless permit significant emissions of CFCs to occur even after their planned phaseout since many of these substances are "banked" in refrigerators and aerosols and, in any case, not all countries have signed the Montreal Protocol.

These trends in economic growth and emissions are projected forward to the year 2200. The resultant scenario is close but not identical to the IPCC's IS92a scenario (see Tables 2 and 3).

## 4. Results

This section outlines the results which emerge from the model when it is run using the input values described above. Results are reported only up to the year 2100 to avoid any problems associated with the assumption of a terminal date.

**Table 3.** Business as usual economic growth assumptions.

| Year | GNP ($tr) | GGNP ($tr) | % difference |
|---|---|---|---|
| 1995 | 26.27 | 26.27 | 0.0 |
| 2005 | 35.73 | 35.72 | 0.0 |
| 2015 | 47.25 | 47.22 | –0.1 |
| 2025 | 60.87 | 60.82 | –0.1 |
| 2035 | 76.67 | 76.55 | –0.2 |
| 2045 | 94.75 | 94.52 | –0.2 |
| 2055 | 115.31 | 114.89 | –0.4 |
| 2065 | 138.65 | 137.94 | –0.5 |
| 2075 | 165.20 | 164.04 | –0.7 |
| 2085 | 195.48 | 193.68 | –0.9 |
| 2095 | 230.15 | 227.46 | –1.2 |

Source: See text.

**Table 4.** The impact of controls on the climate.

| Year | No controls warming (°C) | Optimal control warming (°C) |
|---|---|---|
| 1995 | 0.38 | 0.38 |
| 2005 | 0.41 | 0.41 |
| 2015 | 0.49 | 0.49 |
| 2025 | 0.63 | 0.60 |
| 2035 | 0.79 | 0.76 |
| 2045 | 1.00 | 0.94 |
| 2055 | 1.22 | 1.14 |
| 2065 | 1.46 | 1.36 |
| 2075 | 1.71 | 1.59 |
| 2085 | 1.96 | 1.81 |
| 2095 | 2.20 | 2.04 |

Source: See text.

In the BAU scenario, global temperature rises to 2.2°C by the end of the 21st century (see Table 4) though the committed temperature rise by that time is somewhat higher. This temperature rise has only a limited impact reducing GGNP by just 1.2% below baseline GNP (see Table 3). At the same time, income has increased tenfold while population has only doubled so this loss does not seem to be of much importance. Per capita incomes grow monotonically with the input assumptions used here even if no action is taken to reduce GHG emissions.

To begin with, the marginal damage from these unchecked emissions (see Table 5) amounts to $6.07 per ton of carbon, $47 per ton of methane and $884 per ton of Nitrogen. The marginal damage from CFC-11 is $2,115 and from CFC-12 $4,194. These figures reflect only the role of CFCs as

**Table 5.** Current value marginal damage from GHG and aerosol emissions (\$/ton).

| Year | Carbon | Methane | Nitrogen | CFC–11 | CFC–12 | Sulfur |
|---|---|---|---|---|---|---|
| 1995 | -6.07 | -47 | -884 | -2,115 | -4,194 | +404 |
| 2005 | -8.44 | -68 | -1,267 | -3,129 | -6,089 | +642 |
| 2015 | -11.47 | -98 | -1,778 | -4,523 | -8,654 | +1,014 |
| 2025 | -15.19 | -138 | -2,439 | -6,376 | -12,024 | +1,563 |
| 2035 | -19.66 | -191 | -3,276 | -8,772 | -16,342 | +2,334 |
| 2045 | -24.92 | -260 | -4,316 | -11,804 | -21,757 | +3,375 |
| 2055 | -31.00 | -346 | -5,590 | -15,570 | -28,434 | +4,735 |
| 2065 | -37.98 | -456 | -7,136 | -20,183 | -36,545 | +6,467 |
| 2075 | -45.90 | -592 | -8,987 | -25,763 | -46,266 | +8,633 |
| 2085 | -54.80 | -760 | -11,178 | -32,431 | -57,750 | +11,305 |
| 2095 | -64.69 | -967 | -13,732 | -40,287 | -71,028 | +14,567 |

Source: See text.

radiatively important gases and not as agents which deplete the ozone layer. If these concerns were taken into account the marginal damage from CFCs would be very much higher. The marginal damage from these substances is also very sensitive to the assumption that 80% of the impact on radiative forcing is offset by a corresponding reduction in stratospheric ozone. The damage figure will rise and fall approximately pro rata with the assumed ozone offset.

Sulfate aerosols confer benefits in this model amounting to \$404 per ton of sulfur in the decade centered around 1995 rising to a surprising \$14,567 by the end of the next century when the stock of GHGs in the atmosphere is much higher than today. These values simply reflect the ability of sulfate aerosols to fend off global warming. They do not reflect the damage done by these emissions as precursors of acid rain. Were the acid rain damage component of these emissions to be included in the analysis then the marginal benefits of sulfur emissions would fall and might become negative. The shadow prices for sulfur have been included merely to emphasize the extent to which dealing with one problem (acid rain) may aggravate another (global warming).

In current value terms, all of these damage figures rise quickly through time. But if one wished to evaluate a project like afforestation which would remove carbon at points of time in the future it would be necessary to discount these values. The need to do this substantially reduces the attractiveness of long-term carbon removal schemes. However, in scenarios where a much greater cutback in emissions is called for (perhaps because damages are deemed to be high or the climate more sensitive to radiative forcing) then afforestation might yet have a role to play.

The relative damage potential of the various gases differs from what might be expected on a global warming potential basis. This occurs for a number of reasons, mainly because the GWPs are a measure of the summed radiative forcing of a unit of gas relative to that of $CO_2$ but radiative forcing is not proportional to economic damage. For example, although the GWP of methane is considerably higher than that of $CO_2$ the latter has a much longer lifetime. A ton of $CO_2$ emitted today will be around for longer than a ton of methane. And since concentrations of GHGs are rising over time the $CO_2$ will impact at a time when the damage done by emissions is greater. On the other hand, because this occurs further in the future we care less about it.

Turning now to the optimal control scenario, the optimal cutback in carbon emissions appears to be 6.9% in the decade centered around 1995 rising to 14.5% by the end of the next century (see Table 6). These controls on carbon emissions seem rather modest. They are, of course, dependent on, among other things, the strong assumption that noncarbon GHG emissions do not change as carbon emissions are cut. If, for instance, carbon reductions also reduced methane emissions from coal mines being closed then the "price" of abatement would fall and the optimal amount of abatement would rise. On the other hand, sulfur emissions would probably fall too if power producers started to switch away from coal. The optimal reduction in carbon emissions is sensitive to large-scale attempts to cut sulfur emissions. Cutting sulfur emissions ceteris paribus increases the optimal cutback in carbon emissions in this model. This seems to suggest that ambitions to reduce sulfur emissions need to be tempered somewhat while carbon emissions reductions require to be stepped up.

The emissions tax rates necessary to drive the economy along the optimal trajectory are described in Table 7. Naturally, these tax rates are lower than the figures for marginal damage in the no controls BAU scenario due to the decrease in emissions. In the decade centered around 1995, the optimal carbon tax is $5.87 which is 20 cents less than the marginal damage figure without abatement. Whereas the two sets of figures differ only a little in this scenario the difference for other scenarios might be much greater. The optimal taxes for methane over the same period are $45 and for Nitrogen $833. The optimal taxes on CFC-11 and CFC-12 are $2,115 and $4,194, respectively. The shadow values suggest that the scheme for removing methane outlined earlier is not and will not become cost-effective.

**Table 6.** Optimal reduction in fossil fuel emissions of carbon.

| Year | Percentage reduction |
|---|---|
| 1995 | 6.9 |
| 2005 | 7.7 |
| 2015 | 8.6 |
| 2025 | 9.5 |
| 2035 | 10.3 |
| 2045 | 11.1 |
| 2055 | 11.9 |
| 2065 | 12.6 |
| 2075 | 13.3 |
| 2085 | 13.9 |
| 2095 | 14.5 |

Source: See text.

**Table 7.** Current value optimal tax rates on GHG and aerosol emissions ($/ton).

| Year | Carbon | Methane | Nitrogen | CFC–11 | CFC–12 | Sulfur |
|---|---|---|---|---|---|---|
| 1995 | -5.87 | -45 | -833 | -2,003 | -3,945 | +397 |
| 2005 | -8.14 | -65 | -1,111 | -2,941 | -5,706 | +620 |
| 2015 | -11.06 | -92 | -1,658 | -4,227 | -8,070 | +967 |
| 2025 | -14.67 | -129 | -2,266 | -5,933 | -11,171 | +1,467 |
| 2035 | -19.02 | -178 | -3,034 | -8,135 | -15,136 | +2,188 |
| 2045 | -24.18 | -241 | -3,987 | -10,916 | -20,101 | +3,147 |
| 2055 | -30.19 | -320 | -5,154 | -14,365 | -26,212 | +4,397 |
| 2065 | -37.12 | -420 | -6,565 | -18,581 | -33,624 | +5,986 |
| 2075 | -45.03 | -545 | -8,254 | -23,673 | -42,492 | +7,969 |
| 2085 | -53.97 | -698 | -10,250 | -29,748 | -52,954 | +10,410 |
| 2095 | -63.93 | -886 | -12,572 | -36,895 | -65,081 | +13,384 |

Source: See text.

The plan for reducing $N_2O$ emissions becomes active in the second half of the next century.

With so little abatement being desirable, the temperature change associated with the optimal climate policy looks very similar to the BAU temperature change (see Table 4). In fact, the optimal control and BAU paths for temperature rise look identical for the next thirty years and only begin to diverge by the end of the next century. At that time, the temperature rise associated with the optimal policy is 2.04°C – only 0.16°C less than in the BAU scenario.

Comparing the flow of green income in the BAU and the optimal control scenario reveals that they are also almost identical. The optimal control

**Table 8.** The present value of future income under different protocols ($tr).

| Policy | P.V. of income | % Diff. to op. con. |
|---|---|---|
| Optimal control | 1,481 | – |
| Business as usual | 1,481 | −0.01 |
| Stabilize emissions (6 Gt C) | 1,474 | −0.5 |
| Stabilize concentration (400ppm) | 1,457 | −1.6 |
| Limit change to 0.1°C/decade | 1,472 | −0.6 |
| No greenhouse effect | 1,484 | +0.2 |

Source: See text.

GGNP exceeds the BAU GGNP by just 0.2% at the end of the next century. In terms of the impact on the present value of future income up to the year 2200, the percentage difference between the doing nothing and following the best policy available is approximately 0.01%. Even when applying the optimal control, very little can be done to retrieve the losses in GGNP caused by the existence the carbon constraint. The remedy, as they say, is almost as bad as the disease.

By introducing further constraints into the model, it is possible to examine the present value of future income associated with other protocols which have from time to time been proposed (Table 8). Naturally all of these are inferior to the optimal control. The first protocol – that of stabilizing global emissions at 6 Gt C annually – reduces the present value of future income by 0.5% relative to the optimal control solution. A policy of stabilizing the atmospheric concentration of $CO_2$ at 400ppm on the other hand is tremendously costly and involves a reduction of 1.6% in the present value of future income relative to the optimal control solution. Limiting the rate of temperature change to 0.1°C per decade is also unnecessarily costly and entails a loss in the present value of income amounting to 0.6%. Somewhat surprisingly, all three protocols are worse than doing nothing at all.

The present value cost of the greenhouse problem itself is estimated to be $3 trillion representing about 0.2% of the present value of future income. This is the amount that we should be prepared to pay for information leading to a cost-free solution to the global warming problem.

## 5. Conclusions

This paper has presented a new applied model of the optimal control of global warming. The model can demonstrate how differing assumptions regarding the costs of abatement and the damage potential from global warming translate into different policy recommendations. Taking input assumptions implicit in the IPCC's IS92a best guess scenario, the model is used to estimate the shadow price of the five main GHGs and the optimal cutback in emissions. These shadow prices represent the marginal rate at which gases may be traded while holding the present value of climate damage constant. The paper also makes clear the difference between the marginal damages concept and the optimal tax rates. The marginal damage figures relate to the damage done per ton of emissions when no abatement activity is undertaken. The optimal tax rates, on the other hand, refer to the taxes necessary to drive the economy along the optimal abatement path. The optimal tax on carbon is currently $5.87 with the input assumptions used here while the marginal damage figure is 20 cents higher.

The paper has also sought to demonstrate the extent to which dealing with the acid rain problem may aggravate the global warming problem. The conclusion here is not necessarily that we should think twice about large-scale desulfurization measures but that if large-scale desulfurization measures are seen as imperative, the cloak of protection sulfate aerosols provide disappears and a much greater degree of control would have to be exercised over carbon emissions.

The paper examines present value of future income under the optimal control and the business as usual scenarios. The message seems to be that it matters little whether carbon emissions are cut or not but that protocols to stabilize emissions or concentrations must be resisted. However, it is important to emphasize the tentative nature of these findings. They rely upon a particular set of views relating to the abatement cost function, the damage function, and the sensitivity of the climate to heightened radiative forcing. If the reduction in carbon emissions yields significant secondary benefits or if the costs of a carbon tax can be offset by reducing other distortionary taxes then a much greater degree of abatement may be desirable. Moreover, this analysis proceeds by replacing the uncertain parameters with their expected values. The question the model therefore address is what would be the optimal policy to follow if all the parameters were known with perfect certainty. But since it is absolutely not the case that all parameters are known with perfect certainty the results of these exercises are not policy relevant and may yield poor policy advice. Attempts to compute the optimal control under uncertainty indicate that, at least in the context of somewhat arbitrary assumptions regarding the form the uncertainty, the use of expected values can alter the policy prescriptions obtained from these models significantly. But because of the arbitrary nature of assumptions regarding the probability distributions used in such analyses, it would be wrong to take the findings of uncertainty analyses as being anything more than purely illustrative.

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# Modeling the Global Society–Biosphere–Climate System: Computed Scenarios*

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## Abstract

This paper presents scenarios computed with IMAGE 2.0, an integrated model of the global environment and climate change. Results are presented for selected aspects of the society-biosphere-climate system including primary energy consumption, emissions of various greenhouse gases, atmospheric concentrations of gases, temperature, precipitation, land cover and other indicators. Included are a "Conventional Wisdom" scenario, and three

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variations of this scenario: (i) the Conventional Wisdom scenario is a reference case which is partly based on the input assumptions of the IPCC's IS92a scenario; (ii) the "Biofuel Crops" scenario assumes that most biofuels will be derived from new cropland; (iii) the "No Biofuels" scenario examines the sensitivity of the system to the use of biofuels; and (iv) the "Ocean Realignment" scenario investigates the effect of a large-scale change in ocean circulation on the biosphere and climate. Results of the biofuel scenarios illustrate the importance of examining the impact of biofuels on the full range of greenhouse gases, rather than only $CO_2$. These scenarios also indicate possible side effects of the land requirements for energy crops. The Ocean Realignment scenario shows that an unexpected, low probability event can both enhance the build-up of greenhouse gases, and at the same time cause a temporary cooling of surface air temperatures in the Northern Hemisphere. However, warming of the atmosphere is only delayed, not avoided.

# 1. Introduction

Although climate-related research usually centers on one aspect or spatial scale of the climate change issue, in reality climate issues involve interrelated elements of the society, biosphere, and the climate system. This wide range of issues are reflected, for example, in the reports of IPCC's first assessment (IPCC, 1990a,b,c). The purpose of this paper is to present scenarios which capture some of the scope and detail of these interrelated issues. These scenarios are computed by the IMAGE 2.0 model, an integrated model of the global environment and climate change.

IMAGE 2.0 consists of three sub-systems of models – "Energy-Industry", "Terrestrial Environment", and "Atmosphere-Ocean". The model gives roughly equal weight to each of these sub-systems. The Energy-Industry models compute the emissions of greenhouse gases in 13 world regions as a function of energy consumption and industrial production. End use energy consumption is computed from various economic/demographic driving forces. The Terrestrial Environment models simulate grid-scale changes in global land cover based on climatic and socioeconomic factors, and the flux of $CO_2$ and other greenhouse gases between the biosphere and atmosphere. The Atmosphere-Ocean models compute the buildup of greenhouse gases in the atmosphere and the resulting zonal-average temperature and precipitation patterns.

The time horizon of model calculations extends from 1970 to 2100, and many terrestrial calculations are performed on a grid of 0.5° latitude by 0.5° longitude; economic-based calculations (relating to energy, industrial production, and agricultural demand) are performed for 13 world regions rather than on a global grid. Climate calculations are performed on a two-dimensional grid of 100 latitudinal bands and nine or more vertical layers in both the atmosphere and ocean.

The fully linked model has been tested against data from 1970 to 1990, and after calibration, can reproduce the following observed trends: regional energy consumption and energy-related emissions, terrestrial flux of carbon dioxide and emissions of other greenhouse gases, concentrations of greenhouse gases in the atmosphere, and transformation of land cover. The model can also simulate the observed latitudinal variation of annual average atmospheric temperatures (averaged over a climatologic period).

An overview of the content and testing of IMAGE 2.0 is given in a companion paper (Alcamo *et al.*, 1994). The Energy-Industry system is described in de Vries *et al.* (1994); the Terrestrial Environment sub-system in Klein Goldewijk *et al.* (1994), Kreileman and Bouwman (1994), Leemans and van den Born (1994), and Zuidema *et al.* (1994); and the Atmosphere-Ocean sub-system in Krol and van der Woerd (1994) and de Haan *et al.* (1994).

The following scenarios are described in this paper:

*(i) Conventional Wisdom Scenario* – This scenario makes conventional assumptions about future demographic, economic, and technological driving forces. This is a reference scenario in that it makes no assumptions about climate-related policies. Input data for the main driving forces are based partly on the assumptions of the IS92a scenario of the Intergovernmental Panel on Climate Change (IPCC, 1992).

*(ii) Biofuel Crops Scenario* – The Conventional Wisdom and Biofuel Crops scenarios have identical amounts of biofuel usage in the global energy system, and only differ in their assumptions about how/where modern biofuels are grown. In the Conventional Wisdom scenario, biofuels are assumed to come from sources that do not require new cropland, whereas the Biofuel Crops scenario assumes that a substantial amount of biofuels come from new cropland. [In this paper, the terms biofuels and biomass are used interchangeably and both refer to modern biofuels from crop residues, energy crops, plantations and similar sources rather than traditional biofuels such as fuelwood. The IMAGE 2.0 energy model (de Vries *et al.*, 1994) has separate categories for modern biomass, fuelwood and renewables (excluding modern biomass and fuelwood) such as hydroelectric, solar and wind power.]

**Table 1.** Overview of scenarios.

| Name of scenario | Global population | Global economic growth | Bio-fuels included? | Biofuels require new crop-land? | Changed ocean circulation |
|---|---|---|---|---|---|
| Conventional Wisdom | 11.5 B by 2100 | 1990–2025: 2.9 % $a^{-1}$<br>2025–2100: 2.3 % $a^{-1}$ | YES | NO | NO |
| Biofuel Crops | As Conventional Wisdom | As Conventional Wisdom | YES | YES | NO |
| No Biofuels | As Conventional Wisdom | As Conventional Wisdom | NO | n.a. | NO |
| Ocean Realignment | As Conventional Wisdom | As Conventional Wisdom | YES | NO | YES |

Note: Only global totals given in this table; see Tables 3–6 for selected regional values.

*(iii) No Biofuels Scenario* – In this other variation of the Conventional Wisdom scenario, the sensitivity of the global climate system to modern biofuel use is investigated. For this scenario biofuels are removed from the Conventional Wisdom scenario and are replaced by oil.

*(iv) Ocean Realignment* – This "surprise" scenario investigates the consequences on the global society-biosphere-climate system of a major change of the ocean's circulation pattern.

Table 1 compares the key assumptions of the four scenarios, and Table 2 summarizes the input data needed to produce these scenarios. The world regions included in IMAGE 2.0 are listed in Table 3. The input data of the scenarios are reviewed in Section 2 of this paper, and scenario results are reported in Section 3. We note that scenarios ii, iii, and iv can also be viewed as sensitivity studies (although not sensitivity analysis in the conventional use of the term) of the Conventional Wisdom scenario.

# 2. Conventional Wisdom Scenario

## 2.1. Assumptions of "Conventional Wisdom" scenario

The "Conventional Wisdom" scenario is based on conventional assumptions about socioeconomic trends. Estimates of future population and economic growth are taken from the IS92a scenario of the Intergovernmental Panel on Climate Change (IPCC, 1992). The IS92a scenario is an intermediate case out of six "reference" scenarios developed by the IPCC. Although the IS92a scenario is an intermediate scenario, the IPCC did not propose it to be the

**Table 2.** Main scenario-dependent variables in IMAGE 2.0.

| Category of inputs | Variables |
|---|---|
| Socio-economic | Population (total and urban) |
| | GNP |
| Energy-related | Value added of industrial output |
| | Value added of commercial services |
| | Private consumption |
| | Number of passenger vehicles |
| | Fuel mix |
| | Fuel prices |
| | Efficiency of primary energy conversion |
| | Autonomous efficiency improvements |
| | Emission factors |
| Agriculture-related | Food trade, export/import |
| | N fertilizer use |
| | Technology-related crop yield increase |
| | Animal production coefficient |
| | Ratio of concentrate:roughage for livestock |
| | Fraction of animal feed provided by a particular crop |
| Related to atmosphere-ocean | Ocean circulation pattern |

most likely scenario. We have made the decision to interpret its assumptions (for example, population and GNP) as the "conventional wisdom". At the same time we do not pass judgement on the feasibility or desirability of the scenario's assumptions.

*Population Assumptions*

The regional population assumptions of Scenario IS92a (Table 3) are based on World Bank estimates, which are close to UN's medium projection (IPCC, 1992). According to this scenario world population will more than double by the year 2100, reaching 11.5 billion people.

The scenario of urban vs. rural population in each region (Table 4) is based on extrapolating the urbanization trend between 1970 and 1990 in each region up to a maximum of 85% urbanization. The future linear increase is consistent with UN estimates for Africa and Asia up to year 2025 (WRI, 1990); the assumed maximum 85% urbanization is the UN estimate for Latin America in 2025 and corresponds to the current percentage of urbanization

**Table 3.** Regional population assumptions for Conventional Wisdom Scenario, in millions.

| Region | 1990 | 2000 | 2025 | 2050 | 2100 |
|---|---|---|---|---|---|
| Canada | 27 | 28 | 29 | 28 | 27 |
| USA | 250 | 270 | 302 | 298 | 295 |
| Latin America | 448 | 534 | 715 | 824 | 877 |
| Africa | 642 | 844 | 1540 | 2208 | 2875 |
| OECD Europe | 378 | 393 | 407 | 395 | 388 |
| Eastern Europe | 123 | 131 | 143 | 149 | 148 |
| CIS | 289 | 306 | 335 | 350 | 347 |
| Middle East | 203 | 272 | 508 | 730 | 937 |
| India + S. Asia | 1171 | 1412 | 1970 | 2375 | 2644 |
| China + C.P. Asia | 1248 | 1431 | 1756 | 1896 | 1963 |
| East Asia | 371 | 447 | 624 | 752 | 837 |
| Oceania | 23 | 24 | 25 | 24 | 24 |
| Japan | 124 | 131 | 136 | 132 | 130 |
| World | 5297 | 6223 | 8490 | 10161 | 11492 |

Source: IPCC (1992), Scenario "IS92a".

**Table 4.** Regional urban population assumptions for Conventional Wisdom Scenario, in percent of total population.

| Region | 1990 | 2025 | 2100 |
|---|---|---|---|
| Canada | 77 | 80 | 85 |
| USA | 75 | 78 | 84 |
| Latin America | 71 | 85 | 85 |
| Africa | 34 | 54 | 85 |
| OECD Europe | 78 | 85 | 85 |
| Eastern Europe | 71 | 85 | 85 |
| CIS | 66 | 80 | 85 |
| Middle East | 57 | 85 | 85 |
| India + S. Asia | 26 | 39 | 66 |
| China + C.P. Asia | 33 | 63 | 85 |
| East Asia | 36 | 61 | 85 |
| Oceania | 80 | 81 | 83 |
| Japan | 77 | 85 | 85 |

Source: 1990 data – WRI (1990).

in some northern European countries, where a maximum may have been reached.

**Table 5.** Regional economic growth assumptions for Conventional Wisdom Scenario, in GNP annual percentage growth.

| Region | 1990–2025 | 2025–2100 |
|---|---|---|
| Canada | 2.06 | 1.31 |
| USA | 2.09 | 1.25 |
| Latin America | 1.85 | 2.20 |
| Africa | 1.57 | 2.39 |
| OECD Europe | 2.06 | 1.31 |
| Eastern Europe | 1.87 | 1.18 |
| CIS | 1.87 | 1.18 |
| Middle East | 1.36 | 1.98 |
| India + S. Asia | 2.97 | 2.84 |
| China + C.P. Asia | 4.23 | 3.07 |
| East Asia | 2.97 | 2.84 |
| Oceania | 2.71 | 1.28 |
| Japan | 2.71 | 1.28 |

Source: IPCC (1992), Scenario "IS92a".

*Economic Growth Assumptions*

Economic growth assumptions (Table 5) follow those of Scenario IS92a of the IPCC (1992) and take into account recent changes in Eastern Europe and the Commonwealth of Independent States (CIS), as well as consequences of the Persian Gulf war. The IPCC (1992) reports that the GNP growth assumptions of this scenario are at the low end or below the recent range of World Bank forecasts. Nevertheless, the IS92a scenario implies a rapid increase in income per capita in the developing world, although a large income gap remains in the year 2100 between developed and developing regions.

*Energy-related Assumptions*

The energy-related variables for an IMAGE 2.0 scenario are listed in Table 2. We briefly describe them in this section, while more details are given in de Vries, *et al.* (1994).

To compute future end use consumption of energy, assumptions are required about future levels of "activity" in each end use sector. The measures of activity are: value-added of industrial output (industry sector), value-added of services (commercial sector), private consumption (residential sector), number of passenger vehicles (transport sector), and GNP ("other" sector). These data are summarized in Table 6.

**Table 6.** Assumed activity levels for energy end-use sectors.

| | Value added industrial output($ cap$^{-1}$ a$^{-1}$) | | | | | Value added commercial services($ cap$^{-1}$ a$^{-1}$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Region | 1970 | 1990 | 2025 | 2050 | 2100 | 1970 | 1990 | 2025 | 2050 | 2100 |
| Canada | 3141 | 4282 | 8746 | 12114 | 23240 | 3686 | 7114 | 14529 | 20124 | 38607 |
| USA | 3635 | 4629 | 9555 | 13020 | 24172 | 6338 | 9210 | 19011 | 25903 | 48091 |
| Latin America | 535 | 619 | 1222 | 2099 | 6199 | 723 | 915 | 1796 | 3190 | 10070 |
| Africa | 335 | 268 | 491 | 848 | 2531 | 241 | 295 | 520 | 1036 | 4112 |
| OECD Europe | 3025 | 4189 | 8556 | 11851 | 22736 | 4251 | 6791 | 13869 | 19210 | 36854 |
| Eastern Europe | 646 | 1122 | 2058 | 2637 | 4330 | 861 | 1138 | 2509 | 3537 | 7033 |
| CIS | 1850 | 2560 | 4210 | 5640 | 10123 | 617 | 1341 | 6094 | 8164 | 14653 |
| Middle East | 1524 | 1299 | 2357 | 3523 | 7873 | 641 | 1094 | 2221 | 3981 | 12789 |
| India + S. Asia | 45 | 82 | 353 | 688 | 2619 | 65 | 111 | 388 | 862 | 4254 |
| China + C.P. Asia | 93 | 375 | 1249 | 2413 | 9008 | 38 | 131 | 1062 | 2547 | 14633 |
| East Asia | 159 | 490 | 1519 | 2819 | 9713 | 207 | 513 | 1451 | 3214 | 15779 |
| Oceania | 2768 | 3470 | 8853 | 12164 | 22965 | 4571 | 6370 | 16251 | 22329 | 42155 |
| Japan | 3032 | 6330 | 16147 | 22186 | 41887 | 3895 | 7409 | 18900 | 25969 | 49029 |

| | Private consumption ($ cap$^{-1}$ a$^{-1}$) | | | | | Number of passenger vehicles (vehicles per 1000 cap) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Region | 1970 | 1990 | 2025 | 2050 | 2100 | 1970 | 1990 | 2025 | 2050 | 2100 |
| Canada | 5024 | 6969 | 14234 | 19715 | 37824 | 327 | 472 | 600 | 605 | 615 |
| USA | 6528 | 9341 | 19281 | 26272 | 48774 | 450 | 566 | 600 | 604 | 611 |
| Latin America | 1022 | 1211 | 2244 | 3718 | 10202 | 30 | 73 | 132 | 135 | 140 |
| Africa | 455 | 456 | 770 | 1367 | 4305 | 12 | 15 | 43 | 55 | 61 |
| OECD Europe | 4440 | 6882 | 14056 | 19469 | 37350 | 197 | 375 | 420 | 420 | 420 |
| Eastern Europe | 1077 | 1305 | 2732 | 3761 | 7126 | 34 | 145 | 215 | 222 | 237 |
| CIS | 2503 | 4388 | 6928 | 9282 | 16661 | 18 | 59 | 215 | 222 | 237 |
| Middle East | 1038 | 1396 | 2362 | 4165 | 12958 | 12 | 41 | 75 | 75 | 75 |
| India + S. Asia | 175 | 241 | 672 | 1249 | 4310 | 1 | 3 | 16 | 36 | 59 |
| China + C.P. Asia | 137 | 323 | 1496 | 3213 | 14826 | 0 | 3 | 15 | 35 | 58 |
| East Asia | 321 | 658 | 1944 | 3924 | 15987 | 5 | 16 | 43 | 56 | 61 |
| Oceania | 4645 | 6083 | 15516 | 21320 | 40251 | 307 | 413 | 485 | 485 | 485 |
| Japan | 4259 | 7860 | 20050 | 27549 | 52011 | 102 | 254 | 315 | 315 | 315 |

Source: IPCC (1992), Scenario "IS92a".

*Industrial Output and Services.* For OECD regions, it is assumed that the value-added of industrial output and services remains at their current fraction of GNP. Therefore, as GNP in a region increases according to the Conventional Wisdom scenario, the value-added of industrial output and commercial services in this region proportionately increases. As for non-OECD regions, they are assumed to follow the historical pattern of structural change of OECD economies, i.e., as GNP rises, industrial output initially increases, then peaks and declines; meanwhile the decline of industrial output is paralleled by an increase in commercial services (Maddison, 1991). In this scenario, non-OECD regions are assumed to follow this pattern. The fraction of GNP devoted to industrial output increases, peaks, and then declines while the fraction of GNP devoted to commercial services increases when the industrial output fraction decreases.

*Private Consumption.* Private consumption in OECD regions remains fixed at its current fraction of GNP. This means that private consumption increases proportionately to GNP. By comparison, in developing regions this fraction is not fixed, but is assumed to increase to the current average fraction in OECD countries, as GNP in the developing region approaches the current average GNP of OECD countries.

*Passenger Vehicles.* Studies of historical trends in transportation have shown that the number of vehicles in a society are proportionately related to wealth, but are also constrained by the availability of roads, the density of populations, and other country-specific factors (Grübler and Nakićenović, 1991). As a result it is probably not wise to assume that there is a universal relationship between income and vehicles per person, nor that there is a typical time period by which each region will reach the saturation number of vehicles. For our estimates we use technological diffusion data from different countries which indirectly take into account constraints to number of vehicles (Grübler and Nakićenović, 1991). We use these data to estimate the saturation value of vehicles per capita for each region; we further assume that saturation will be reached in year 2100. For the year 2025, we use vehicle estimates from the U.S. EPA (1990) for different regions, and interpolate for years in-between. An exception is made for the four world regions currently having very low levels of vehicle usage (Africa, India plus South Asia, China plus Centrally Planned Asia, and East Asia). For these regions we assume that the current global average (61 vehicles/1000 cap) will be reached in year 2100. For intermediate years, we assume that the increase in vehicles in these four regions will follow a typical "S curve" trajectory, as proposed by Grübler and Nakićenović (1991).

*Fuel Mix and Prices.* The trend of greenhouse gas emissions from each region's energy economy is closely related to the amount and mix of fuels consumed. The IMAGE 2.0 model endogenously computes the amount of energy consumed in each of five end-use sectors (industry, commercial, residential, transport, and "other") of each region, based on the activity levels just described. However, the fuel mix in each sector is prescribed (although version 2.1 of IMAGE will endogenously compute the fuel mix in each region.) For the Conventional Wisdom scenario, the fuel mix for each sector (i.e. the fraction of total end use energy consumption delivered by each energy carrier) has been estimated from results of the model used to generate the IS92a scenario (IPCC, 1992; Pepper *et al.*, 1992).

The computation of end use energy consumption in IMAGE 2.0 also depends on a scenario of future fuel prices which are used to determine the level of energy conservation. Future trends in prices of coal, gas and oil are the same for each region and are taken from the Edmonds-Reilly model (Edmonds and Reilly, 1985). For coal, the price index (scaled to 1975) is 1.55 in 2050 and 2.37 in 2100. For gas, the index is 4.10 in 2050 and 7.71 in 2100, and for oil 2.46 in 2050 and 2.38 in 2100. Prices of fuelwood are held constant. Prices of biomass are held constant until 2025 and are then assumed to be 10% higher than current prices in 2050, and 20% higher in 2100.

*Energy Conversion Efficiency.* Emissions of greenhouse gases also depend on the energy used to convert primary to secondary energy, which in turn depends on the assumed efficiency of electricity and heat generation. For the Conventional Wisdom scenario, it was assumed that efficiency of converting coal, gas, and oil to electricity increases linearly with time from its 1990 value (which varies from region to region) to the value of 0.50 in 2100 in OECD regions, Eastern Europe, CIS and Middle East; and to 0.45 in 2100 in other regions. Other assumed conversion efficiencies are presented in de Vries *et al.* (1994).

*Autonomous Efficiency Improvements.* Another important variable affecting end use consumption of electricity and heat are so-called "autonomous" factors that lead to improvements in end use energy efficiency. By definition, these are improvements that are *not directly related to increases in fuel prices.* For electricity, autonomous improvements of the energy intensity are assumed to arise from technological development rather than from higher fuel prices. For energy in the form of heat, we assume that technologies for delivering heat become cheaper, making price-driven energy conservation more attractive. The assumed rate of improvement is region-specific, ranging from 0 to 2% $a^{-1}$ for heat and 0 to 5.5% $a^{-1}$ for electricity (de Vries *et al.* , 1994). The higher rates of improvement are assigned to developing regions under the assumption that they can realize large gains in their currently inefficient energy systems.

*Emission Factors.* In order to compute future emissions of greenhouse gases, it is also necessary to assign future emission factors to these gases. For the Conventional Wisdom scenario, it is assumed that emission controls lead to decreases of emission factors of $NO_x$ in all sectors, $CH_4$ in fuel production, and CO and VOC in transport. Emission factors for $N_2O$ in transport are assumed to increase as a side effect of catalyst-type emission controls on vehicles. All other emission factors are held constant. More information about these assumptions is available in de Vries *et al.* (1994).

*Agriculture-related Assumptions*

The types of agriculture-related assumptions required for the Conventional Wisdom scenario are presented in Table 2. Details are given in Zuidema *et al.* (1994).

*Food Trade.* Future agricultural demand will strongly affect land cover patterns and these will affect the flux of $CO_2$ and other greenhouse gases from the terrestrial environment. Agricultural demand, of course, depends on the global trade of agricultural commodities. However, since IMAGE 2.0 does not compute world food trade (this is planned for version 2.1), a very simple approach is taken. We assume current exports of food products from the developed world increase by 50% from 1990 to 2050 and level off afterwards. Net exports from developing regions double their 1990 level by 2100. Export of animal products stay constant at their 1990 level, while sugar export is assumed to be zero. The allocation of crop exports to importing regions is weighted according to the crop consumption of importing regions.

*Crop Yield.* Future land cover patterns will greatly depend on the need for agricultural land, and this in turn will depend on the potential yields of crops. There are two aspects to these yields – The first is the potential yield resulting from local climate and unmanaged soil conditions; this is computed by the Terrestrial Vegetation submodel of IMAGE 2.0 (see Leemans and van den Born, 1994) and is not a scenario variable. The second is the influence of fertilizer and other technological inputs (tractors, management know-how) on yield. These variables must be prescribed for each scenario. The yield increase due to nitrogen fertilizer is based on a representative yield response curve for cereals from Addiscot *et al.* (1991). Future nitrogen fertilizer use is also a scenario variable and is derived from the IS92a scenario of the IPCC. The effect of other technological inputs (tractors, management know-how) on yield after 1990 is based on trends in each region between 1970 and 1990 (see Zuidema *et al.*, 1994).

*Animal Productivity and Other Variables.* The future trend of animal productivity (ratio of non-productive animals versus productive animals, production of meat and dairy products per cow) can influence future land requirements in developing regions because improved productivity can lead to smaller grassland requirements per unit animal product. This scenario assumes that animal efficiencies in developing regions will linearly approach the current (1990) efficiencies in OECD Europe as incomes of these regions approach the current income of OECD Europe. Two other scenario variables also affect future land requirements for animals: the assumed composition of feed (roughage or concentrate) influences the amount of range land required, while the type of crop used to provide feed determines how feed will compete with human requirements for crops. Both of these variables were fixed at their 1990 values. Quantitative information about these assumptions is available in Zuidema *et al.* (1994).

## 2.2. Results of the Conventional Wisdom scenario

Because of the large volume of output generated by the IMAGE 2.0 model for each scenario, we present detailed results for only two of thirteen world regions – OECD Europe from the developed regions, and Africa from the developing regions. Selected results from other regions are presented when they are of particular interest for the scenario. In addition, global calculations are given. Results for the four scenarios are summarized in Table 7.

*Results from Energy-Industry*

For the Conventional Wisdom scenario, the trend of primary energy consumption in OECD Europe is quite different from Africa (Figures 1 and 2). After 2000, energy demand in OECD Europe slowly increases due to slowly increasing population. Also, at the level of economic activity in this scenario (Table 6), the increase in end use energy consumption for each unit increase in economic activity is small compared to Africa and other developing regions because consumption is near saturation. The slowly increasing trend in primary energy consumption is actually outweighed by improvements in energy efficiency spurred by higher fuel prices and technological developments. The result is a stabilization of primary energy consumption in the first half of the century (Figure 1). In the second half of the century, energy consumption slightly increases because growth in economic activity outpaces the rate of

**Table 7.** Summary of scenario results. These are global average or total results unless otherwise specified.

| Year/ scenario | $CO_2$-emissions from energy /industry | Carbon cycle ($Pg\ C\ a^{-1}$) Net bio-sphere flux[a] | Ocean flux[a] | Methane emissions ($Tg\ CH_4\ a^{-1}$) | Atmospheric concentrations $CO_2$ (ppm) | $CH_4$ (ppm) | Trop. $O_3$ | Change of agricult. area ($10^3\ km^2$) | Change of forest area ($10^3\ km^2$) | Average surface temperature (°C) Northern hemisph. | Southern hemisph. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *1990* | 6.1 | −1.2 | −1.6 | 492 | 358 | 1.7 | - | 26.7 | 47.2 | 14.2 | 13.0 |
| *2050* | | | | | | | [b] | [b] | [b] | [c] | [c] |
| Conv. Wisdom | 15.2 | −7.2 | −3.0 | 688 | 522 | 2.5 | +11.6% | +9% | −26% | +1.4 | +1.0 |
| Biofuel Crops | 15.2 | −6.0 | −3.1 | 692 | 534 | 2.6 | +12.6% | +30% | −32% | +1.5 | +1.0 |
| No Biofuels | 17.0 | −7.5 | −3.2 | 677 | 539 | 2.4 | +9.0% | +9% | −26% | +1.4 | +1.0 |
| Ocean Realign. | 15.2 | −4.5 | −3.1 | 686 | 563 | 2.6 | +12.7% | +12% | −27% | +0.0 | +1.1 |
| *2100* | | | | | | | | | | | |
| Conv. Wisdom | 24.0 | −8.2 | −4.2 | 778 | 777 | 2.3 | +10.0% | +14% | −27% | +2.4 | +1.8 |
| Biofuel Crops | 24.0 | −6.7 | −4.5 | 793 | 821 | 2.4 | +12.0% | +65% | −31% | +2.7 | +2.0 |
| No Biofuels | 29.2 | −8.9 | −4.8 | 746 | 857 | 1.7 | ±0.2% | +15% | −27% | +2.4 | +1.9 |
| Ocean Realign. | 24.0 | −6.7 | −4.1 | 778 | 863 | 2.4 | +11.7% | +18% | −28% | +1.2 | +2.0 |

[a]Minus sign indicates net *sink*.

[b]Percentages are relative to 1990.

[c]2050 and 2100 are absolute changes in °C relative to 1990.

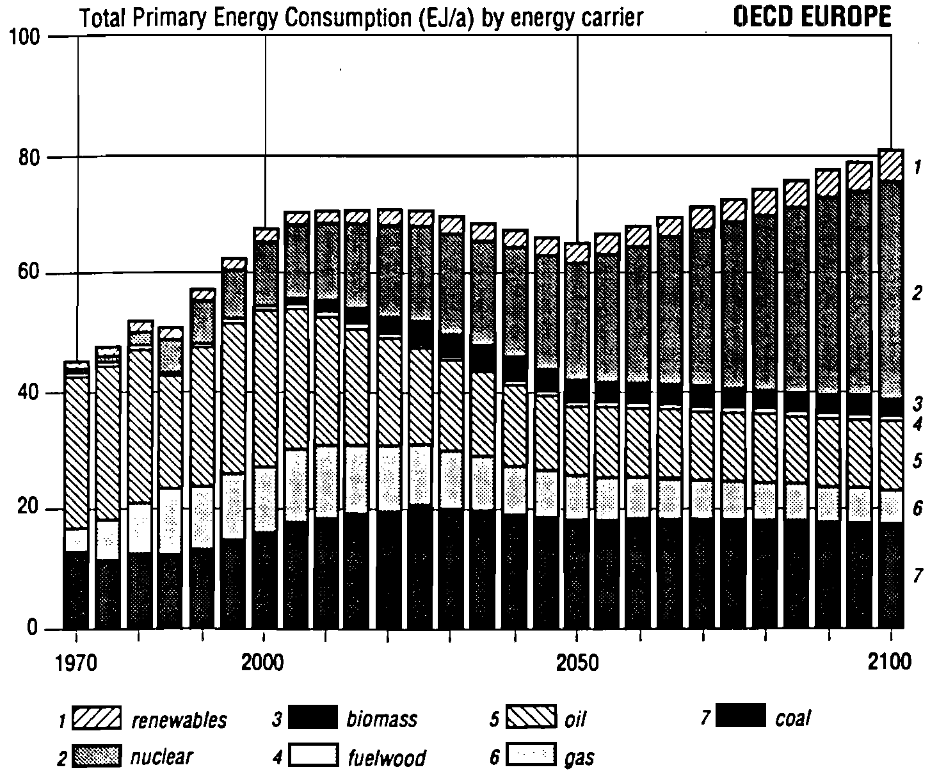



**Figure 1.** Total primary energy consumption by energy carrier in OECD Europe (EJ $a^{-1}$).

energy conservation stimulated by energy price increases. We remind the reader that this is meant to be a climate-policy-free scenario, and therefore does not consider that future taxes or other economic policy instruments could boost energy prices still higher and stimulate further conservation.

By contrast to OECD Europe, large increases in population and income in Africa lead to tremendous increases in consumption of all fuels in the second half of next century (Figure 2). Moreover, the increase in end use energy consumption for each unit increase in economic activity remains relatively high in the next century because Africa has a high energy intensity relative to its level of economic activity at the start of the simulation (1970).

Since we will be analyzing different biofuel-related scenarios later, we note here that modern biofuels (excluding fuelwood, dung, and other "traditional biofuels") account for 14.4 EJ $a^{-1}$ of Africa's primary energy consumption in 2050 and 57.7 EJ $a^{-1}$ in 2100. For OECD Europe, these figures

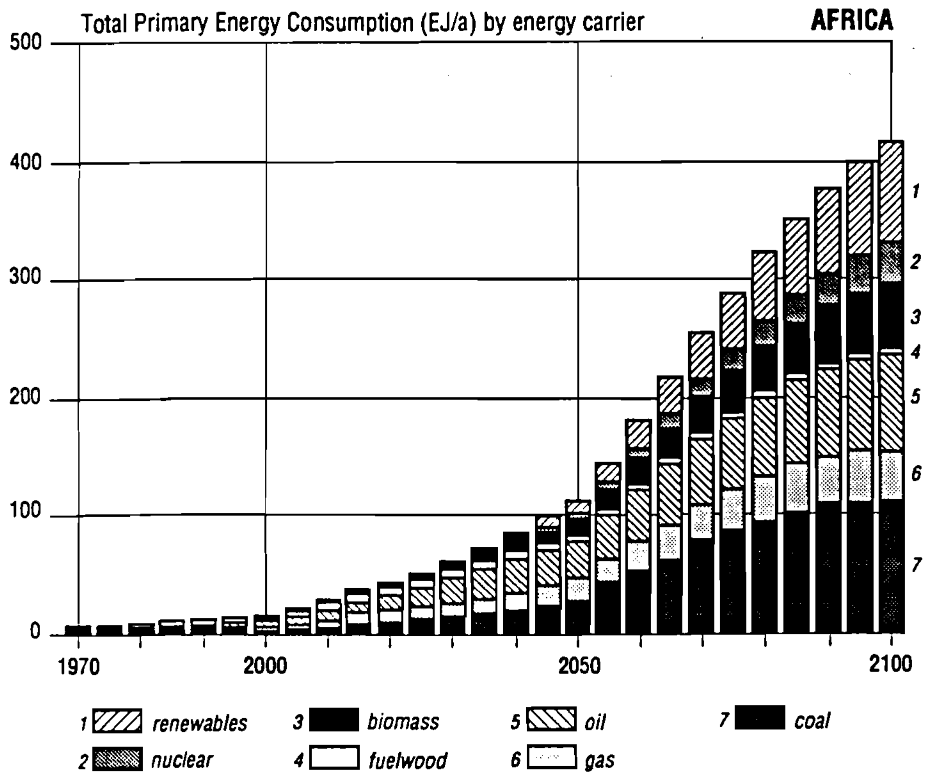



**Figure 2.** Total primary energy consumption by energy carrier in Africa (EJ $a^{-1}$).

are 4.1 EJ $a^{-1}$ in 2050 and 3.3 EJ $a^{-1}$ in 2100, and for the world, 74.1 EJ $a^{-1}$ in 2050 and 208.0 EJ $a^{-1}$ in 2100. By comparison, the "Renewables-Intensive Global Energy Scenario" of Johansson *et al.* (1993b) includes 206 EJ $a^{-1}$ of world biomass consumption in year 2050.

The trend in European emissions is also quite different from Africa's trend (Figures 3 and 4). Emissions of $CO_2$ from the energy system in OECD Europe decline due to the combined effect of slowly increasing energy consumption and a shift to low or non-$CO_2$ fuels (Figure 3). Currently, the main source of $CO_2$ in OECD Europe is power generation, followed by the sectors of industry and transport (Figure 3). According to this scenario, future power generation will account for an even greater share of total emissions from energy in OECD Europe.

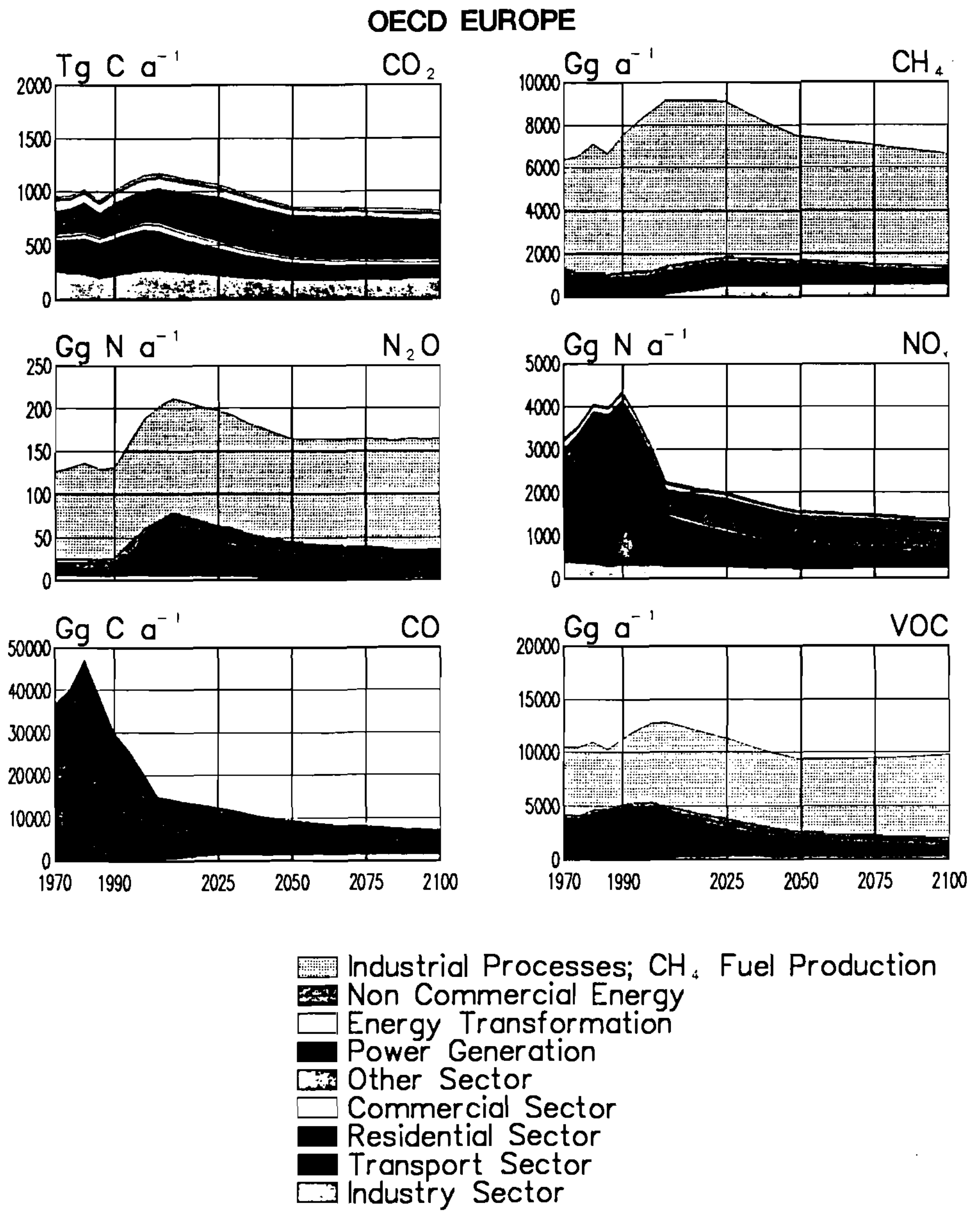



**Figure 3.** Annual emissions from energy consumption and industrial processes in OECD Europe.

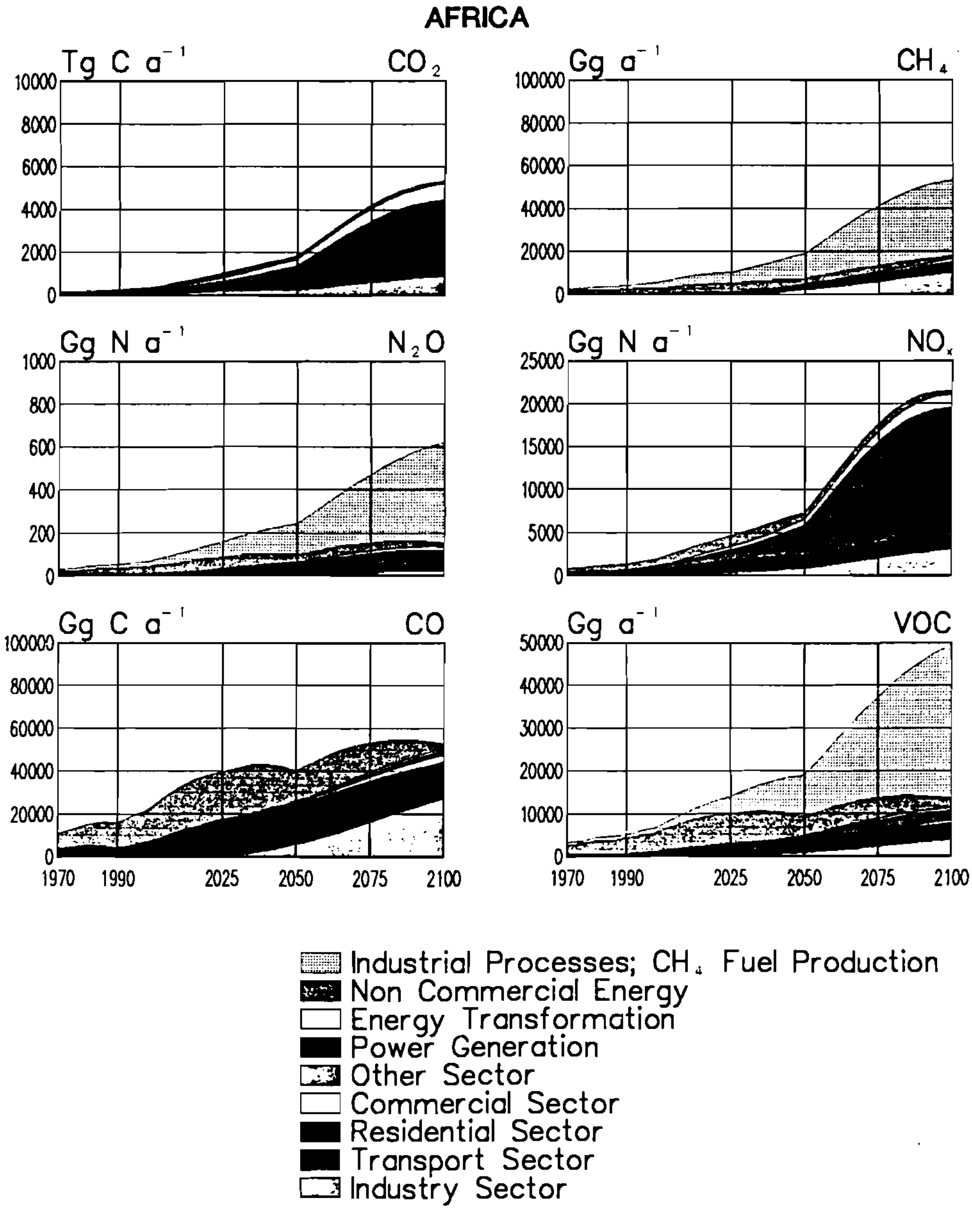



**Figure 4.** Annual emissions from energy consumption and industrial processes in Africa.

After an initial increase, emissions of $O_3$ precursors (CO, $NO_x$, and VOC) and $N_2O$ decrease because the consumption of end use energy decreases in the transport sector, one of the main sources of these emissions. The emissions of $O_3$ precursors also decrease because of assumed air pollution controls in various energy sectors. Emissions of $CH_4$ are reduced because of a shift from fossil fuels to nuclear power in OECD Europe (according to this scenario) and increased efficiencies.

Emissions of $CO_2$ and other gases from Africa spiral upwards following increased energy consumption and industrial activity (Figure 4). By 2030, Africa's $CO_2$ emissions surpass OECD Europe's emissions. For this scenario, the main source of energy-related $CO_2$ emissions in Africa is power generation (as in OECD Europe), but the second most important source is the residential sector. Future emissions of $CH_4$ mainly stem from losses in the gas distribution system, while large increases in $N_2O$ arise from increasing industrial activity. Most of the increase in $NO_x$ emissions comes from power generation, while increases in VOC emissions can be attributed to increased industrial production for which no emission controls are assumed. The increase in CO emissions in the second half of the next century stems from energy consumed by industry.

The trend of $CO_2$ emissions from other developed regions (USA, Canada, Eastern Europe, CIS, Oceania, and Japan) resembles OECD Europe's trend (although trends in the CIS are somewhat anomalous in showing a strong increase up to 2025) while regions in the developing world are closer to Africa's trends. The pattern of global $CO_2$ emissions shows that increasing emissions from developing regions prevail over the stabilization of emissions in OECD regions (Figure 5). As a result, global $CO_2$ emissions increase from 6.1 Pg C $a^{-1}$ in 1990 to 24.0 Pg C $a^{-1}$ in 2100. Emissions of other energy-related greenhouse gases show similar increases over the simulation period.

Estimates of emissions of $CO_2$ from the energy/industry system for this scenario fall within the range of the minimum (IS92c) and maximum (IS92e) scenarios of the IPCC (1992). This is not too surprising since some of the inputs of the intermediate scenario, IS92a, are also used as inputs to the Conventional Wisdom scenario. Emissions of the Conventional Wisdom scenario fall in the upper range of the IPCC scenarios because we compute a somewhat higher total primary energy consumption (1815 EJ $a^{-1}$ in 2100) than the IS92a scenario (1453 EJ $a^{-1}$ in 2100), and because different emission factors are assumed.

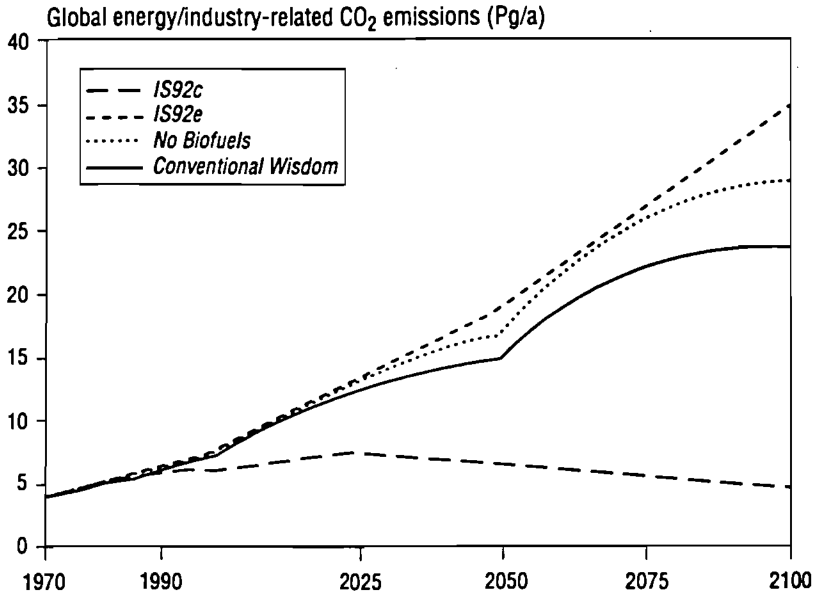



**Figure 5.** Global energy/industry-related $CO_2$ emissions for IMAGE 2.0 scenarios and IS92 scenarios (Pg $a^{-1}$).

*Results from Agriculture and Land Cover*

Greenhouse gas emissions from land use/land cover are related to the type and extent of land cover and the intensity of different types of land use. In the IMAGE 2.0 model, shifts in land cover are computed from changes in demand for agricultural commodities and fuelwood which in turn stem from population and economic growth. The model also takes into account technological improvements in crop yield and animal productivity, as well as changes in the potential vegetation and crop productivity related to climate and current soil conditions, and the current location of different types of land cover (Zuidema *et al.*, 1994). Estimation of agricultural demand begins with computation of per capita intake of different commodities according to 8 categories of crops and 5 types of animal products. Most of the non-meat calories consumed by inhabitants of OECD Europe consist of temperate cereals, but per capita consumption of this commodity declines over the simulation period (Figure 6a). Overall consumption of both vegetable and meat products level off by 2025 because per capita consumption of most commodities is at or near saturation.

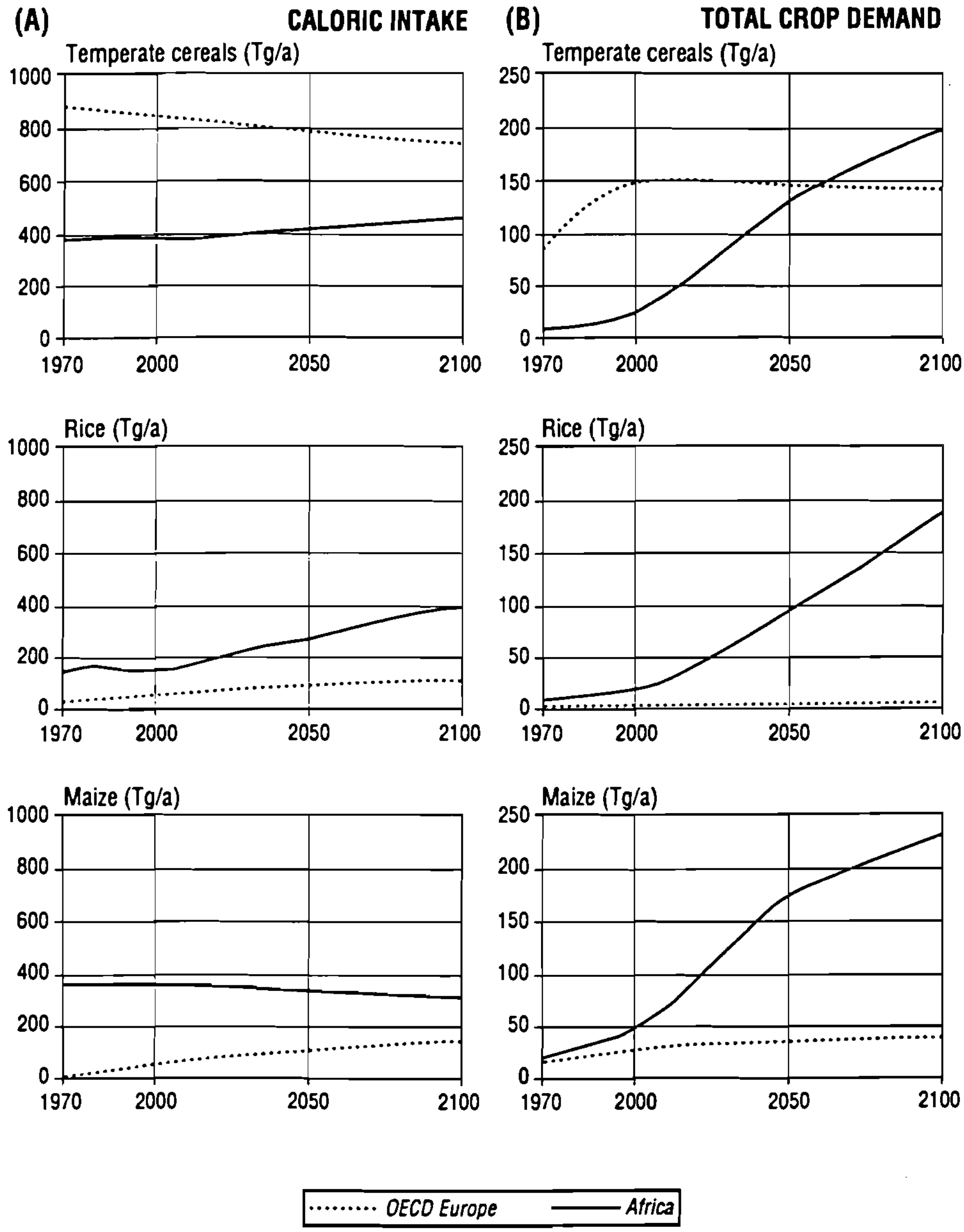



**Figure 6.** Trends in agricultural demand for OECD Europe and Africa: (a) Caloric intake (kcal $cap^{-1}$ $day^{-1}$), (b) Total crop demand (Tg $a^{-1}$).

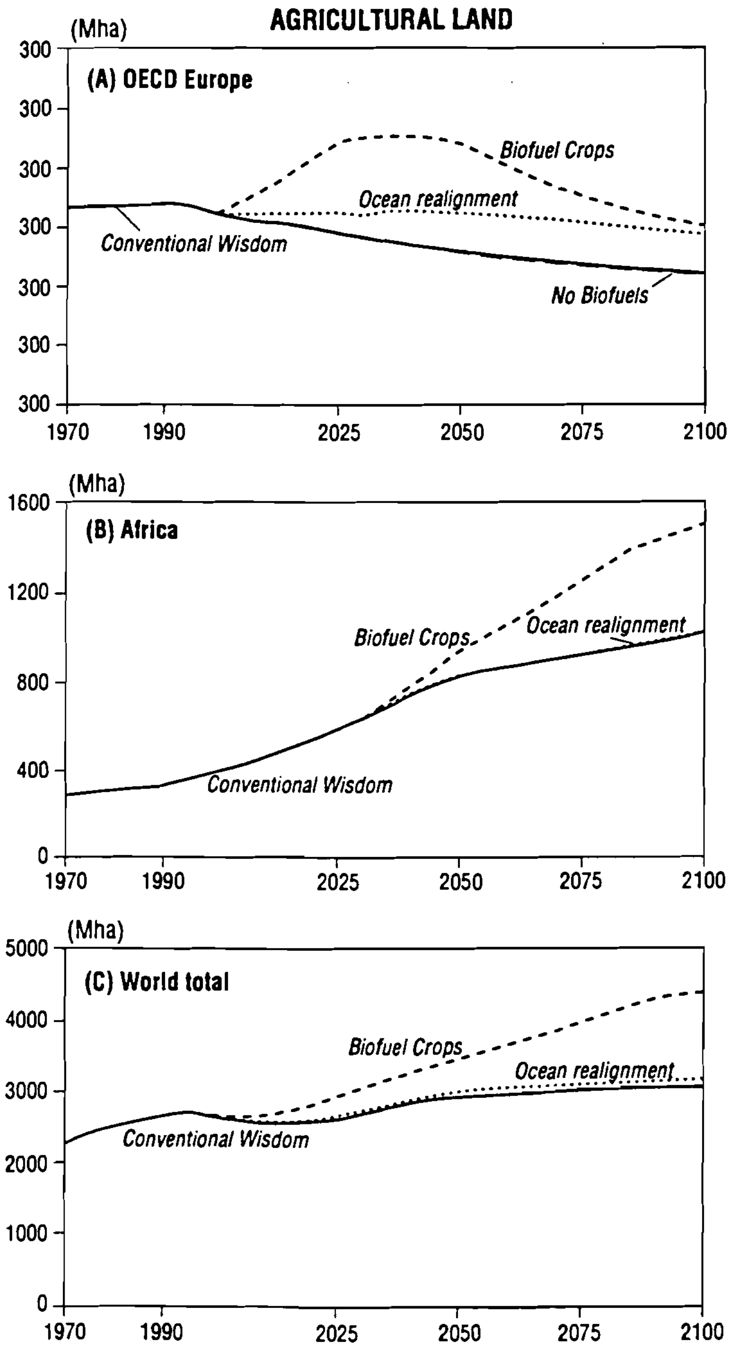



**Figure 7.** Trends in amount of agricultural land for Conventional Wisdom scenario: (a) OECD Europe, (b) Africa, (c) World.

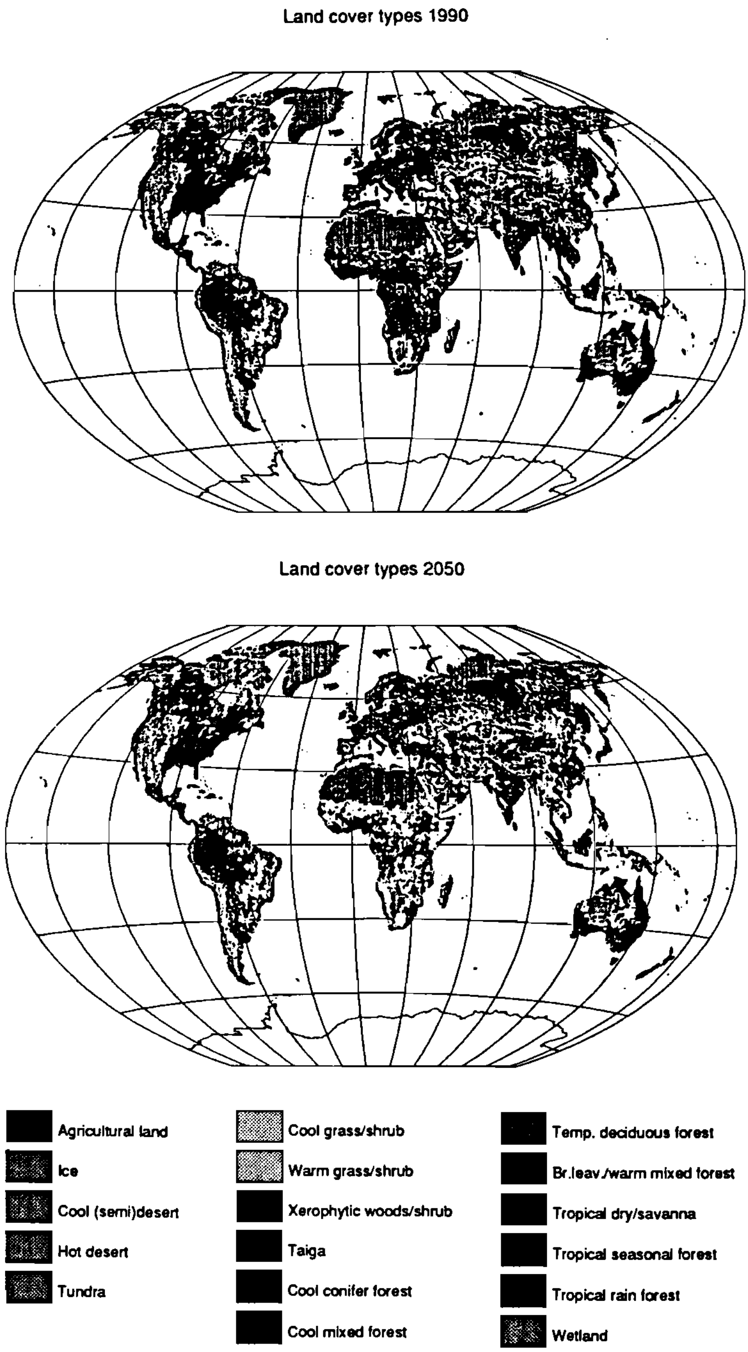



**Figure 8.** Global land cover: (a) 1990, (b) Conventional Wisdom scenario, 2050.

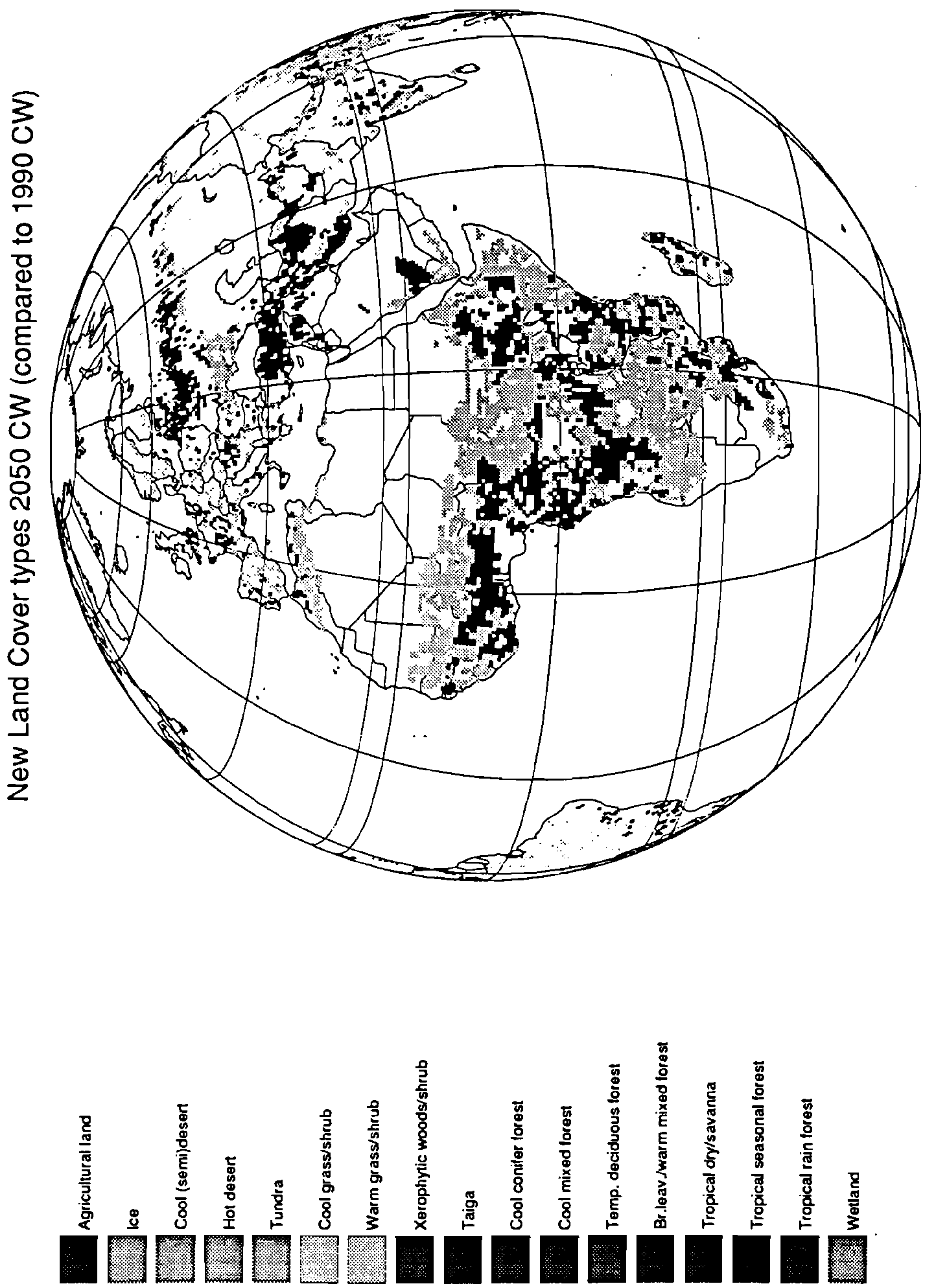



**Figure 9(a).** Land cover changes, Conventional Wisdom scenario, year 2050 compared to year 1990.

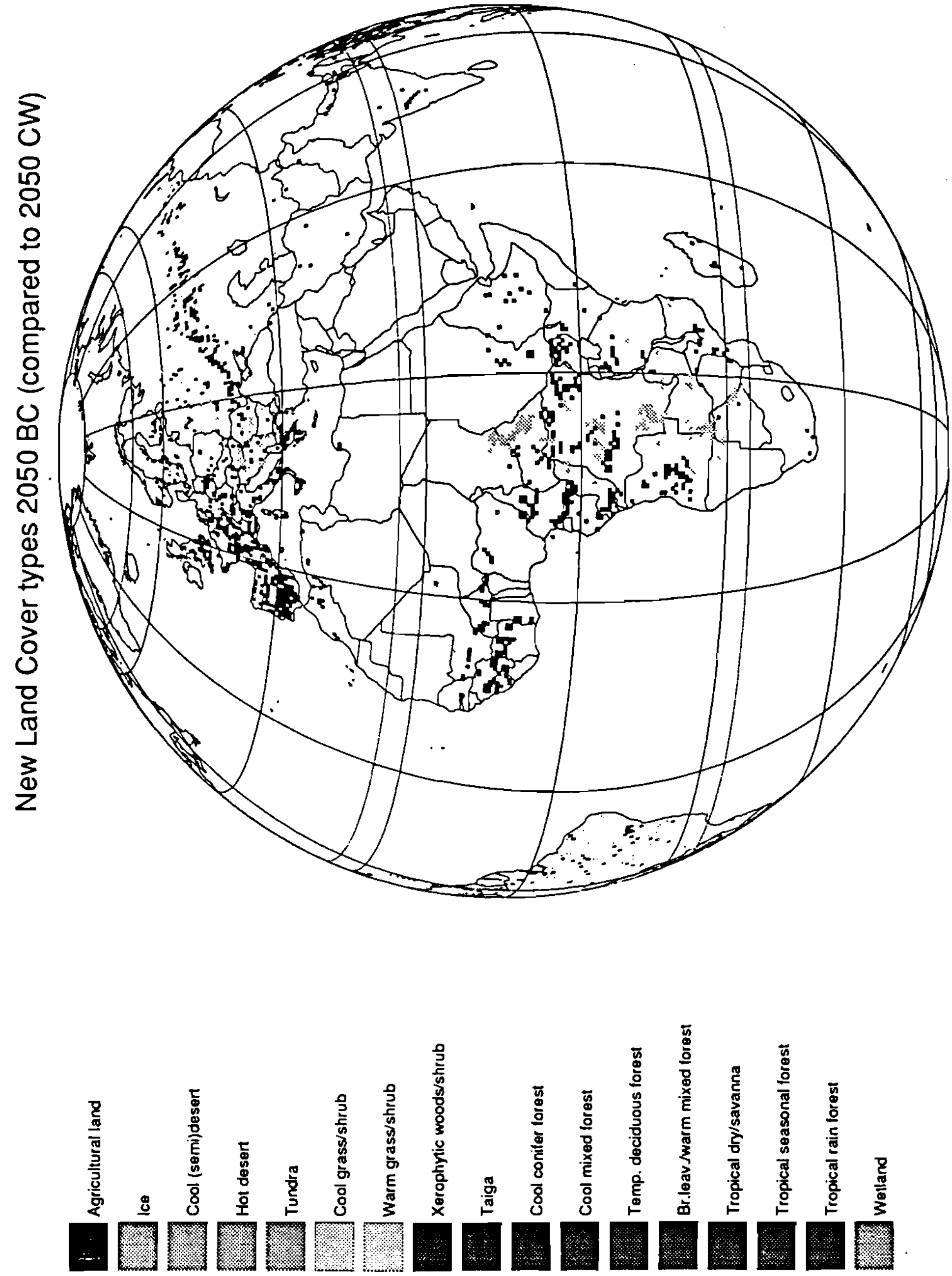



**Figure 9(b).** Land cover changes, Biofuel Crops scenario, year 2050, compared to Conventional Wisdom scenario, year 2050. These are land cover types which change in addition to the changes portrayed in Figure 9a.

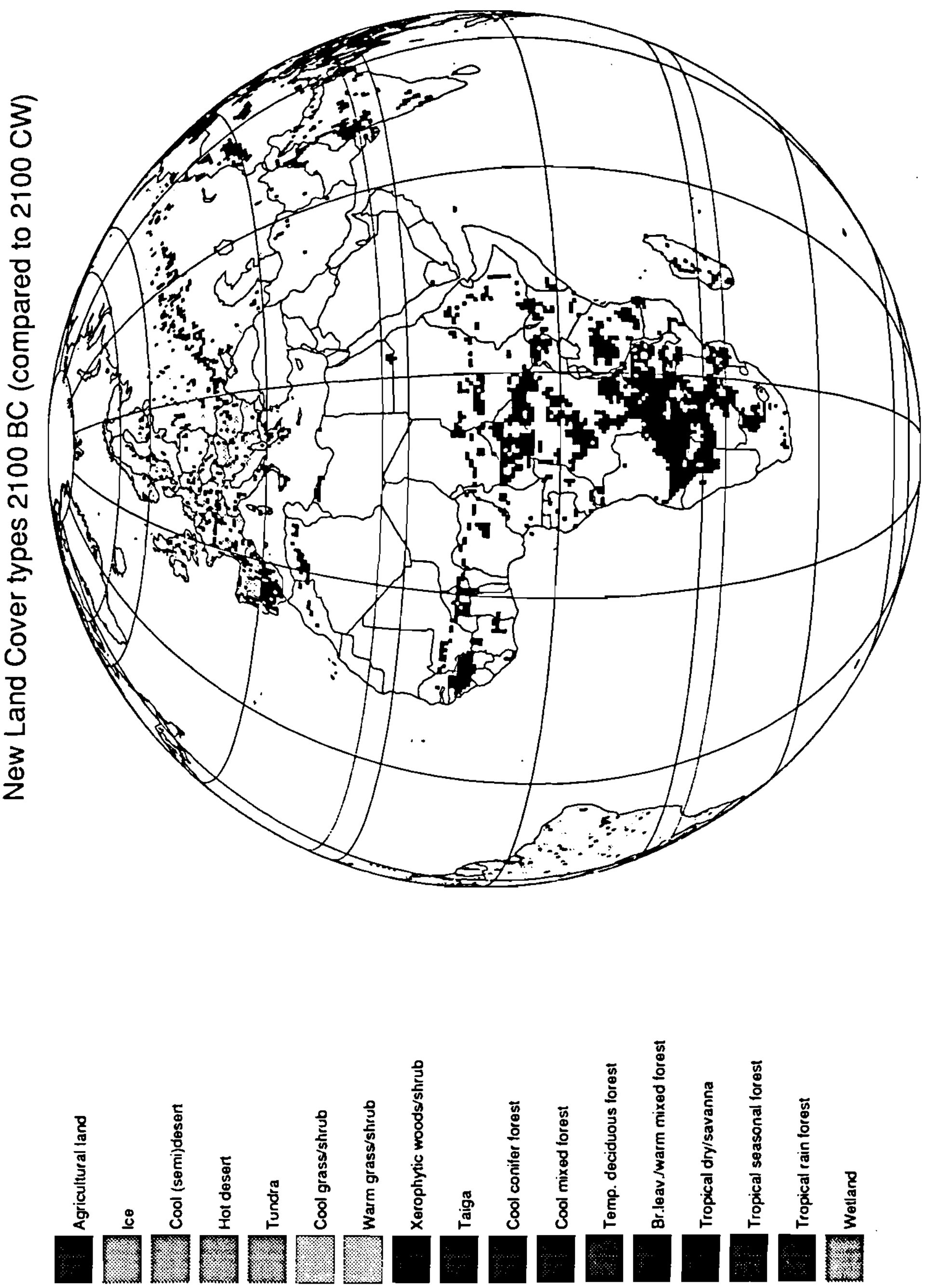



**Figure 9(c).** Land cover changes, Biofuel Crops scenario, year 2100, compared to Conventional Wisdom scenario, year 2100.

The leveling off of demand for animal products leads to stable numbers of most types of livestock after 2025. This leads to a stabilization of the amount of feed required for these animals, which together with a decrease in human consumption of cereals and other crops, leads to a leveling off or decline of total crop demands (Figure 6b). Less area is needed in Europe to grow crops as the total demand for crops levels off and crop yields increase per hectare because of more favorable future climate, increased fertilizer use, and technological crop improvements (Figures 7, and compare Figures 8a and b). As a consequence, some agricultural land reverts to its climate-potential land cover. In the case of Europe this is mostly deciduous forests (Figure 9a).

By contrast, increased income in Africa leads to an increase in per capita consumption of most agricultural commodities (Figure 6a). The larger per capita meat demand and increase in population leads to a large increase in the number of animals. Rising per capita food consumption is multiplied by increased population so that total crop demand in Africa rises steeply between 1990 to 2100 (Figure 6b). To satisfy the demand for crops and meat products, the model computes that extensive new areas will be needed for agriculture and grassland (Figure 7b, and compare Figures 8a and b), even though fertilizers and other inputs are assumed to enhance yield per hectare. The amount of agricultural land increases from 325 to 980 Mha between 1990 and 2100 (Figure 7). The expansion of agricultural land and grassland (Figure 9b) is mainly at the expense of savanna and tropical forested areas (Figure 8a). By the year 2060 the demand for grassland cannot be met since all savanna and forest have been cleared; subsequently animal densities increase on the available grasslands. We note that this scenario assumes that most food demand in Africa is met by growing crops within the region, rather than by importing food from Europe and other regions with excess agricultural land. Since this scenario assumes that per capita income increases substantially in Africa, it can be argued that Africans may grow less of their own food in the future, and import more.

Globally, the amount of agricultural land expands to the end of next century, when it begins to level off (Figure 7c and Table 7). Not only Africa experiences a huge expansion of grassland and agricultural land, but also Asia, and the Middle East (Figure 8). In Asia this leads to extensive deforestation. At the same time, the trends discussed above for Europe also apply to North America and all of the CIS; for example, forests replace abandoned agricultural land in Siberia and on the East Coast of USA and Canada (Figure 8).

*Comparing Emissions from Energy/Industry and Land*

Global emissions coming from natural sources, land activity, and energy/industry are compared in Figure 10. Land-related emissions of $CO_2$ are connected mostly with the process of deforestation. According to the Conventional Wisdom scenario, the global rate of deforestation dwindles in the second half of next century. This occurs because either forests have disappeared (for example, in Africa and India plus South Asia) or because stabilizing food demand and increasing crop yield slow the expansion of agricultural and range land (in the case of Latin America). A consequence of declining deforestation rates is that land-related $CO_2$ emissions are unimportant in the second half of next century (Figure 10). A related issue, the role of the biosphere in the carbon cycle, is taken up below.

Methane is emitted mostly from land-related sources (e.g., wetlands and animals). Since agricultural activity expands in the next century, $CH_4$ emissions continue to increase (Figure 10). Emissions of $N_2O$ are also chiefly land-related (from natural soils in particular) and increase because of moisture and temperature feedbacks to soil.

Land-related emissions of ozone precursors ($NO_x$, CO, and VOC) stem from seasonal savanna burning, biomass burning following deforestation, and agricultural waste burning. Emissions from savanna and biomass burning will decrease steadily because of the declining rate of deforestation rates and dwindling extent of savanna lands. By comparison, the main sources of $NO_x$ and VOC emissions are related to energy and industry rather than land use, and these sources continue to rise throughout the next century, especially because of expanded economic activity in developing regions (Figure 10). The net result is that total $NO_x$ and VOC emissions continue to increase. The situation is similar for CO, except that land-related emissions make up a much larger part of total emissions. Consequently, the decrease in land-related emissions outweighs the increase in energy/industry emissions, and total emissions decline after 2025 (Figure 10). More information about land-related emissions for the Conventional Wisdom scenario is given by Kreileman and Bouwman (1994).

*Results Concerning Total Carbon Fluxes*

In this section we focus on the total flux of carbon because of its important contribution to radiative forcing. To compute the flux of carbon between the biosphere and atmosphere, the IMAGE 2.0 model takes into account plant primary productivity, soil respiration and burning of biomass from cleared

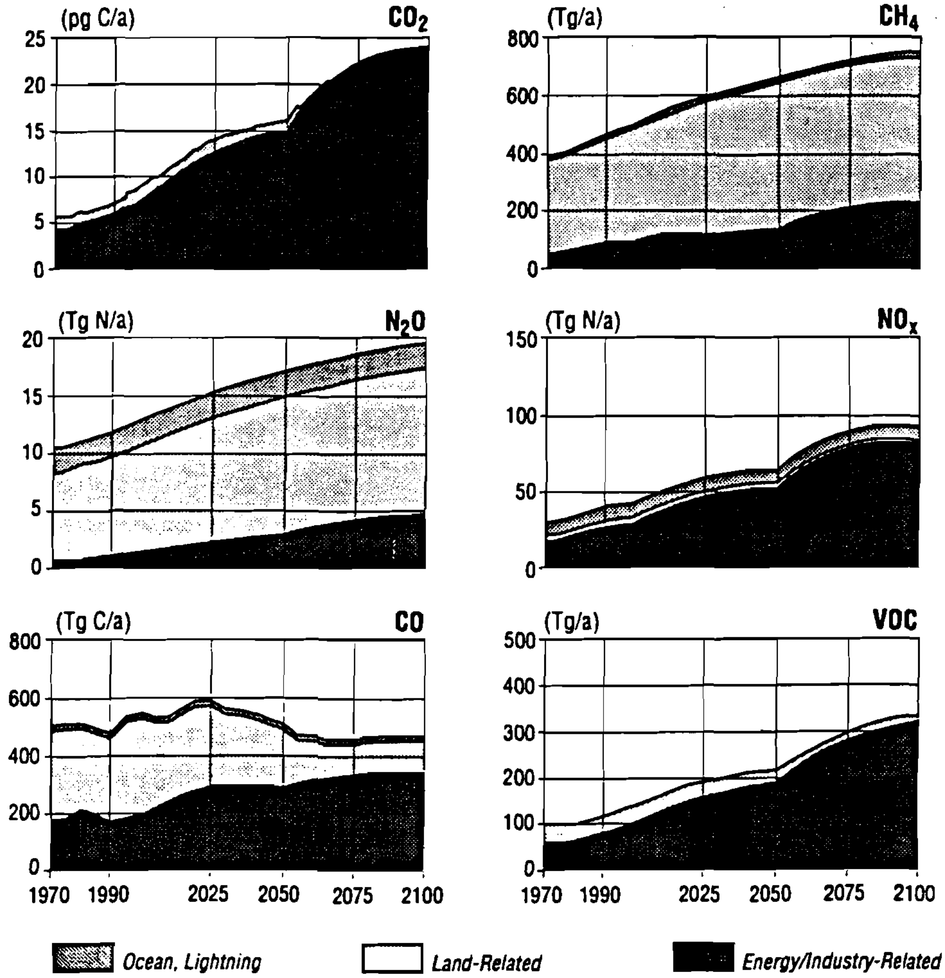



**Figure 10.** Global emissions of greenhouse gases and ozone precursors from natural, land-related, and energy/industry-related sources.

land (Klein Goldewijk *et al.*, 1994). In addition, the rate of soil respiration depends on moisture availability and temperature, and the rate of plant productivity depends on $CO_2$ air concentration, temperature, and the length of the growing season. For reference, the calculated 1990 carbon fluxes are presented in Figure 11a and discussed in Alcamo *et al.* (1994) and Klein Goldewijk *et al.* (1994). The year 2050 fluxes (Figure 11b) show increased uptake in the northern boreal forests due to increased temperature and $CO_2$, and in the USA and Europe also because of reversion of agricultural land to forest. At the same time, many areas of Africa and Asia become new sources of $CO_2$ owing to expansion of grassland and agricultural land and the resulting burning of biomass and increased soil respiration. In Latin America, forests continue to act as sinks because of assumed climate feedbacks (see Klein Goldewijk *et al.*, 1994). The net effect of these different trends is that the biosphere acts as a larger and larger sink of atmospheric $CO_2$, increasing from 1.2 Pg C $a^{-1}$ in 1990 to 8.2 Pg C $a^{-1}$ in 2100 (Figure 12a). The ocean also behaves as a net sink of $CO_2$ according to IMAGE 2.0 calculations, increasing from 1.6 Pg C $a^{-1}$ in 1990 to 4.2 Pg C $a^{-1}$ in 2100. This is mostly due to higher atmospheric concentrations of $CO_2$.

As noted above, the source of $CO_2$ from the world's energy/industrial system increases from 6.1 in 1990 to 24.0 Pg C $a^{-1}$ between 1990 and 2100. The sum of these fluxes in 2100 result in a net build-up of 11.6 Pg C $a^{-1}$ in the atmosphere.

*Results from Atmosphere and Climate*

Because of the above described changes in global carbon flux, $CO_2$ in the atmosphere increases from 358 ppm (slightly above measured concentrations) to 777 ppm between 1990 and 2100 (Figure 13a). At the same time, methane concentrations rise steadily from 1.7 ppm in 1990 to 2.5 ppm in 2050, but slowly decrease afterwards (Figure 13b). The initial increase is due to increasing emissions, as well as depletion of its atmospheric sink, hydroxyl radical. The atmospheric concentration of hydroxyl recovers when CO emissions decline after 2025, and begins to serve as a more effective sink for $CH_4$. Consequently, $CH_4$ in the atmosphere slowly declines after 2050 although its global emissions continue to increase (Figure 10). The concentration of $N_2O$ follows its upward emissions trend, increasing from 305 to 430 ppb between 1990 and 2100, while CFCs decline over this period due to the assumption of a partial compliance to the London Amendments of the Montreal Protocol, leading to a phase out of all CFCs by 2075.

The net effect of the changes in greenhouse gas concentrations is a substantial increase in surface temperature in both the Southern and Northern Hemispheres (Figure 14a). Model results show the zonal pattern of temperature change that is typical of more complicated general circulation models, namely a lower temperature increase in the tropics because of extensive heat flux from this region, with a substantially higher increase in temperate regions (Figure 14a). Around the equator, surface temperatures between 1970 and 2100 increase about 1.5°C, whereas in the middle northern latitudes the increase is around 3 to 5°C (Figure 14a). Temperature changes in the

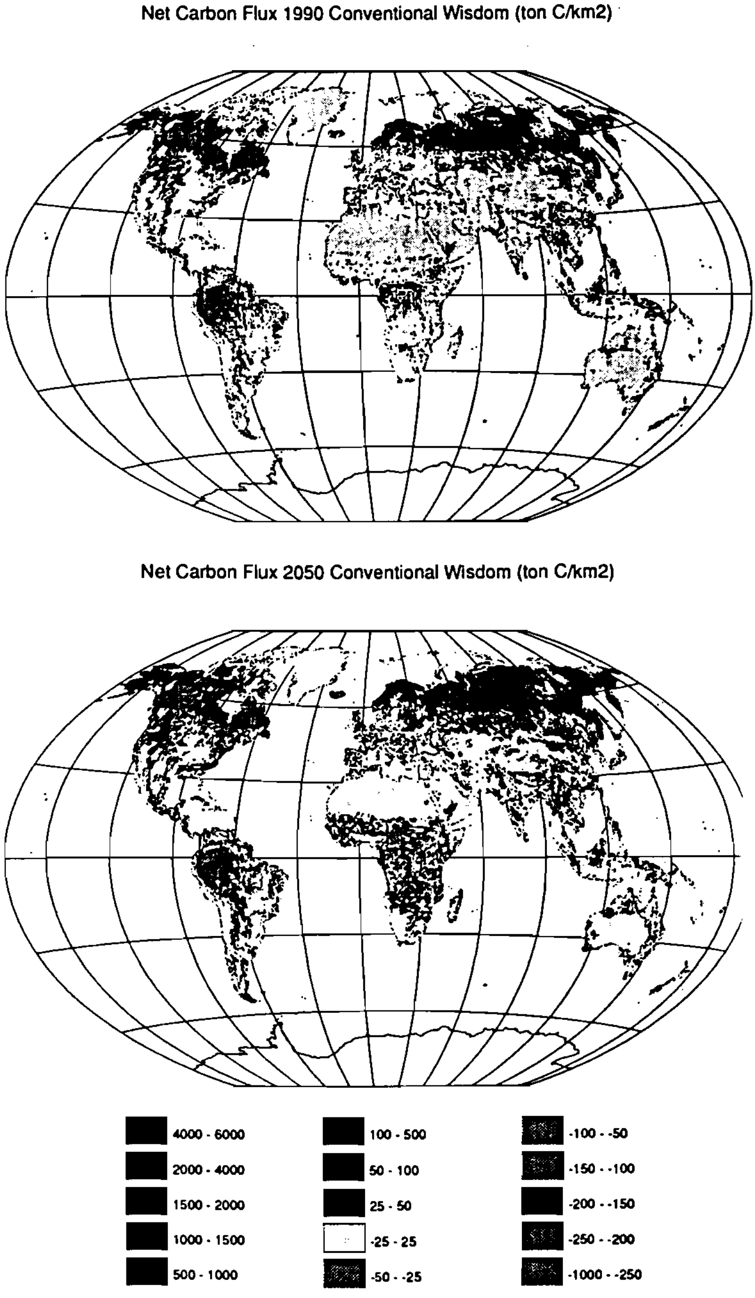



**Figure 11(a-b).** Flux of C between the biosphere and atmosphere, (a) year 1990, (b) Conventional Wisdom scenario, year 2050. Negative numbers indicate a net biospheric sink of C (t C $km^{-2}$ $a^{-1}$).

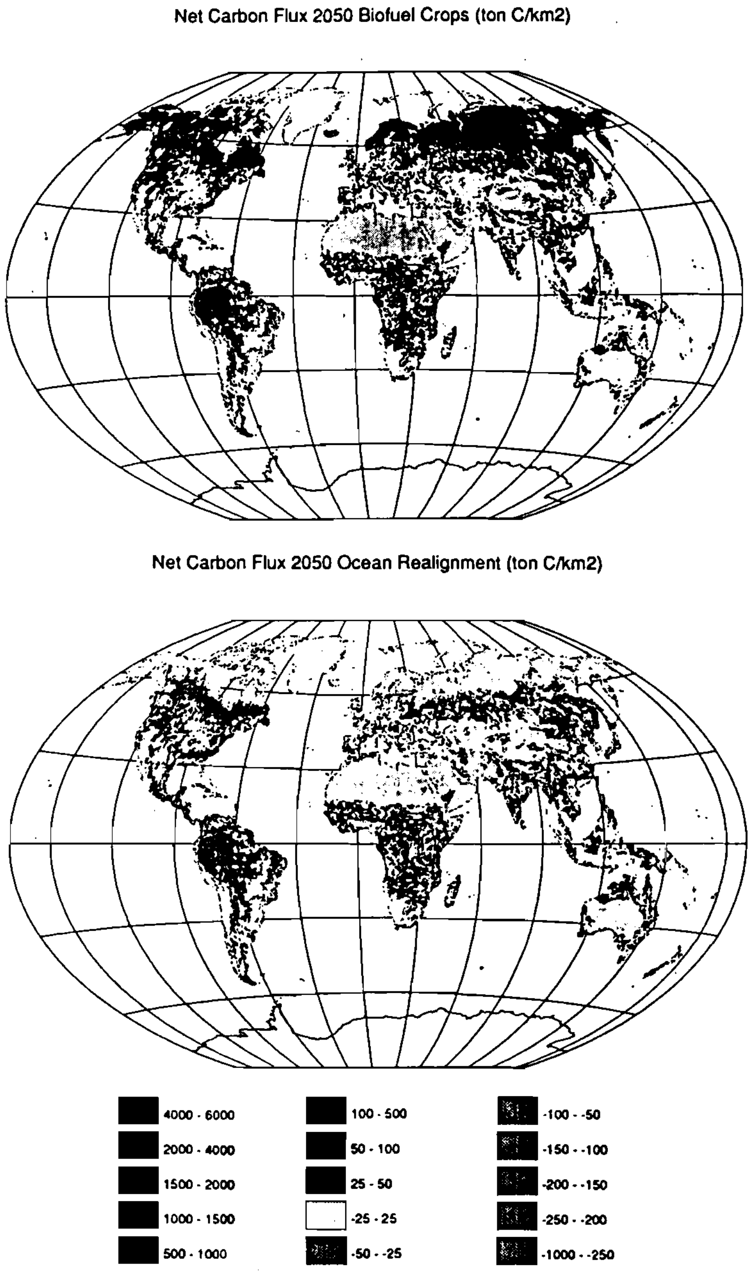



**Figure 11(c-d).** Flux of C between the biosphere and atmosphere, (c) Biofuel Crops scenario, year 2050, (d) Ocean Realignment scenario, year 2050. Negative numbers indicate a net biospheric sink of C (t C $km^{-2}$ $a^{-1}$).

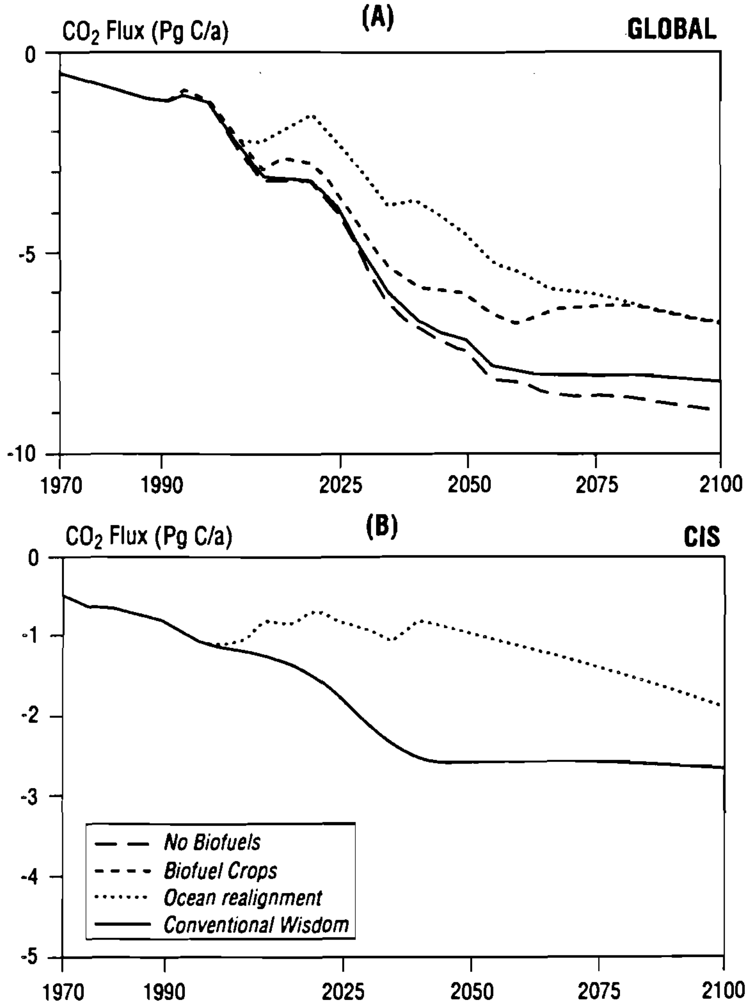



**Figure 12.** Net carbon flux between the biosphere and atmosphere: (a) Global, (b) CIS.

Southern Hemisphere are smaller than in the Northern Hemisphere because of the modifying effects of the South's larger surface area of ocean (Figures 14a and 15).

Since calculations of society, biosphere, and climate are coupled in IMAGE 2.0, increases in surface temperature affect potential crop productivity, productivity of existing vegetation, and the rates of emissions of different greenhouse gases (e.g., $N_2O$ from soils). These factors profoundly affect

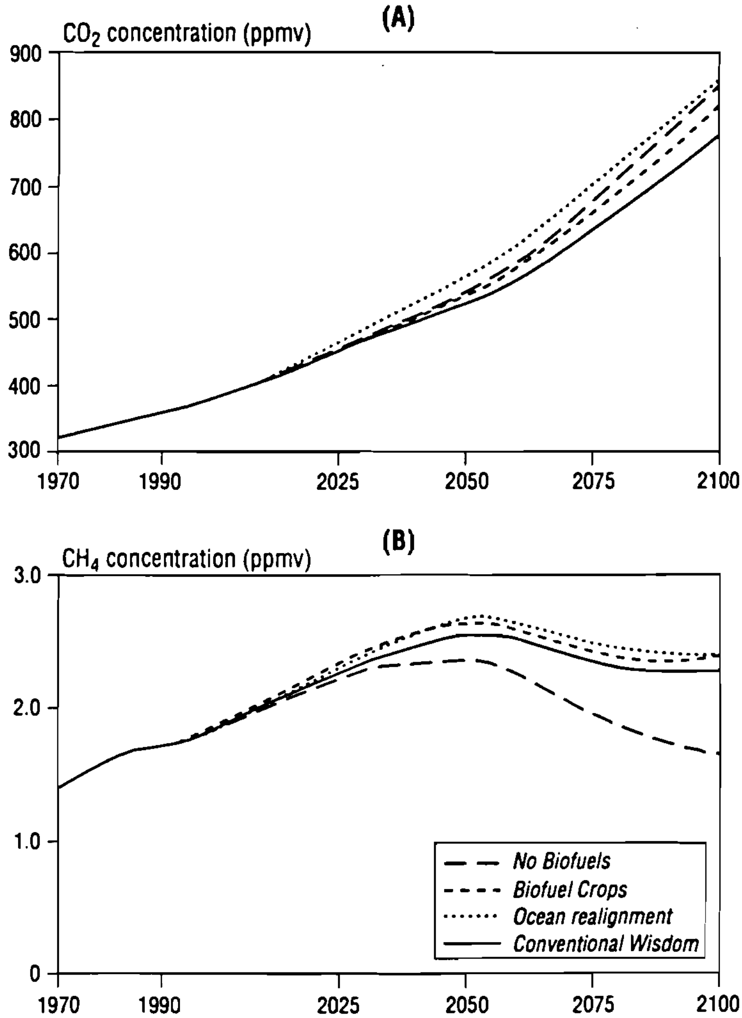
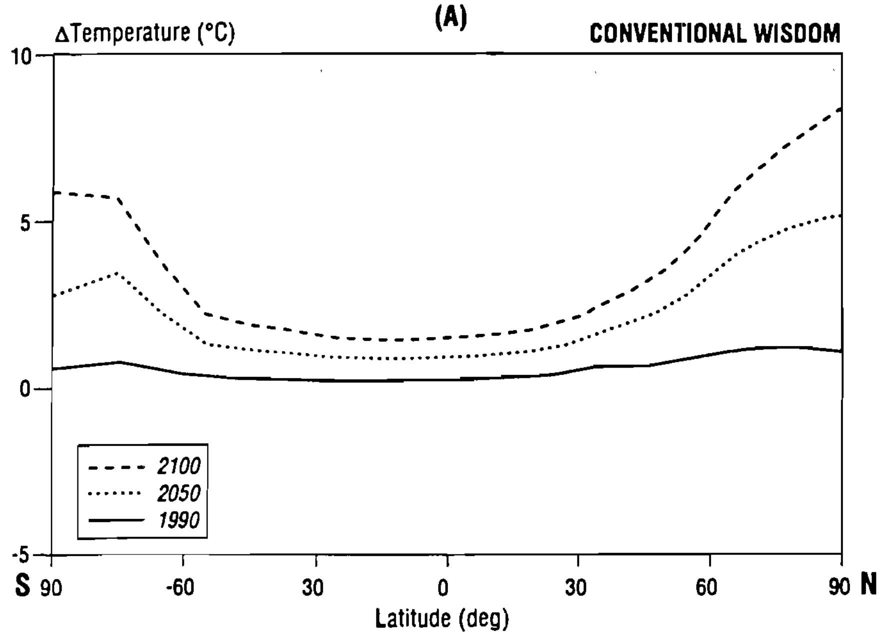



**Figure 13.** Atmospheric concentrations of greenhouse gases: (a) $CO_2$, (b) $CH_4$.

atmospheric levels of greenhouse gases, which in turn affect surface temperatures and other aspects of climate, which again feed back to potential crop productivity, productivity of vegetation, and so on, until the loop is closed in the society-biosphere-climate system for each model time step.



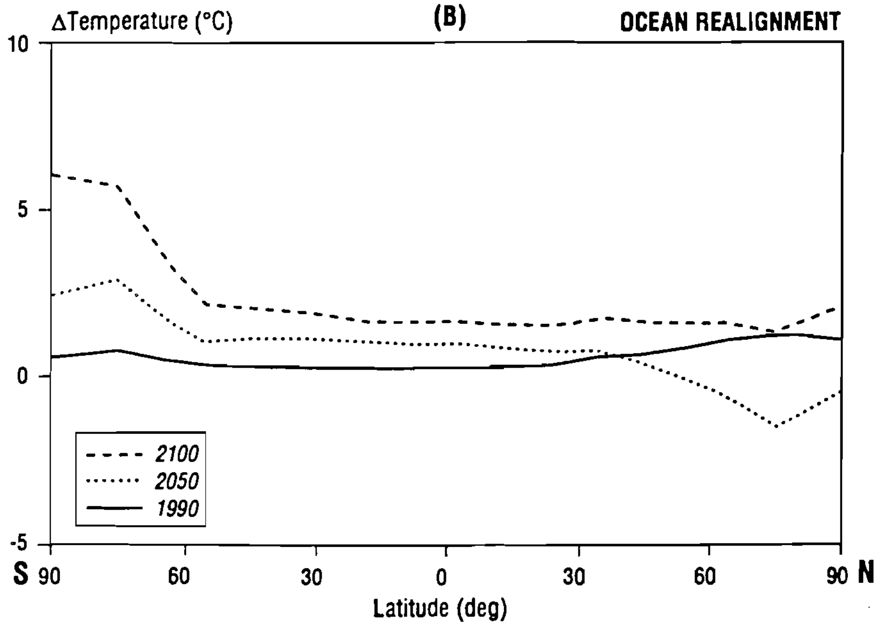




**Figure 14.** Latitudinal profile of change of atmospheric surface temperature relative to 1970: (a) Conventional Wisdom scenario, (b) Ocean Realignment scenario.

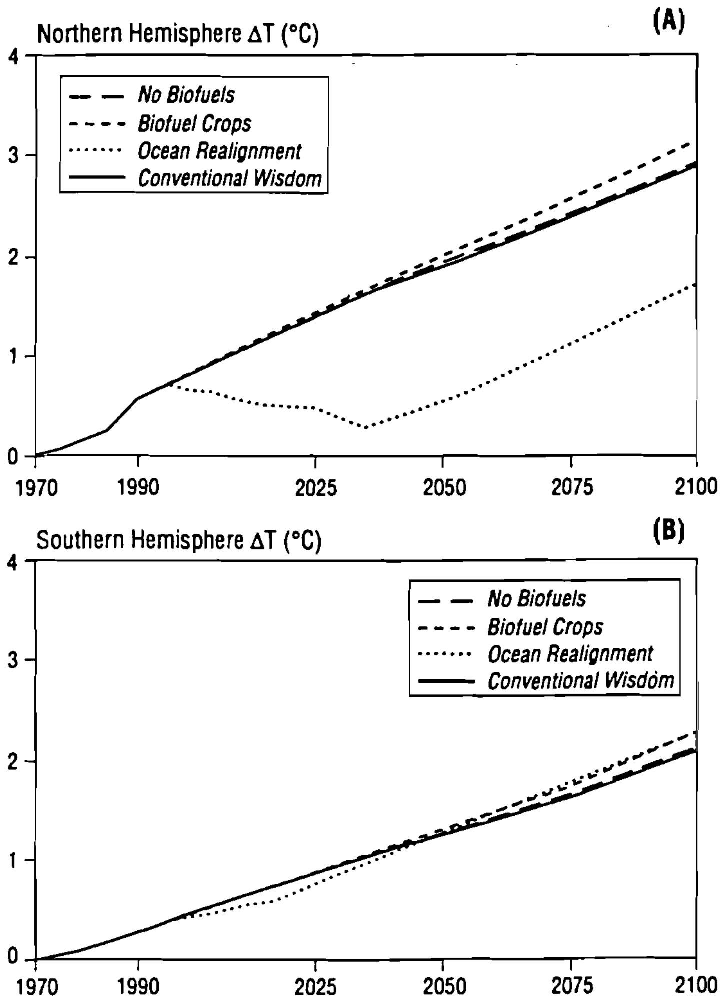



**Figure 15.** Trend of change of atmospheric surface temperature: (a) Northern Hemisphere, (b) Southern Hemisphere.

*Synopsis of Conventional Wisdom results*

The Conventional Wisdom scenario provides a comprehensive (but incomplete) picture of the chain of consequences following "conventional wisdom" driving forces. Energy use and industrial activity slows down in OECD regions, while it rapidly expands in other regions. $CO_2$ and other emissions related to energy/industry follow this pattern. At the same time the leveling off of population and a small marginal increase in per capita consumption leads to a stabilization of per capita food demand. This, and improved crop yields per hectare due to technology and improved climate, leads to a decline in total crop and animal demands. As a result, agricultural area shrinks, and the resulting forestation leads to greater uptake of $CO_2$ by the biosphere in the north.

In developing regions, large increases in population and GNP also increases energy consumption and industrial activity, leading to increased emissions. The demand for food also greatly increases, and results in expanding agricultural and grassland areas, depleting forests and savanna in Africa and Asia, and increasing flux of $CO_2$ between the biosphere and atmosphere. The net global effect of these trends is a rapidly increasing atmospheric level of most greenhouse gases, and significant increase in surface temperatures.

# 3. Biofuel Crops Scenario

## 3.1. Assumptions of "Biofuel Crops" scenario

The Conventional Wisdom scenario assumes that biofuels used in the world's energy system are derived from crop residues and other sources that do not require new cropland. Consequently, the use of biofuels does not lead to an increase in agricultural area. The assumptions of the "Biofuel Crops" scenario are the same as the Conventional Wisdom scenario except that it assumes that a large fraction of biofuels will be provided by energy crops grown on additional cropland. Specifically:

- Biofuels used in the transport sector of tropical or partly tropical regions (Latin America, Africa, and East Asia) are derived from sugar cane, and in other regions from maize.
- Of the biofuels used in other energy sectors, 60% are assumed to come from crop residues and other sources not requiring new cropland. The remaining 40% of the demand comes from elephant grass (*miscanthus sp.*) grown on new cropland. This is a C4 species with a potential maximum yield of about 50 t $ha^{-1}$ $a^{-1}$, and a plausible worldwide range because of its relatively high potential productivity in both temperate and tropical climates (Figure 16). Elephant grass is also a good indicator species because its growing properties resemble that of eucalyptus, poplar, willows, and other crops that may be used for biofuels.

The preceding assumptions can be compared to those of Johansson *et al.* (1993a) who assume in the Renewables-Intensive Energy Scenario (RIGES)

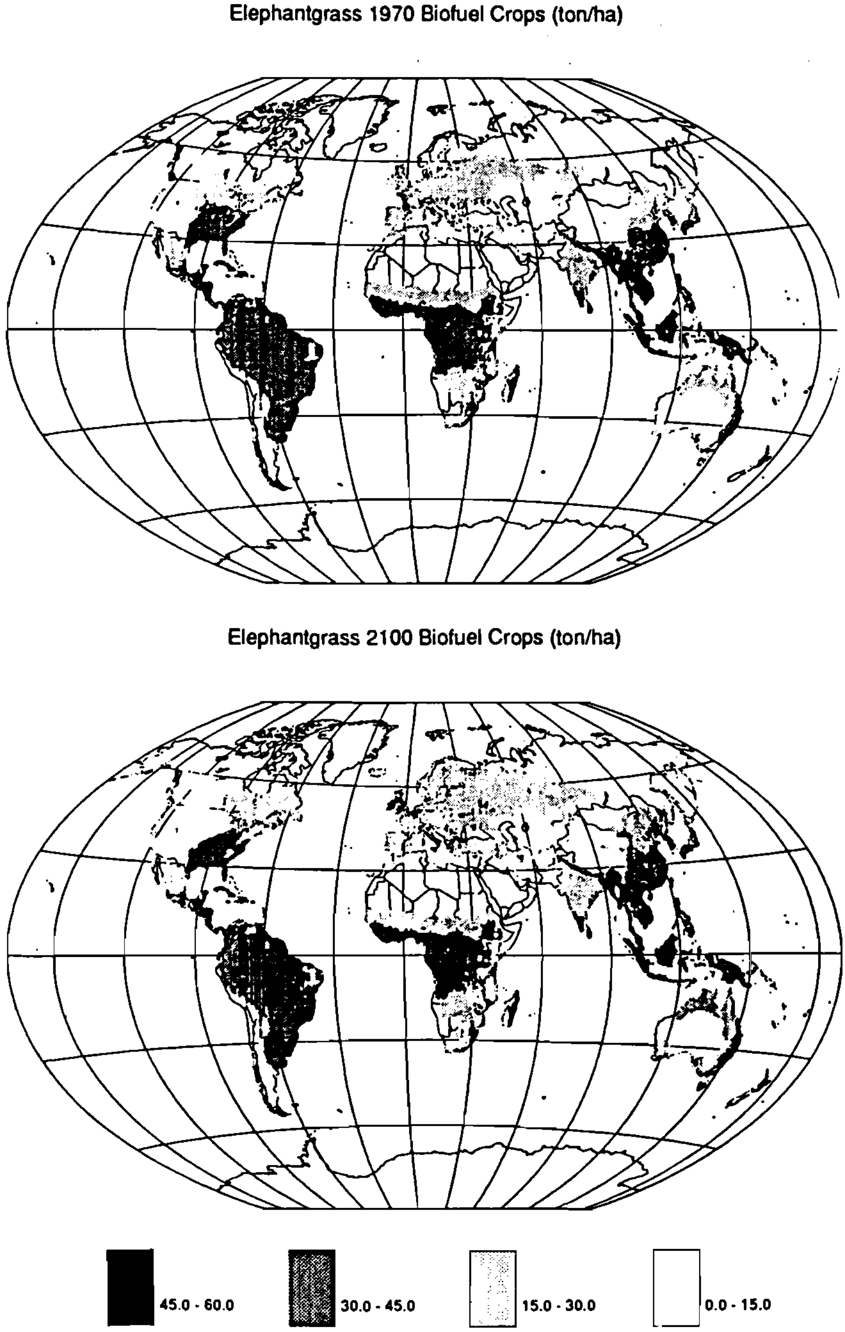



**Figure 16.** Potential productivity of elephant grass: (a) 1970, (b) Biofuels Crops scenario, 2100. (Tons dry weight $ha^{-1}$ $a^{-1}$).

that about 55% of world biomass supplies in the year 2025 are provided by energy crops grown mainly on "excess" cropland in industrialized countries.

It is emphasized that land requirements for biofuels are likely to be overestimated because we assume ad hoc that a large percentage of biofuels must come from energy crops on new cropland. Some studies contend that large quantities of biofuels can be provided on marginal lands outside of prime cropland (see, for example, Swisher, 1993 and Woods and Hall, 1993). In addition, we only take into account three energy crops, whereas there are many other crops that might be better suited to a particular climate and soil and consequently have higher local yields. Moreover, we do not consider the costs of growing the assumed energy crops, which in reality should lead to efficient use of land.

All other assumptions in this scenario are the same as in the Conventional Wisdom scenario.

## 3.2. Results of the "Biofuel Crops" scenario

The energy-related assumptions for this scenario are the same as the Conventional Wisdom scenario, so the computed energy-related emissions are also identical (Table 7).

IMAGE 2.0 takes into account the growing characteristics of the energy crops and estimates their change in potential productivity as climate changes. As an example, in this scenario the potential productivity of elephant grass increases between the years 1970 and 2100 especially in Canada and Russia due to changes in temperature and precipitation (Figure 16). Changes in productivity, together with the change in demand for these biofuels, leads to the allocation of additional agricultural land for these crops. The reader is referred to Leemans and van den Born (1994) and Zuidema *et al.* (1994) for descriptions of the methodology for calculations of potential crop productivity and land cover changes.

As to changes in land cover, we again focus on Europe and Africa as examples. Figure 9a depicts the new land cover types that appear between 1990 and 2050 according to the Conventional Wisdom scenario. As noted previously, large new areas of grassland and agricultural land are needed in Africa to satisfy increased food demand, whereas forested areas reappear in Europe because of stabilizing food demand and increased crop yield. Figure 9b shows the additional agricultural areas required in year 2050 for energy crops according to the Biofuels Crops scenario (over and above the new agricultural areas shown in Figure 9a).

In year 2050, 14% more agricultural area is required for biofuel crops in Africa and 71% more for OECD Europe as compared to the Conventional Wisdom scenario (Figures 7a and b). In OECD Europe this leads to deforestation instead of the forestation computed in the Conventional Wisdom scenario. The relatively small increase of agricultural land in Africa for year 2050 can be explained by the relatively small absolute amount of modern biofuels used in the first half of the 21st century. The use of biofuels in Africa becomes more substantial in the second half of the century, and this is reflected in the land cover simulation which indicates large new areas of agricultural land necessary for energy crops (Figure 7b, and compare 9b and 9c). By comparison, the use of biofuels declines in the second half of the century in Europe, and the yield per hectare of energy crops increases because of technology. Consequently, less area is required for biofuels in 2100 than in 2050 (Figure 7a, and compare 9b and 9c).

Not only will Africa require substantial new agricultural areas for biofuels in this scenario, but globally a 20% increase is required for 2050 and 45% for 2100 (Figure 7c, Table 7). Since agriculture replaces forests and other land cover types capable of assimilating more carbon, there is a substantial reduction in the carbon assimilated by the biosphere (Figures 11c and 12a). What follows is an increase in atmospheric $CO_2$ in year 2100 from 777 ppm in the Conventional Wisdom scenario to 821 ppm in this scenario (Figure 13a). This results in a slight increase in temperature for the Northern and Southern Hemispheres, as compared to the Conventional Wisdom scenario (Figure 15, Table 7).

### *Synopsis of Results of Biofuel Crops Scenario*

Summing up, following the assumptions of this scenario, the need for biofuels may take up large amounts of new agricultural land in the world. A consequence of expansion of agricultural land is a reduction of the $CO_2$ assimilated by the biosphere, a small increase in atmospheric $CO_2$ as compared to the Conventional Wisdom scenario, and somewhat larger global warming. However, we reiterate that the energy cropland requirements assumed in this scenario may be exaggerated since it may be possible to provide a much larger fraction of biofuels from agricultural wastes, plantations on marginal land, and other non-cropland sources (see, for example, Woods and Hall, 1993; Johansson *et al.* (1993a and b). Moreover, the requirements for land would not have been as large, nor the reduction in C uptake by the biosphere so great, if energy crops/trees had been selected that were better suited to local climate and soil. Perhaps this scenario provides a useful estimate of the upper range of land requirements of biofuels.

# 4. "No Biofuels" Scenario

## 4.1. Assumptions of "No Biofuels" scenario

As described earlier, the Conventional Wisdom scenario assumes that biofuels will make a significant contribution to the world's future energy consumption. Indeed, this is the conventional wisdom of current energy studies (see, for example, World Energy Council, 1993). In the "No Biofuels" scenario, we investigate the sensitivity of the climate system to biofuel use. For this scenario, we remove the biofuels specified in the Conventional Wisdom scenario (other than fuelwood). We further assume that oil will be used if biofuels are not available. This is a fairly good assumption for the transport sector where oil and other liquid fuels are the major energy carriers. For other sectors, however, it is rather difficult to decide on the fuel that would be used in place of biofuels. For example, coal can be used as well as oil in power generation. Consequently, the use of oil is simply a default assumption for this sensitivity study. We note that the total supply of oil, required by this scenario over the next century does not exhaust the presently known oil reserves.

All other assumptions are the same as the Conventional Wisdom scenario.

## 4.2. Results of the "No Biofuels" scenario

Removing biofuels from the energy system results in an increase in $CO_2$ emissions of 1.8 Pg C $a^{-1}$ in year 2050, and 5.2 Pg C $a^{-1}$ in year 2100 over the Conventional Wisdom scenario (Table 7). This is because biofuel combustion is assumed to have zero net C emissions (because an equal amount of $CO_2$ is assumed to be assimilated by regrown biomass). The difference is relatively small in 2050 as compared to 2100 because the Conventional Wisdom scenario assumes that biofuel use will increase greatly in Africa and Asia in the second half of next century. Following the rise in emissions, atmospheric concentrations of $CO_2$ are also larger in this scenario as compared to the Conventional Wisdom scenario; the concentration is 17 ppm greater in 2050, and 80 ppm in 2100.

Methane emissions and atmospheric concentrations, on the other hand, decrease relative to the Conventional Wisdom scenario because unit emissions of $CH_4$ from biofuels are higher than from oil (Figure 13). This is a crucial result and depends on the implicit assumption of how biofuels are burned. If they are gasified, for example, most of the $CH_4$ would be utilized rather than emitted to the atmosphere. However, scenario assumptions imply that it is combusted without gasification. Lower emissions of $CH_4$ lead to lower concentrations of this substance in the atmosphere. This also applies to CO and $NO_x$, two other important precursors of tropospheric ozone. The lower concentrations of $O_3$ precursors leads to lower concentrations of tropospheric ozone.

The net effect of these changes on radiative forcing are important. The increase in $CO_2$ concentration tends to increase radiative forcing, while the decrease in $CH_4$ and tropospheric $O_3$ tends to decrease it. The net effect is a very small difference in the change of surface temperature between this and the Conventional Wisdom scenario (Figure 15 and Table 7).

*Synopsis of Results of No Biofuels Scenario*

Summing up, emissions from biofuels result in lower atmospheric levels of $CO_2$, but higher levels of $CH_4$ and $O_3$. The net result is a small difference in climate change between scenarios with and without biofuels. These results point out the importance of taking into account all emissions as well as the composition of the atmosphere. However, as noted above, these conclusions also depend on assumptions about biomass utilization.

These results also raise interesting questions – How sensitive are scenario results to the assumed mix of fuels that are used instead of biofuels? How does the effect of biofuels on tropospheric ozone depend on the background atmospheric concentration of ozone precursors? What influence does the timing of introduction of biofuels have on the rate of climate change?

# 5. "Ocean Realignment" Scenario

## 5.1. Assumptions of "Ocean Realignment" scenario

The previous scenarios have examined the effect of human driving forces on the society-biosphere-climate system. In this scenario we examine the influence of an unexpected change of natural driving forces on the system, namely, the slowing down of ocean circulation and reduction in the downwelling rates in the North Atlantic and Antarctic Circumpolar Ocean. We base our assumptions on the model experiments of Mikolajewicz *et al.* (1990) who examined the effects of an increase of surface air temperatures due to a doubling of $CO_2$ on the thermohaline circulation of the ocean. We adapted their results by modifying the fixed two-dimensional circulation scheme contained in the IMAGE 2.0 ocean model so that deep water formation assumed in the model: (1) decreases to 30% of its original volume in the North Atlantic in the period 1990 to 2040, and (2) reduces to 55 % of its original volume in the Antarctic Circumpolar Ocean over the same period. Afterwards the circulation is taken to remain constant.

We emphasize that this scenario is meant to illustrate a low probability, "surprise" occurrence. Indeed, the rapidness of the changes in ocean circulation found by Mikolajewicz *et al.* are likely to be due to the nature of their modeling exercise, namely, that they omitted the effect of ocean feedbacks on the atmospheric energy balance. The IPCC notes that such rapid changes in ocean circulation are not computed by models that take ocean feedbacks into account (IPCC, 1992).

Other assumptions are the same as in the Conventional Wisdom scenario.

## 5.2. Results of the "Ocean Realignment" scenario

The decrease of downwelling and slower ocean circulation has the important effect of reducing the northward transport of heat in the Atlantic (see de Haan *et al.* , 1994 for more details). What follows is a net cooling north of 40° N up to the year 2050 (Figures 14b and 15a). This scenario has less of an effect on the Southern Hemisphere because ocean circulation is not as significantly modified there (Figures 14b and 15b).

Cooling in the Northern Hemisphere has an important influence on the global build-up of greenhouse gases. For example, carbon uptake is especially reduced in northern boreal forests because of their extensive area, the cooling they are exposed to, and the assumed relationship between net primary productivity and temperature (Figure 11d). (See Klein Goldewijk *et al.*, 1994 for a description of this relationship.) This effect is particularly pronounced in CIS where C uptake in year 2050 decreases from 2.6 Pg C $a^{-1}$ to 1.0 Pg C $a^{-1}$ between the Conventional Wisdom and Ocean Realignment scenarios (Figure 12b). The global biospheric uptake of the two scenarios differs by about 2.7 Pg C $a^{-1}$ in year 2050 (Figure 12a). With reduced C uptake, atmospheric $CO_2$ reaches 90 ppm higher than the Conventional Wisdom scenario in year 2100 (Figure 13a).

Another effect of the cooler temperatures in this scenario is a lower mixing ratio of water vapor in the atmosphere. This results in lower production of hydroxyl radical, which is the main atmospheric sink of $CH_4$. Consequently, $CH_4$ concentrations are higher in this scenario than in the Conventional Wisdom scenario (Figure 13b). Although higher levels of greenhouse gases increase radiative forcing, this is compensated by the reduced transport of heat from the tropics. Nevertheless, the trend of declining surface temperatures in the Northern Hemisphere is reversed after 2035 because of the increase in radiative forcing (Figures 14b and 15a). However, by the end of the century the temperature gain in the middle latitudes is only 1.5°C as compared to 3 to 5°C in the Conventional Wisdom scenario (Figures 14a,b).

Cooler temperatures also reduce potential crop productivity which leads to larger land requirements for the same amount of agricultural demand. This is especially important in the northern temperate regions such as the CIS where the area of agricultural land in year 2100 increases from 137 Mha in the Conventional Wisdom scenario to 164 Mha in this scenario. In Eastern Europe, agricultural area in 2100 increases from 61 to 70 Mha, and in OECD Europe from 111 to 146 Mha (Figure 7). The larger area of agricultural land comes partly at the expense of forest land; in year 2100 there is 60 Mha less global forest area in the Ocean Realignment scenario than in the Conventional Wisdom scenario (see Table 7).

*Synopsis of the Ocean Realignment Scenario*

A change in the circulation of the ocean can result in a temporary cooling rather than warming of the Northern Hemisphere. This cooling would reduce uptake of carbon in the northern boreal forests and other areas, and leads to a greater build-up of $CO_2$ in the atmosphere than in the Conventional Wisdom scenario. The build-up of $CO_2$ and other gases will eventually reverse the cooling trend, although temperatures will remain substantially cooler in the Northern Hemisphere as compared to the Conventional Wisdom scenario up to 2100 and beyond. One outcome of the cooler temperatures is the need for more land to produce the same amount of food in the North (assuming no change in trade patterns), and subsequently a lower rate of forestation of abandoned land. We repeat, however, that this is a low probability scenario and is most useful in illustrating the large differences between the Conventional Wisdom scenario, and an unexpected "surprise" scenario. These differences underscore the need to test the robustness of climate policies against different kinds of uncertainties and "surprises" (Clark, 1986).

# 6. Discussion and Conclusions

Although the foregoing scenarios are fairly comprehensive, they omit many factors that could alter their outcome and conclusions, and that require further study. For example, the land cover simulations assume that the expansion of agricultural land and grassland will lead to the elimination of all forest and savanna areas in some regions without considering that society's intervention will probably prevent it from disappearing altogether. Related to this, the IMAGE 2.0 model does not take into account land costs or other economic factors that would slow the depletion of land and energy resources. Also of relevance to assessing agriculture and other impacts, the simulation does not include extreme climate events, such as extended cold or dry periods, which could have long term effects on agriculture if frequently occurring.

As a general comment, because of the omissions of the model, it is best to view the scenarios in this paper as a type of sensitivity study that can provide insight into couplings and linkages in the society-biosphere-climate system. With this in mind, we review some of the scenarios' main conclusions:

## 6.1. Conventional Wisdom scenario

- The slowing of population and economic growth in developed regions, together with increased conservation, leads to stabilization of energy- and industry-related emissions. This also results in shrinking agricultural area, and forestation of abandoned cropland. This forestation, and the effect of climate feedbacks on vegetation, enhances the uptake of $CO_2$ to the northern terrestrial biosphere.
- Rapid population and economic growth in developing regions increases emissions from energy and industry, and leads to expansion of agricultural land and initially grassland at the expense of forests and savannas. Later, the expansion of agricultural land encroaches on grasslands which implies increasing animal densities on the remaining grasslands and perhaps accelerated land degradation. Rapidly changing land cover also increases greenhouse gas flux from the terrestrial environment in the first half of the next century.
- Globally, emissions of all greenhouse gas emissions and ozone precursors increase, with the exception of CFCs and CO. Emissions of CFCs decrease because of assumed partial compliance with the Montreal Protocol, and CO emissions because of diminishment of its land-based sources – deforestation and savanna burning.

- The increase of $CO_2$ emissions from developing regions outweighs the enhanced carbon sink in the Northern Hemisphere. Consequently, there is a considerable increase of $CO_2$ in the atmosphere (along with most other greenhouse gases), and a significant increase in surface temperatures.

## 6.2. Biofuel Crops scenario

- According to the assumptions of this scenario, a substantial amount of new agricultural area will be required to deliver biofuels in the next century.
- Trends of land requirements for biofuels are quite different in different regions. In Africa, land requirements are fairly small in 2050 but are much greater in 2100, whereas in Europe, land requirements are proportionately larger in 2050, but decrease toward 2100. These results arise from different regional trends in energy consumption, market share of biofuels, crop yield improvements, and other factors.
- One consequence of the biofuel assumptions in this scenario is that the expanded agricultural areas take up less C than the land cover they replace. Therefore, overall C uptake of the biosphere decreases, resulting in a small increase in atmospheric $CO_2$ as compared to the Conventional Wisdom scenario.

## 6.3. No Biofuels scenario

- Not using biofuels in the global energy system results in higher atmospheric concentrations of $CO_2$, but lower concentrations of $CH_4$ and $O_3$.
- The net result of changes in atmospheric composition is that there is little net difference in radiative forcing between the Conventional Wisdom scenario which contains biofuels and the No Biofuels scenario.
- The preceding results depend on assumptions about how biofuels are combusted. For example, the build-up of $CH_4$, and perhaps tropospheric $O_3$ associated with biofuels use, could be averted by gasifying biofuels.

## 6.4. Overall conclusions about biofuels

Based on the two biofuel scenarios we conclude:

- In order to maximize the benefits (and minimize the costs) of biofuels on the global environment, it is important to give attention to the type of biomass species, to the processes by which they are combusted and delivered (utility boilers, gasification units, etc.), and to their associated emission factors.

- To properly assess the impacts of biofuels, it is also important to analyze their influence on the complete range of greenhouse gases.
- Land requirements for biofuels can have important side impacts, e.g., on the uptake of carbon by the terrestrial biosphere, that should be taken into account in impact assessments.
- We emphasize that these scenarios probably overestimate land requirements for biofuels because: (i) only three possible energy crops were taken into account, whereas there are many other crops that are likely to be better suited to a particular local climate and soil, (ii) it may be possible to provide a much larger fraction of biofuels from agricultural wastes, plantations on marginal land, and other non-cropland sources than was assumed in these scenarios.

The authors note here that the "top-down" analysis of biofuels as presented in this paper cannot substitute for "bottom-up" analyses of biofuels which focus on selecting the optimum energy crop for different locations (see, e.g., Swisher, 1993; Woods and Hall, 1993). Many factors having to do with local crop suitability, cultural values, and institutional factors can be included in a bottom-up analysis in order to optimize the production/delivery of biofuels and minimize their impacts. But only some of these factors have been incorporated in our approach. On the other hand, it is difficult for a bottom-up analysis to link local/regional biofuel development with the global biosphere/climate system as is done in IMAGE 2.0. It is our view that the two approaches are complementary by providing different and useful types of information for evaluating biofuel development.

## 6.5. Ocean Realignment scenario

- This scenario illustrates that an unexpected, low probability natural event – in this case a slowing down of the Atlantic's circulation – can both enhance the build-up of greenhouse gases, and at the same time cool surface air temperatures in the Northern Hemisphere.
- An increase in surface temperature in the Northern Hemisphere is not avoided, only postponed.
- One side effect of the hemispheric cooling is the lowering of crop productivity in the Northern Hemisphere relative to the Conventional Wisdom scenario, and the larger requirements for agricultural land.
- The large differences between this scenario and the Conventional Wisdom scenario emphasize the importance of testing the robustness of

climate policies against different kinds of uncertainties and "surprises" (Clark, 1986).

In summing up, the Conventional Wisdom and biofuel scenarios illustrate the many cross impacts that can ensue from human-related driving forces. The Ocean Realignment scenario makes the same point about unexpected changes in natural driving forces. Both emphasize the importance of simulating as comprehensively as possible the complete chain of processes in the global society-biosphere-climate system, both in time and in space.

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# An Integrated Framework to Address Climate Change (ESCAPE) and Further Developments of the Global and Regional Climate Modules (MAGICC)*

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## Abstract

ESCAPE (the **E**valuation of **S**trategies to address **C**limate change by **A**dapting to and **P**reventing **E**missions) is an integrated climate change assessment model constructed between 1990 and 1992 for DGXI of the Commission of the European Community by a consortium of research institutes headed by the Climatic Research Unit (CRU). It has been designed to enable the user to generate future scenarios of greenhouse gas emissions (through an energy-economic model), examine their impact on global climate and sea level (through two independent global climate models), and illustrate some of the consequences of this global climate change at a regional scale for the European Community (through a regional climate scenario generator and impact models). We provide a very brief overview of the ESCAPE model which, although innovative, suffers from a number of major limitations. Subsequent work in the CRU has concentrated on improvements to the global climate module and work has also just commenced on an improved regional climate scenario generating module. These improvements will lead to a new integrated climate change assessment model, MAGICC (Model

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for the Assessment of Greenhouse gas Induced Climate Change) which can easily be incorporated into new larger integrated frameworks developed by other institutes.

# 1. Introduction

Predicting future global climate change requires an interdisciplinary perspective which encompasses the physical, social, and political sciences. Policy makers, charged both with identifying possible national response strategies to climate change and with negotiating international conventions and protocols, need tools which enable them to estimate the implications for climate and climate change impacts of a wide range of policy options and which can provide a concise overview of the uncertainties surrounding global climate change (Dowlatabadi and Morgan, 1993). A prototype tool has recently been developed for the Directorate General for Environment, Nuclear Safety and Consumer Protection (DGXI) of the Commission of the European Community. This model framework is called ESCAPE: the Evaluation of Strategies to address Climate change by Adapting to and Preventing Emissions. The model was developed over an 18 month period extending from November 1990 to May 1992, with contributions from over 15 institutions in Europe and North America and coordinated by the Climatic Research Unit at the University of East Anglia, UK. The interactive computerized framework allows one to explore the implications of different climate-related policies both for global-mean climate and for indicators of the economic and environmental impact of climate change within Europe. The model provides a clear assessment of the scientific uncertainties surrounding the prediction of future climate change and its impacts. ESCAPE is well documented; both a User Manual (CRU, 1992a) and a Scientific Description (CRU, 1992b) of the model are available on request. A paper summarizing the ESCAPE framework, including some illustrations of analyses undertaken with this model, has been prepared (Rotmans *et al.*, 1994).

ESCAPE represents a pioneering attempt to provide an integrated framework to address global climate change. A number of major limitations to the model are recognizable. This paper is divided into two parts. First, a very brief overview of ESCAPE is presented and some of the limitations of the model for the purpose of integrated assessments are identified. Second, we report on more recent developments undertaken within the Climatic Research Unit to improve the global and regional climate modules which, when taken together, are now referred to as MAGICC (Model for the

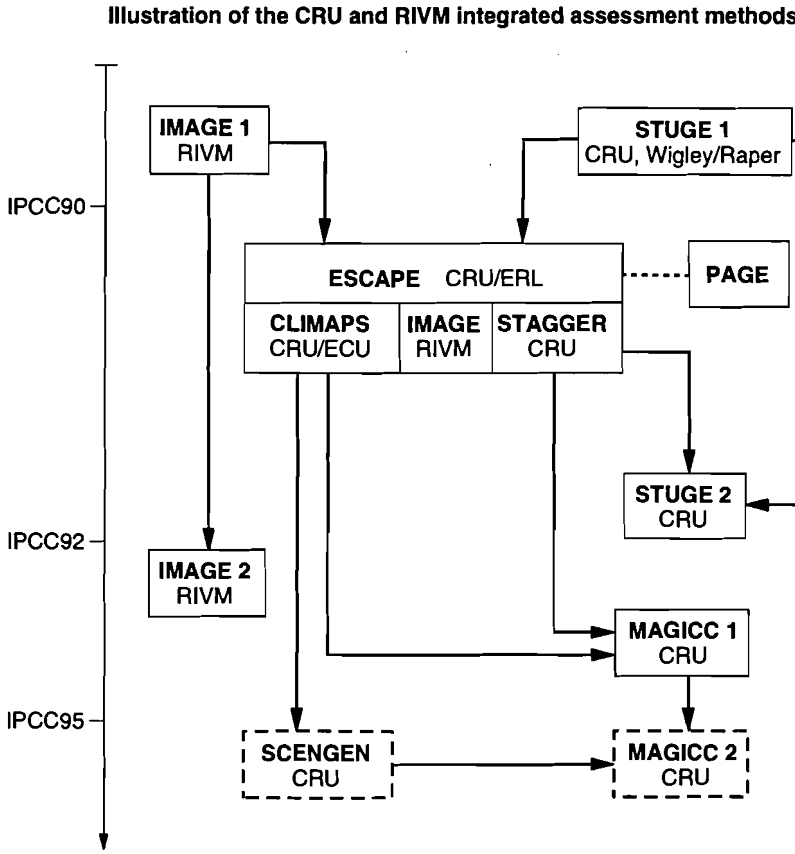


**Figure 1.** Schematic illustration of the evolution of the CRU and RIVM integrated assessment models. The models STUGE (Wigley *et al.*, 1991) and PAGE (Hope *et al.*, 1993) are not discussed in this paper.

Assessment of Greenhouse gas Induced Climate Change). The evolution of models which led to the creation of ESCAPE and MAGICC is summarized in Figure 1.

# 2. The ESCAPE Modeling Approach

## 2.1. Methodology

ESCAPE consists of a suite of linked models (modules) which enables scenarios of greenhouse gas emissions to be constructed and their impact on global and regional climate and sea level and sectors of the European economy to be assessed. Each module in turn consists of a number of coupled sub-models which are reformulated, simpler versions of more elaborate multi-dimensional models which have previously been constructed and described in the literature. In this way "state-of-the-art" science is captured within the ESCAPE framework. ESCAPE comprises four basic modules, which are shown in Figure 2:

- an emissions module. This module, called IMAGE-Emissions, consists of three sub-models: an energy-economics model, a land-use model and a halocarbon model, all developed by RIVM (the National Institute of Public Health and Environmental Protection) in the Netherlands;
- two integrated climate modules, called IMAGE (**I**ntegrated **M**odel to **A**ssess the **G**reenhouse **E**ffect) developed by RIVM, and STAGGER (**S**ea-level and **T**emperature changes **A**fter **G**reenhouse **G**as **E**missions **R**eductions) developed by CRU;
- a climate change impacts module, called CLIMAPS (**CL**imate change **I**mpact **MAP**ping **S**ystem) developed by CRU in conjunction with the Environmental Change Unit at the University of Oxford (ECU), with inputs from RIVM and a number of other institutes.

The four basic modules are linked, but not fully integrated. They differ in complexity, spatial resolution, aggregation level, time step, etc. The default time step for ESCAPE is five years and the projection period is 1990 to 2100. The model users can modify the projection period and the time step according to their own purposes.

The different levels of spatial aggregation in the modules results in an "hourglass" structure to the model. The front-end of ESCAPE, the IMAGE-Emissions module, calculates emissions for four major world regions: the EC, the rest of the OECD, former centrally planned countries of Europe and Asia (CPC), and the rest of the world (ROW). The core part of ESCAPE, the IMAGE and STAGGER climate modules, uses global emissions projections to calculate global-mean changes in atmospheric concentrations, temperature and sea level. The final module, CLIMAPS, assesses the impacts of climate change for Europe at a resolution of 0.5° latitude by 1.0° longitude.

## 2.2. Uncertainties

Predicting future global climate change and its consequences for human society is beset with many uncertainties. These uncertainties may be separated into "scientific uncertainties" (some of which may be narrowed as a result of

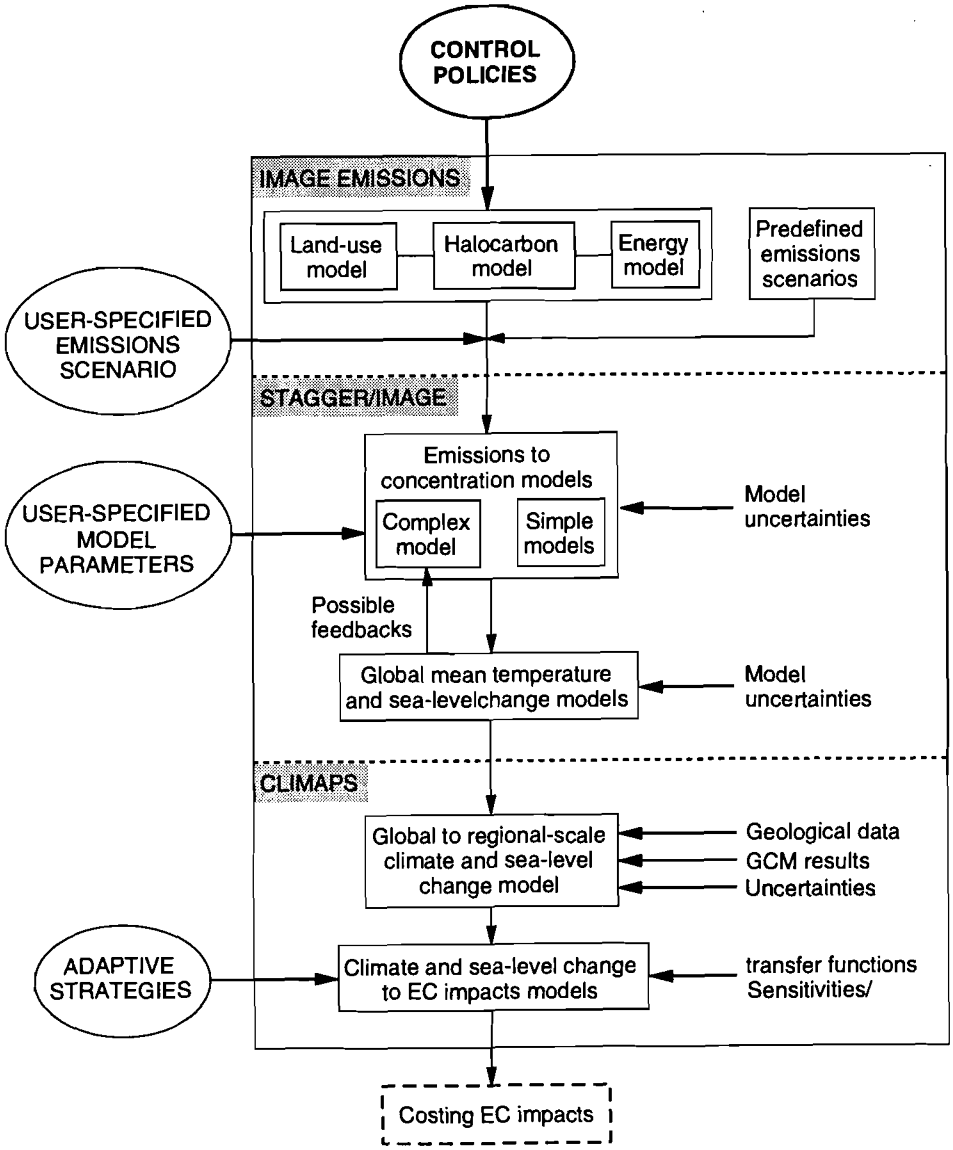


**Figure 2.** A schematic illustration of the framework of the ESCAPE model.

further scientific research) and "economic uncertainties" (those which result from future geo-political, socioeconomic, and demographic evolution and which are inherently "unknowable").

Scientific uncertainties include, for example, incomplete knowledge about the magnitude of the sources and sinks of the various greenhouse gases. For $CO_2$ emissions, the contribution from fossil fuel combustion is well known (with an uncertainty of about 5%), but emissions from land use changes remain poorly known (uncertainties in the order of 50%, Leggett et al., 1992). With respect to the oceanic and terrestrial carbon sinks, the likely errors are of the order of 100%. The only well known component of the global carbon budget is the past atmospheric concentration of carbon dioxide. The gas-cycle uncertainties with respect to methane are even larger (although, since methane is not the dominant greenhouse gas, these are not so important with regard to actual climate change). While the overall magnitude of global methane emissions is reasonably well-known, estimates of methane emissions from individual sources are highly uncertain (Rotmans *et al.*, 1992).

Another important source of uncertainty originates from our deficient knowledge of the key physiological, chemical, and biological processes within the climate system itself. Illustrative of this is the inadequate understanding of the many potential feedback responses to increasing atmospheric $CO_2$ and rising temperatures (Vloedbeld and Leemans, 1993). Feedback processes can either amplify (positive feedback) or damp (negative feedback) the response of the climate system to anthropogenic greenhouse gas emissions and can be separated into geophysical and biogeochemical feedbacks.

The former feedbacks (for example, those due to water vapor and sea-ice) are caused by physical processes in the atmosphere-ocean-cryosphere system which directly affect the response of climate to radiative forcing. These determine the value of the climate sensitivity (defined as the equilibrium warming of global-mean surface air temperature resulting from a doubling of $CO_2$ concentration) which is still poorly known (it probably ranges from 1.5 to 4.5°C). Reducing uncertainties in this parameter should have high priority, although the best strategy for achieving this is far from clear. The latter feedbacks (for example, the $CO_2$-fertilization feedback) may affect the concentrations of the greenhouse gases themselves and thus the radiative forcing, and may also alter the response of the climate system to any given radiative forcing. New biogeochemical feedbacks continue to be identified and/or quantified, as witnessed by the negative forcing roles played by stratospheric ozone and fossil fuel related emissions of sulphur dioxide (Isaksen *et al.*, 1992).

Despite these major gaps in our scientific knowledge of the response of the climate system to forcing, the most precarious scientific aspect of assessing the significance of global climate change is the estimation of its ecological and socioeconomic impact. In many cases, even the direction of the impact cannot be stated confidently (Tegart *et al.*, 1990). It is clear, therefore, that our knowledge of the phenomenon of climate change is far from complete. In view of these uncertainties, the interpretative and instructive value of an integrated model such as ESCAPE is far more important than its predictive capability, which is limited by the incomplete knowledge upon which it is constructed. The ESCAPE analysis was, however, the first major attempt to synthesize current scientific understanding of the causes and impacts of global climate change due to the enhanced greenhouse effect into one integrated framework.

## 2.3. Deficiencies and limitations of ESCAPE

The modeling framework of ESCAPE is a linked set of modules, rather than a single fully integrated model. Consequently, validation of the individual sub-models of ESCAPE is more important than an overall validation of the model. All the sub-models described here have been extensively tested and results from most of them have appeared in the scientific literature. Some of the outstanding limitations of the individual models are identified below.

Some limitations of the end-use energy model are:

- estimation of the income and price elasticities of energy demand is hampered by the lack of information;
- there are no interactions between the different regions – this would require a global trade model;
- the model contains an extremely simple supply model which neglects any coupling between demand related trends and response from the energy supply industry.

The land-use model within ESCAPE has a number of structural limitations:

- the present model is more a "book-keeping system" than a dynamic model, in the sense that most non-linear causalities are excluded. The problem, however, is that the basic mechanisms which form the driving forces behind land-use change differ from region to region;
- this version of the land-use model is based on GNP-demand functions which are derived from global cross-sectional data. This implies that results may not be valid for individual countries;
- developments in trade patterns are not included. Coupling the model to trade models would make it more realistic;

- relationships between per capita national income and consumption levels are extremely uncertain. For global projections, the functions used are valid, but for regional projections the functions are not adequate;
- as they have common sources, the land-use model should be fully coupled to the end-use energy model. The interrelations between the two models which need to be improved are the demand and production of firewood, the demand for ethanol, and the production of crops used for biofuel production.

With regard to the core climate modules IMAGE and STAGGER:

- the photochemical tropospheric modules of IMAGE and STAGGER are an oversimplification of complex reality. These modules should be further improved and validated against one-, two-, and three-dimensional photochemical models;
- more feedback processes should be incorporated. In addition, recent quantification of additional climate forcing mechanisms should be incorporated, such as the negative forcing effect of sulfate ($SO_2$-derived) aerosols and negative feedback due to stratospheric ozone depletion (Wigley and Raper, 1992). These effects are included in MAGICC.

With respect to the CLIMAPS module:

- the methodology to produce regional climate change patterns assumes that the spatial pattern of the enhanced greenhouse signal remains constant with time. This is somewhat uncertain, although it seems to be a reasonable assumption at least for much of Europe. Further examination of results from coupled ocean-atmosphere GCM experiments would be useful in this respect;
- the climate change impacts for the various economic and environment sectors are not translated into damage costs. This translation has, however, been attempted outside the ESCAPE modeling framework (ERL, 1992);
- the impacts on the sectors of the economy should be fed back to the energy and land-use sub-models in order to adjust the initial GDP assumptions. This linkage is missing.

Some of these limitations have been addressed in IMAGE 2 (which is a recently completed major revision by RIVM of the IMAGE 1 model) and through further developments which have been undertaken within the Climatic Research Unit (and which are now referred to as the MAGICC model). Other limitations represent more fundamental difficulties faced by all integrated modeling initiatives.

# 3. The MAGICC Modeling Approach

## 3.1. The global climate model

MAGICC (Model for the Assessment of Greenhouse gas Induced Climate Change) provides internally-consistent estimates of global-mean temperature and sea level change between 1990 and 2100 resulting from scenarios of anthropogenic emissions, viz. $CO_2$, $CH_4$, $N_2O$, the halocarbons, and $SO_2$. So that comparisons can be made, the user must specify two emissions scenarios. These are called the Reference scenario and the Policy scenario. The global-mean temperature projections may be used to scale General Circulation Model (GCM) results in order to produce regional scenarios of climate change in Europe (as in ESCAPE), or globally and for other regions (as in SCENGEN, see below).

MAGICC is an integrated model constructed of individual model components that are highly parameterized simple models which, nevertheless, capture the essential features of more complex models in the different fields of research. (Such models are often referred to as "reduced-form" models.) The integrated model is therefore computationally highly efficient, and takes only a few seconds to run on a personal computer. The model is designed to allow users to alter key model parameters in order to easily conduct sensitivity analyses.

One of the model components is an upwelling-diffusion climate model (Wigley and Raper, 1987) as used by the Intergovernmental Panel on Climate Change (Houghton *et al.*, 1990; referred to below as IPCC90). The sea level rise models are also updated versions of the models used by IPCC90 (which we developed in conjunction with Warrick and Oerlemans, 1990), with improvements described in Raper *et al.* (1994) and Wigley and Raper (1993). The projections made in the IPCC90 report have subsequently been updated by Wigley and Raper (1992) incorporating new scientific results and the new set of greenhouse gas (GHG) emission scenarios produced by the IPCC in 1992 (Leggett *et al.*, 1992). In order to do this, it was necessary to develop the gas-cycle models which are incorporated into MAGICC. These, and the other model components, are described briefly below.

A schematic representation of the integrated model is given in Figure 3. Specified GHG emission scenarios are first used as input to gas-cycle models to obtain estimates of future atmospheric concentrations. The concentration projections for the individual gases may be examined graphically during the interactive session.

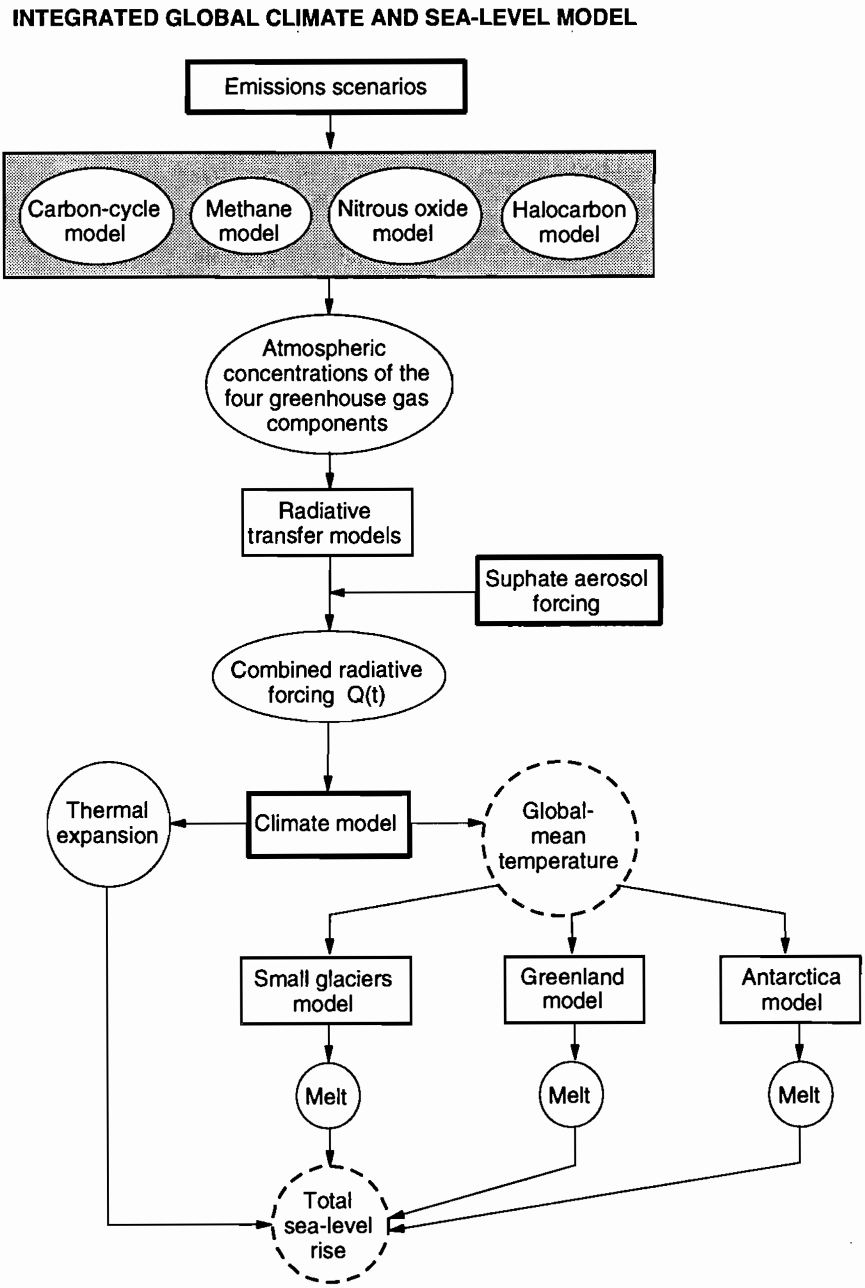


**Figure 3.** A schematic illustration of the global climate and sea level module of MAGICC.

The carbon cycle model (Wigley, 1993) is based on a convolution ocean model (Maier-Reimer and Hasselmann, 1987) that allows the efficiency of atmospheric-to-ocean gas exchange to be varied. The terrestrial component of the carbon cycle model incorporates a $CO_2$ fertilization feedback which enables the contemporary carbon budget to be altered to agree with observations and account for uncertainty in these observations (past emissions due to deforestation are particularly uncertain). The methane model (Osborn and Wigley, 1994) expresses the atmospheric lifetime of methane as a function of atmospheric composition. The effects of uncertainties in the present lifetime of methane and/or uncertainties in future lifetime changes may be explored. Also, the contribution to radiative forcing from stratospheric water vapor produced through the oxidation of methane may be included. The lifetime of nitrous oxide and the halocarbons can also be specified. Stratospheric ozone depletion feedback may be included. Default values for all these parameters are, however, provided.

A range of values for the negative forcing due to sulfate aerosols may be used to account for uncertainties in this factor. Because of the very short atmospheric lifetime of sulfate aerosols, the radiative forcing is expressed as a function of $SO_2$ emissions, so that a gas-cycle model is not needed. For all gases, except $SO_2$, the atmospheric concentrations resulting from the gas cycle models are converted to radiative forcing using radiative transfer model results following Shine *et al.* (1990). MAGICC allows the radiative forcing contributions of the various gases to be graphically compared.

The resulting total global-mean radiative forcing (partitioned by land/ocean and by hemisphere for the aerosol component) drives the upwelling-diffusion energy balance climate model. This model calculates hemispheric-mean vertical ocean temperature change profiles (40 levels from the surface to 4000 m) from 1765–2100. There are four model parameters which determine the rate at which heat is taken up by the ocean. However, the single most important parameter in determining uncertainty in future temperature and sea level is the climate sensitivity. The climate sensitivity may be defined as the equilibrium surface warming for a doubling of atmospheric carbon dioxide ($\Delta T_{2x}$). The IPCC best estimate of $\Delta T_{2x}$ is 2.5°C with a range of 1.5 to 4.5°C. MAGICC runs the climate model six times for each scenario. All three values of $\Delta T_{2x}$ are used with both best guess and user specified values for the other parameters. This generates a range of uncertainty for the temperature projections.

One of the contributing factors to future sea level rise is the thermal expansion of the ocean. Thermal expansion is calculated from the vertical ocean temperature change profiles predicted by the climate model. As with surface temperature, results depend on the climate model parameter settings.

The contribution of the melting of land ice to sea level rise is also considered. Greenland, Antarctica and other small glaciers are treated separately. The Greenland and Antarctic melt models are expressed simply as a sensitivity to temperature change. Uncertainties due to their pre-industrial state (were Greenland and Antarctica in equilibrium in 1765?) and to the regional temperature changes of Greenland and Antarctica relative to global-mean temperature changes can also be explored. A parameter for the possible increased discharge from the West Antarctic Ice Sheet is included. However, the default parameters for Antarctica give a negative contribution to sea level rise because increased accumulation is expected to dominate the other responses to increased temperatures over the next century. The small glacier model includes uncertainty in the initial (1765) ice volume and keeps track of the volume of ice available for melting. In the case of this model, the rate of melting is determined both by a temperature sensitivity parameter and by a collective glacier response time.

To express the large range of uncertainty in the sea level rise projections, high, medium, and low ice melt parameter settings are run with the high, medium, and low temperature projections (due to $\Delta T_{2x}$ uncertainty), respectively. Finally, a comprehensive set of results, both tabular and graphic, may be examined on screen or as hard copy.

To illustrate the use of MAGICC, Figures 4 to 7 and Table 1 result from choosing the central 1992 IPCC emissions scenario (IS92a) as the Reference Scenario and a Policy Scenario which assumes stabilization of global fossil $CO_2$ emissions at 1990 levels by 2000 (CO2STAB).[1] For simplicity, default parameter values are used throughout. However, a range of uncertainty is automatically explored by MAGICC. The resulting best guess temperature and sea level changes, from 1990 to 2100, are 2.47°C and 45.4 cm for IS92a and 1.42°C and 31.0 cm for CO2STAB.

The Climatic Research Unit is continually updating MAGICC. Recent changes to the carbon cycle model (Wigley, 1993) are to be added shortly. These will affect the temperature and sea level predictions. For example, for IS92a, the best guess 2100 atmospheric $CO_2$ concentration is revised downwards from about 740 ppmv to about 680 ppmv. Preliminary results indicate

[1]It should be noted that in this scenario no change was made to the $SO_2$ emissions. This is unrealistic since if $CO_2$ emissions were stabilized, then a reduction in $SO_2$ emissions would also occur. The net forcing of the CO2STAB scenario may therefore be slightly too small.

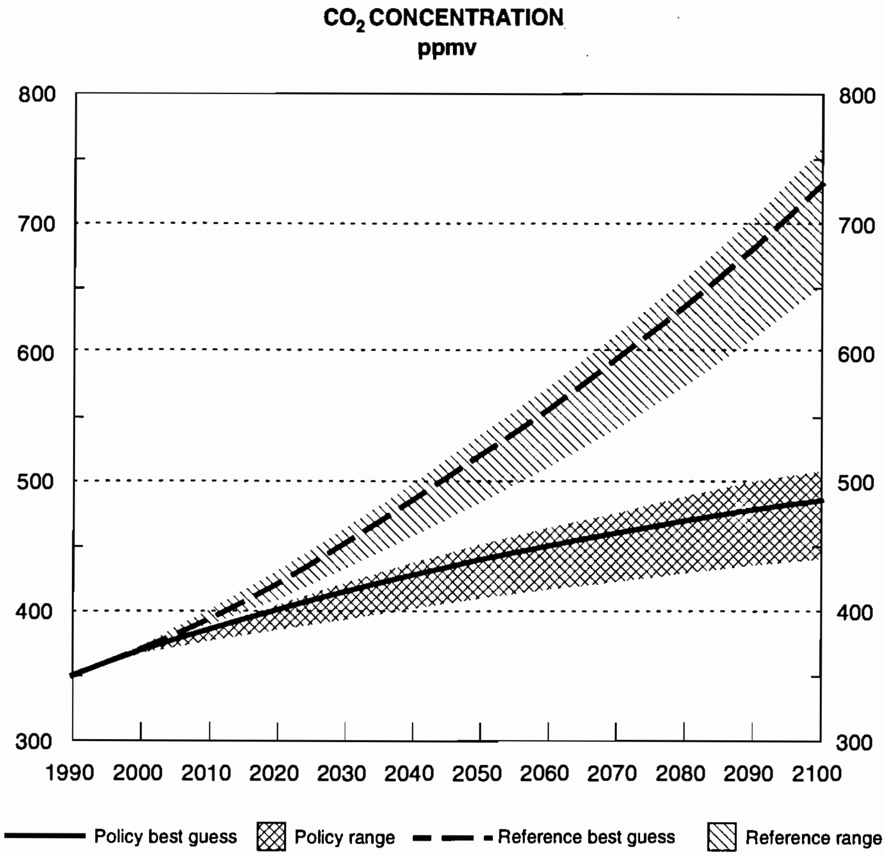


**Figure 4.** An example of output from MAGICC showing the global-mean atmospheric $CO_2$ concentration for the IS92a (Reference) and CO2STAB (Policy) emissions scenarios.

that there will be a decrease in the corresponding best guess temperature projection from 2.5°C to 2.1°C.

## 3.2. The regional climate change scenario generator (SCENGEN)

The current version of MAGICC uses CLIMAPS-Europe (Version 3.2a, January 1994) as its regional scenario generator and impact module. This is a slightly adapted version of the CLIMAPS module (Version 3.1, June 1992) used in ESCAPE Version 1.1a, and models only Europe. The regionalization algorithm in CLIMAPS is a development of that first proposed by Santer *et*

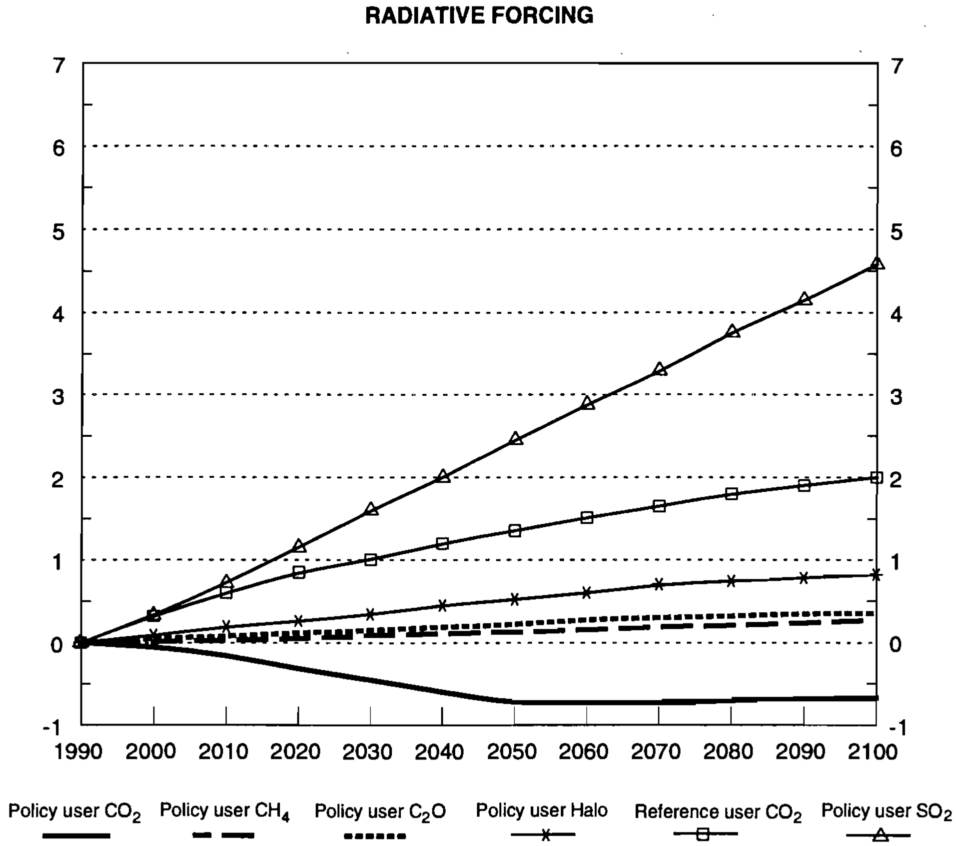


**Figure 5.** An example of output from MAGICC showing the radiative forcing in $Wm^{-2}$ for different gases for the IS92a (Reference) and CO2STAB (Policy) emissions scenarios.

*al.* (1990). Grid point changes in climate for a set of GCM experiments are first normalized by the GCM climate sensitivity (or some equivalent global-mean temperature change for transient results from coupled O/AGCMs) and then averaged to obtain composite patterns of monthly-mean changes of precipitation, temperature, etc., per °C of global-mean warming. These normalized patterns are then scaled up by the transient global-mean temperature change for any selected future year obtained from the upwelling-diffusion model. It is not possible to fully justify this procedure in the space available here, except to note that the composite model control climatologies

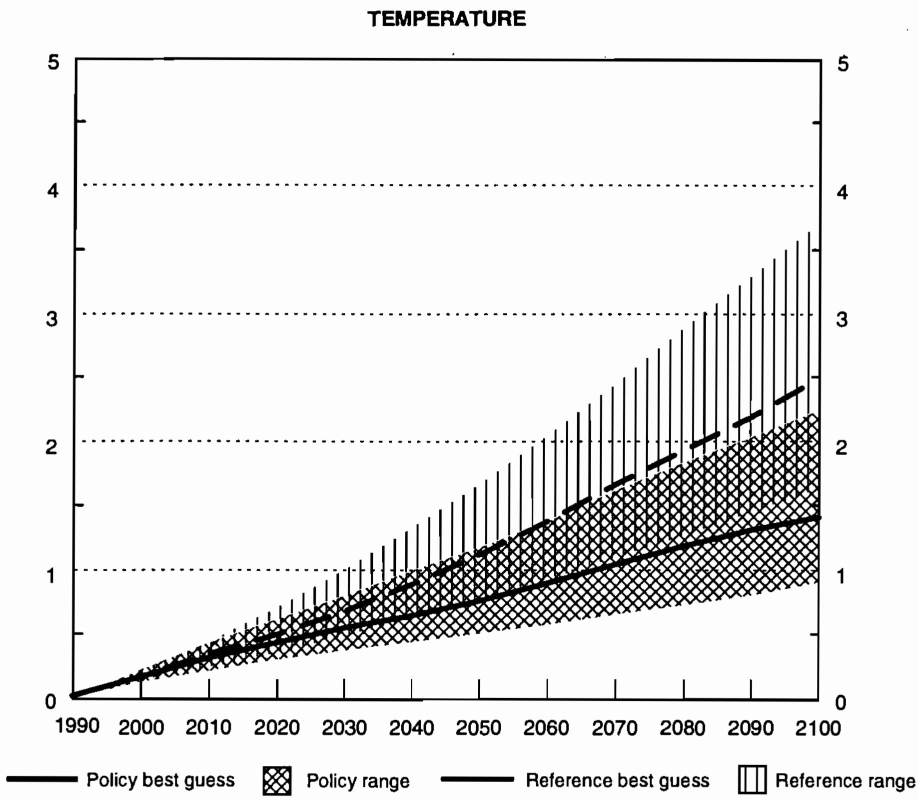


**Figure 6.** An example of output from MAGICC showing the global-mean temperature in °C for the IS92a (Reference) and CO2STAB (Policy) emissions scenarios.

obtained in this way validates better for global and regional precipitation patterns than any individual model used in the compositing.

Future versions of MAGICC will be able to be used in conjunction with SCENGEN, a new global and regional scenario generator which is currently under development in the Climatic Research Unit. It has been designed to allow the user full scope to generate global and regional scenarios of climate change based on a wide range of GCM experimental results of his/her own choosing. Options exist to select scenarios based either on single GCMs or on groups of GCMs. The scenarios may be presented simply as change fields for a given global-mean warming or else added to a baseline climatology to generate an actual future climatology. In Version 1.0 of SCENGEN, global scenarios at 5° resolution and regional scenarios for North America

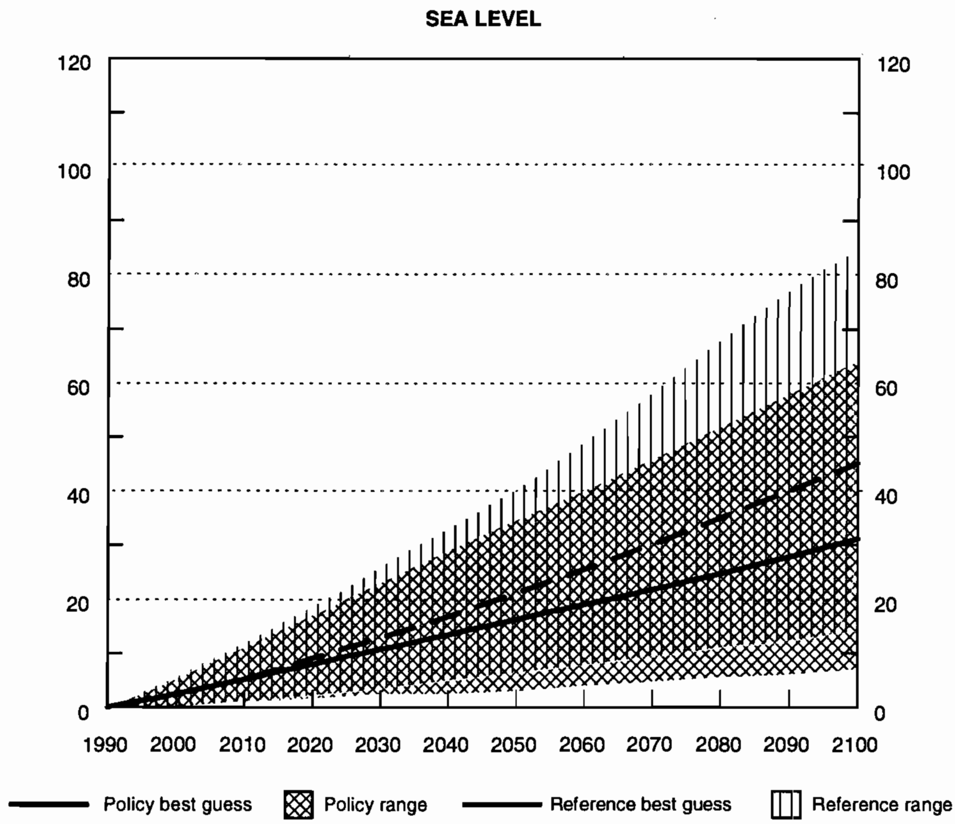


**Figure 7.** An example of output from MAGICC showing the global-mean sea level in cm for the IS92a (Reference) and CO2STAB (Policy) emissions scenarios.

at 1° resolution can be generated. Future versions will add high resolution windows for Europe, East Asia, and Australasia. Scenarios can be viewed on screen and then dumped as ASCII data files for input into other analyses.

As a stand-alone module, SCENGEN can be driven by only one global-mean temperature projection for which SCENGEN can produce a range of regional patterns reflecting inter-GCM differences in the spatial patterns of climate change. SCENGEN has been designed, however, to be used within MAGICC. The entire MAGICC framework will therefore offer the user complete flexibility about the choice of emissions scenario, a range of global-mean temperature projections and then a choice about the origin of the global or regional climate change scenario generated.

**Table 1.** Example model parameter settings for MAGICC.

Policy scenario: CO2STAB
Reference scenario: IS92A

Gas Cycle Parameters (default)

Carbon Cycle
    Model Mode: best guess with feedback
    Temperature feedbacks: none
    Methane Oxidation Term: included

Methane model
    Methane lifetime: best guess
    Temperature feedbacks: none

Nitrous Oxide and Halocarbons: default
    Ozone Feedback: off

Sulfate Forcing: medium

Climate Parameters (default)

| | |
|---|---|
| Sensitivity (deltaT2x): | 2.500 °C |
| Diffusivity (K): | 1.000 $cm^2$/sec |
| Mixed Layer Depth (h): | 90.000 m |
| Sinking Water DeltaT Factor (pi): | 0.200 |
| Upwelling Rate (W): | 4.000 m/yr |

Sea Level Parameters (default)

| | |
|---|---|
| Small Glacier Sensitivity: | 0.250 °C |
| Small Glacier Response Time: | 0.250 years |
| Greenland Sensitivity: | 0.030 cm/yr/°C |
| Antarctic B1: | -0.030 cm/yr/°C |
| Antarctic B2: | 0.010 cm/yr/°C |
| Antarctic Constant: | 0.000 |
| Initial Small Glacier Mass: | 50.000 cm (sea-level equivalent) |

Two spatial scales of display will be used, a global resolution of 5° latitude/longitude and a series of pre-defined regional windows at 1° latitude/longitude resolution. At a global scale, mean monthly, seasonal and annual precipitation and mean surface air temperature change fields at 5° resolution will be displayed. These change fields can be determined from a suite of eleven (currently) GCM experiments (eight equilibrium and three transient), either based on individual GCMs or on user-selected composites. The minimum number of GCMs for a model-composite scenario will be five. Mean global pattern correlation coefficients for precipitation will be displayed to guide the user's GCM selection and these coefficients will be used as weights in the resulting precipitation composite. Composite scenarios will also display a 90% confidence interval around the composite "central estimate" based on inter-GCM pattern differences (Santer *et al.*, 1990). The change fields can be added to a global baseline climatology to generate "actual" climatologies for future years. These global baselines will exist for land areas only and will be based on the period 1961–1990.

In Version 1.0 of SCENGEN, only a North American high resolution window will be active. Options will be identical as for the global fields above, except that a wider range of variables can be selected. In addition to mean temperature and precipitation, maximum and minimum temperature, mean 10m wind speed, total cloud amount, and specific humidity will be displayed. The GCM change fields are stored at 5° resolution. For high resolution windows, these will be interpolated down to 1° resolution. The baseline climatologies will be held at 1° resolution. For any displayed scenario, the user will be able to request an output file to be created under the Operating System which will contain the actual scenario data – these files can then be used an inputs for other analyses.

# 4. Conclusions

A number of integrated assessments of global climate change are now being undertaken and a variety of model tools exist which address the problem of global climate change. There are a large number of questions which need to be answered at the outset of an integrated assessment modeling exercise. Three of the more important ones are:

- how does one reconcile the sometimes competing requirements of scientific versus policy-oriented assessments? For example, a policy tool may need to be computationally very efficient to allow multiple experiments to be undertaken in the shortest possible time, whereas a scientific tool may well need to operate much slower owing to the need for greater detail to be modeled;
- how does one define the appropriate level of detail which should be modeled at each stage of the integrated framework? This might concern, for example, either the spatial scale of the assessment (globally lumped or regionally specific) or the degree of parameterization of the physical processes modeled;

- how does one address uncertainty in the assessment? Should uncertainties be concatenated or should "best estimate" rather than the full range of possible parameter values dominate the assessment, and how should the probabilities associated with different parameter values be defined?

There are no "right" answers to these questions. A diversity of approaches – and hence models and hence integrated assessments – is likely to be the most beneficial strategy to follow at the present time. In this paper we have discussed briefly one such integrated assessment model (ESCAPE) and have described recent developments concerning two components of the problem (global and regional climate change) that any integrated model needs to incorporate.

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# Scenario Analysis of Global Warming Using the Asian-Pacific Integrated Model (AIM)

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## Abstract

The Asian-Pacific Integrated Model (AIM) is a large-scale model for scenario analyses of greenhouse gas (GHG) emissions and the impacts of global warming in the Asian-Pacific region. The AIM comprises two main models – the AIM/emission model for predicting GHG emissions and the AIM/impact model for estimating the impacts of global warming – which are linked by the Global GHG Cycle and the Climate Change models. This paper categorizes the scenarios that have been written so far in relation to global warming, and then, given fixed inputs, simulates the effects of global warming taking into account various uncertainties. Next, several recent outcomes from the AIM/impact model are described. Assuming climate change scenarios deduced from AIM/emission and GCM experiments, primary impacts on water resources and natural vegetation are assessed.

## 1. Introduction

Many unresolved issues still surround the problem of global warming. Together with the uncertainties of natural processes such as carbon circulation, the influence of clouds, and heat uptake by the oceans, it is necessary to consider the many uncertainties of human activities such as population growth, economic development, and technological innovation. A range of synopses or scenarios need to be prepared and various possibilities considered for use in the process of policy development.

In the field of systems analysis, the term "scenario" was originally used to refer to descriptions of how situations would change when it is difficult to make quantitative estimates (Quade and Boucher, 1968). Scenarios came to be accepted as substitutes for numerical models. With the development of modeling technology, however, scenarios have become an important tool for linking model analyses to political decisions. Scenarios present important quantitative information such as input conditions and outputs of model simulations to policy makers in short and clear descriptions. They are an efficient method of communication between researchers and policy makers, and also have come to exert a significant influence on political decisions.

Over the past 20 years, a number of models have been applied to the field of global warming (Matsuoka *et al.*, 1992), and a great many scenarios have been prepared. Because global warming is such a long-range phenomenon that is complicated by many uncertainties, it is essential to examine several possibilities to help in the formulation of adequate policies.

This paper categorizes the scenarios that have been written so far in relation to global warming, and then, given fixed inputs, simulates the effects of global warming taking into account the various uncertainties. On the basis of these analyses, the uncertainties surrounding global warming and their political implications can be better understood.

## 2. Global Warming Scenarios to the Present-Day

There are five kinds of scenarios that are important in policy making when considering the adoption of measures to prevent global warming. First, *premise-based scenarios* assume how the fundamental factors that cause global warming, such as population, economic activity, and technology, will change. These scenarios are important for judging the levels of uncertainty of those phenomena and situations that require political action, and so will often form the basis for major policy decisions.

Second, *global warming (climate change) scenarios* assume the quantity of greenhouse gas (GHG) emissions, increases in their atmospheric concentrations and the kinds of climate change that might occur under the premise-based scenarios. The great problem here is how to deal with the uncertainties in natural mechanisms. How the scenarios change when these uncertainties are considered is an essential aspect of the development of policies to prevent global warming.

Third, *impact scenarios* assume the influences of climate change on the natural environment and socioeconomic systems. They describe the damage to human society caused by global warming and are used to show the need for, and equitability of, policies to prevent global warming.

Fourth, *policy scenarios* indicate appropriate times for the introduction of suitable policies to stem global warming at a particular level. They describe what policy makers should do.

Finally, *cost scenarios* give estimates of the increase in the socioeconomic load, such as macroeconomic impacts, if these policy scenarios are adopted. These scenarios are essential for judging the possible impacts of these policies.

Modelers have prepared many scenarios. This paper analyzes the possibility of global warming by examining published premise-based scenarios in detail. This analysis is then used as the basis for fixing the range of input conditions of our own simulations.

## 2.1. Population growth

Figure 1 presents world population estimates that have been calculated and used to date in scenario preparations. The dotted lines show the high estimates; solid lines show low estimates. If the 1990 world population of about 5.3 billion is taken as the reference point, estimates for 2100 range from 3.6 billion (World 3 model) to 109.4 billion (UN, 1992).

The extraordinarily high estimates of the UN (1992) were calculated assuming that the total fertility rate (TFR, the average number of children per woman) in the early twenty-first century would remain as it is now. Mesarovic's high level (the second highest estimate) was calculated assuming that the current rate of increase would continue in the future (Mesarovic and Pestel, 1974). These should be considered as merely calculated values, rather than reliable estimates. The scenario with a population of 3.6 billion in 2100 (World 3) was calculated by the Club of Rome and assumed that the death rate would increase because of environmental pollution. We consider this scenario to be extremely unlikely and reject it. Excluding these extremes, the estimates of population in the year 2100 range from 5.66 billion (Nordhaus and Yohe, 1983) to 19.16 billion (UN, 1992). The highest estimate was calculated using a cohort model that assumed the final value of the TFR was 2.5 and the lowest 1.7.

These TFR values are equal to the respective reproductive rates in Japan in the periods 1947–1950 and 1975–1985, and so seem quite possible in the future. Using the higher estimates, the world population would grow to 28 billion in 2150, but the likelihood of this is also questionable. Population policies that produce a decrease in population, such as the lower scenario, are likely to engender major social problems, such as those arising from an aging society. Such estimates are also considered to be infeasible. We therefore consider the practical range to extend from the 1990 estimates of the World Bank (1991) and Bulatao *et al.* (1990), which assumed that the TFR would become stable at 2.1 (population replacement) comparatively early, to

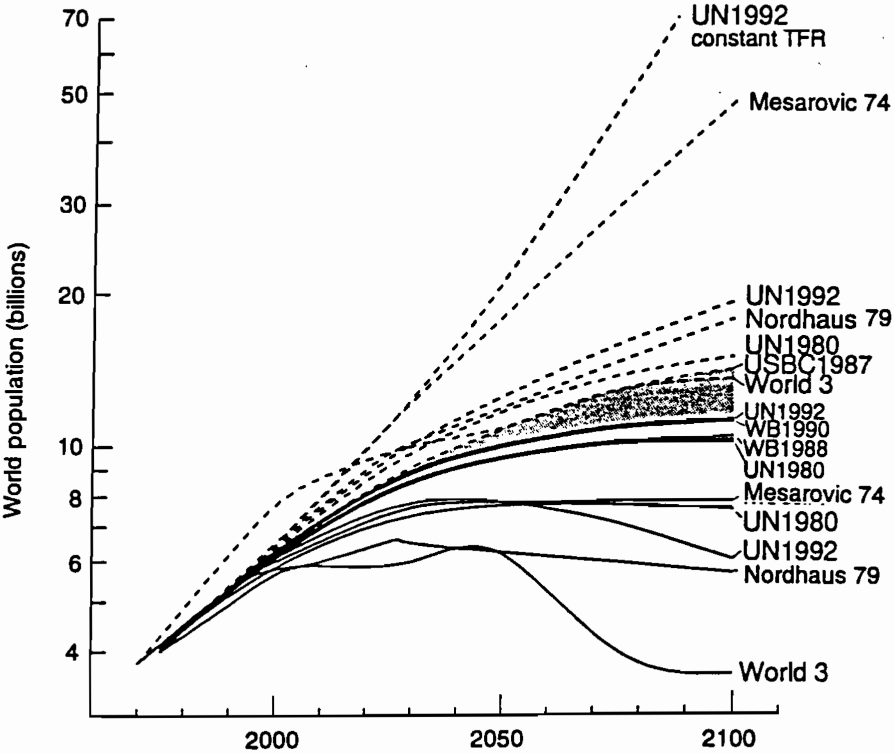


**Figure 1.** Future world population estimates. The dotted lines show high estimates, and solid lines show low estimates. The gray area is the range assumed in this paper.

the 1987 estimate of the U.S. Bureau of the Census (USBC), which assumed that time would be reached somewhat later. The values of both estimates are very close until the beginning of the next century, and then separate. WB (1991) assumed that the world's net reproduction rate, including developing countries, would become 1 by around 2040, while the USBC (1987) assumed this would occur in the century after next. WB (1991) estimates the population will be 11.3 billion in 2100, while the USBC (1987) estimates it to be 13.5 billion.

## 2.2. Economic growth

Figure 2 presents recent estimates of economic growth. In this figure, the dotted lines are per capita GDP values of the OECD nations, and the solid lines are those of Southeast-Asian nations excluding Japan. 90BAU is the

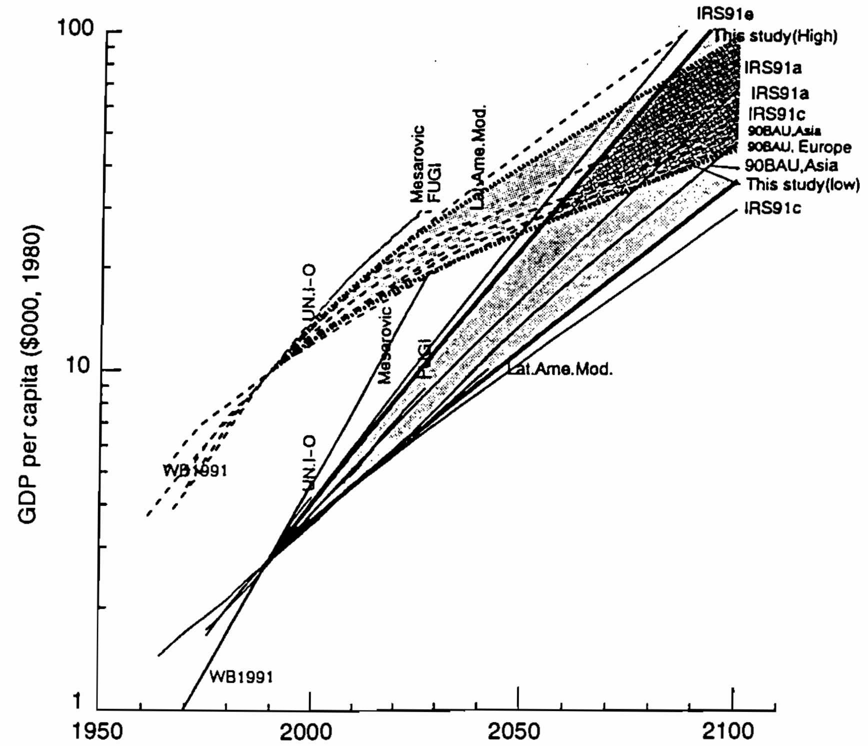


**Figure 2.** Forecasts of economic growth. Dotted lines are OECD countries; solid lines are Southeast-Asian countries excluding Japan. The shaded area denotes the range assumed in this paper.

"Business-As-Usual" case set by the Intergovernmental Panel on Climate Change (IPCC) in its scenario published in 1990 (IPCC, 1990). IRS 91 is the estimate used by the IPCC in its 1991 reevaluation of emissions inventories, and is based on reports from individual nations. IRS91a is used as the standard scenario, which assumes that the rate of economic growth until the beginning of the next century will be 2.4% per year in OECD nations and 4.1% in developing nations. The world average is 2.9%, which is assumed to drop by 0.8 to 1.4% after this time. Other lines represent values calculated in other global models.

Estimated growth rates are higher in developing regions than in developed regions, but it is usually not assumed that developing regions (excluding Southeast Asia) will reach the level of developed regions by 2100. The shaded areas in Figure 2 cover the ±20% range of growth rates used by

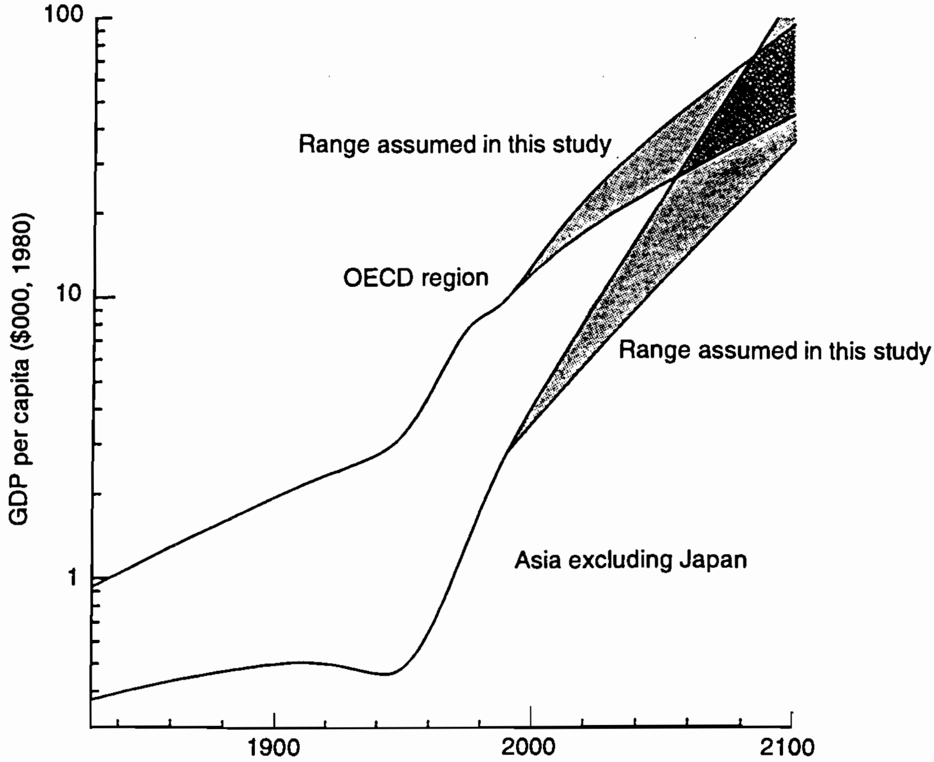


**Figure 3.** Trends of economic growth used in this paper. The shaded area denotes the range assumed in this paper.

IRS91a, and include most reported values. However, these values are a little lower than the World Bank's 1990 estimate of the future growth rate (World Bank, 1991). Figure 3 compares the calculated range with those previously proposed, and this range is also relatively low. Thus, it is generally assumed that the rapid economic growth of the late twentieth century will stabilize in the future.

## 2.3. The relationship between population growth and economic growth

In setting population growth and economic growth assumptions, their correlativity must be considered. A decrease in population growth rates in developing regions, especially fertility rates, increases the potential for saving and promotes the formation of capital. As a result, productivity can increase and economies develop. At present, countries in the South Asian

**Table 1.** Autonomous energy efficiency improvement (AEEI) values of typical recent energy models.

| Modelers | AEEI |
|---|---|
| *From global energy models* | |
| Edmonds *et al.* (1991) | 0.5–1.0% per year |
| Manne and Richels (1990) | 0.0–1.0% per year |
| Vouyoukas (1991) | 1.1% per year in OECD countries |
| Burniaux *et al.* (1991) | 1.0% per year |
| IPCC (1990)[a] | 0.16% per year in USA (Lower Growth Scenario) |
| | 0.46% per year in USA (Higher Growth Scenario) |
| *From feasibility studies of energy efficiency scenarios* | |
| Lovins *et al.* (1981)[a] | 1.12% per year in developed countries |
| | 1.53% per year in developing countries |
| Goldemberg *et al.* (1988)[a] | 2.85% per year in developed countries |
| | 1.40% per year in developing countries |

[a]Estimated.

region in particular are very interested in the impact of this mechanism for the formulation of development strategies, and are directing much effort into creating models and preparing scenarios (Bilsborrow, 1989).

## 2.4. Technological improvement

Table 1 presents autonomous energy efficiency improvement (AEEI) values of some typical recent energy models. Where there is no great attention paid to energy conservation, the annual rate is between 0 and 0.5%, whereas if large energy savings are assumed, this rises to 1.0%.

The implications of some normative energy conservation scenarios can be examined. For example, in the scenario of Lovins *et al.* (1981), between 1975 and 2080, the per capita consumption of primary energy is reduced to 22% in developed regions, and to 50% in developing regions. The scenario of Goldemberg *et al.* (1988) assumes that between 1980 and 2020, per capita energy consumption in developed regions is reduced to 50% and restricted to 110% in developing regions. When these numerical values are converted to annual rates using energy prices during the forecast periods, plus the growth rates of per capita GDP, values of about 1.1 to 2.9% are obtained.

In the Goldemberg scenario, the planning period is 40 years, which is comparatively short. Considering that it will be much more difficult to save energy after this period, it is assumed here that there is little hope for

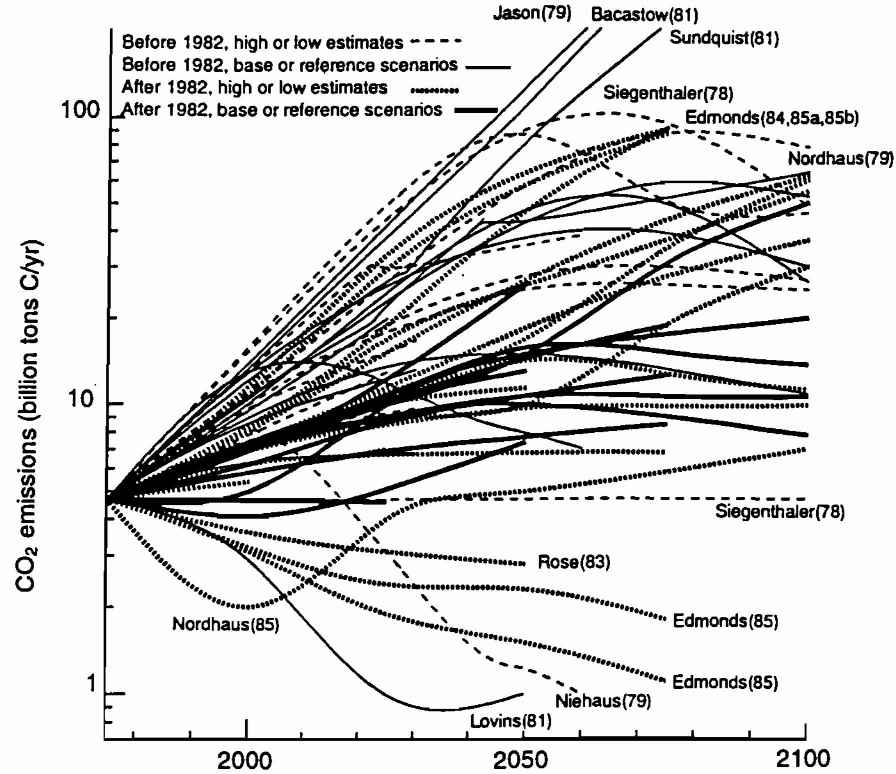


**Figure 4.** Forecasts of $CO_2$ emissions from fossil fuels reported before 1985.

maintaining a 2% annual rate over the long term. Accordingly, this value is excluded, and the annual AEEI rate is assumed to range between 0 and 1.5%. However, it is also recognized that energy savings will vary widely among different energy consumers and regions.

## 2.5. Emissions scenarios

Many quantitative estimates of $CO_2$ emissions from fossil fuel consumption have been prepared. Figure 4 shows estimates reported before 1985. For the year 2050, the lowest estimate is 1 billion t C/yr, while the highest is 100 billion t C/yr. The solid lines are the reference scenarios. Bold lines represent the values published between 1983 and 1985. It can be seen that the results calculated after 1983 are more consistent and lower than those calculated before that time. This is considered to be related to the increased awareness of energy conservation resulting from the second oil crisis of 1979–1980.

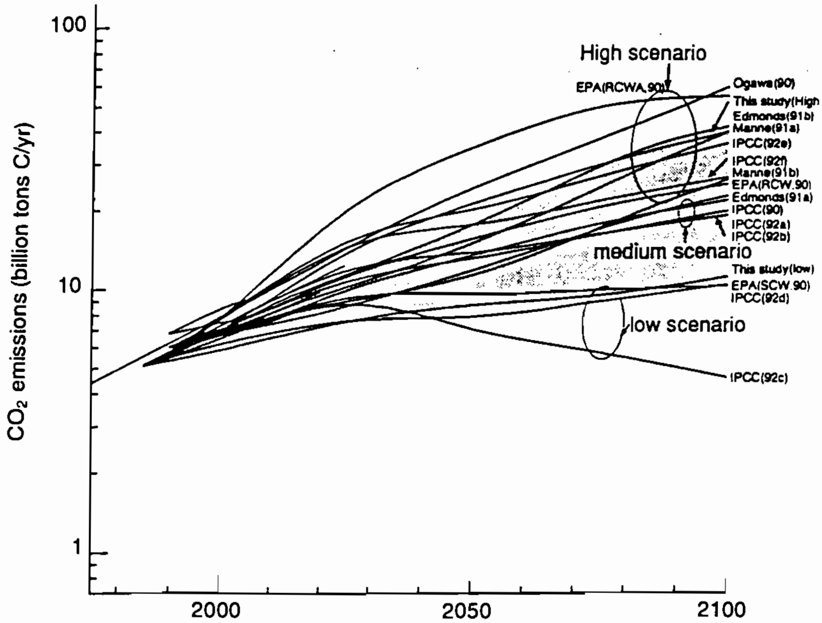


**Figure 5.** Recently reported forecasts of $CO_2$ emissions from fossil fuels. The shaded area denotes the range of calculations used in this paper.

Figure 5 presents more recent estimates of $CO_2$ emissions, which have become even more consistent. This is probably related to increased awareness and understanding of global warming problems. The shaded area in this figure shows the range between the high and low standard scenarios of our simulation estimates.

# 3. Establishing Basic Premises and Global Warming Scenarios

In Section 2, the range of premise-based scenarios of global warming was presented. In this chapter, the scenarios for this study will be presented and explained.

## 3.1. Ranges of socioeconomic assumptions

As our lower limit, we take the World Bank's (1991) population growth estimate that results in 11.3 billion people in the year 2100, and as our upper limit the scenario of the U.S. Bureau of the Census (USBC) that results in a world population of 13.5 billion in 2100. We use the economic growth scenario of Houghton *et al.* (1992), but include ±20% variations in the growth rate as the higher and lower limits, respectively. Thus we assume that the growth rates of the developed countries during the remainder of this century will be between 2 and 3%.

For our AEEI values, we take the energy demand used as the basis of Rapidly Changing World (RCM) scenario of the U.S. Environmental Protection Agency (Lashof and Tirpak, 1990) to be the high efficiency scenario, while our low efficiency scenario is the energy demand used in its Slowly Changing World (SCW) scenario. These end-use energy consumption figures were calculated by Mintzer (1988, developed regions) and Sathaye *et al.* (1987, developing regions), so the AEEI values were calculated back from these figures.

This model considers ten kinds of ozone-depleting gases, such as CFCs and halons, that contribute to the greenhouse effect. We assume that 100% of all developed countries and 85% of all developing countries will reduce their production of nine of these (including CFC-11 and CFC-12), as in the schedule agreed under the Montreal Protocol at the Second Ministerial Conference on the Ozone Layer (London, June 1990). The substitute product HCFC-22 was also considered in the scenario modeling. In 1992, however, it was decided to phase out its use. Our scenario was prepared before this time, and on the basis of consumption estimates from UNEP and others we assumed that its concentration in the atmosphere would increase by 4%/year for the remainder of this century, by 2.5%/year until the middle of the next century, after which time it would remain constant.

The basic scenario for land-use transformation concentrates on deforestation, so we used the estimated land-use change scenario of Houghton (1990) that includes 16 Asian, 36 African and 23 Latin American countries and is based on population growth. The present rate of forest destruction increases exponentially and is assumed to reach 34 million ha/yr by the middle of the next century; tropical forests are assumed to have almost totally disappeared by the end of the next century.

Emissions of methane from landfill waste, $CO_2$ from cement manufacture, and various greenhouse gases from agricultural activities are estimated on the basis of population growth and increases in per capita GDP. No limiting factors are assumed.

### 3.2. Ranges of natural environmental assumptions

To create the global warming mechanism scenario, we integrate climate sensitivity with all the feedback mechanisms.

The nature and future trends of the "missing sink" are unknown, so we assume three scenarios that reflect these uncertainties. Scenario 1 assumes that during the forecast period the size of the sink is fixed at the value for 1985 (1.43 billion t C/yr). This is used as the standard. Scenario 2 assumes that the sink increases in proportion to atmospheric $CO_2$ concentrations. This assumes the operation of some kind of negative feedback. Scenario 3 adopts a pessimistic position and assumes a 2% annual reduction. The standard climate sensitivity is assumed to be 3°C with high and low sensitivities of 4°C and 2°C, respectively.

We have identified five options for feedback mechanisms. The first option is the fertilization effect of $CO_2$, which is a negative feedback. The amount of $CO_2$ that is absorbed by plants is observed to be in direct proportion to atmospheric concentrations, which equals 90 billion t C in the case of a doubling of $CO_2$ (an increase of 280 ppmv). The second feedback mechanism caused by the rise in temperature is the impact of the release of carbon stored in terrestrial ecosystems. The estimated range is quite wide, but we assume it to be 0.5 billion t C/(year °C). The third process is the increase in $CH_4$ emissions caused by increased level of biological activity of organisms in the soil resulting from the rise in temperature. We assume it to be 200 million t $CH_4$/(year °C). The fourth mechanism is the effect of the destabilization of methane hydrates caused by the rise in temperature. Although there are many uncertainties surrounding this process, we use 0.11 billion t $CH_4$/(year °C), which is half the current value, as reported by Lashof and Tirpak (1990).

The fifth feedback mechanism relates to the functioning of the oceans. We assume that if the surface temperature of the oceans compared to that before the Industrial Revolution increases beyond a certain level – in this case 2°C – there will be significant changes in ocean circulation patterns resulting in the shutdown of the oceanic $CO_2$ and heat sinks. This possibility cannot be excluded, although its reliability is low compared with those of the other mechanisms mentioned above.

### 3.3. Simulation cases

The integration of these scenarios and options will be examined to establish our simulation cases. The standard cases are developed by integrating population, economic growth, and AEEI values. Measures to restrict greenhouse gases are not included.

(1) High Standard Scenario: High Population Scenario (assumed by the U.S. Bureau of the Census (1987): 13.5 billion in 2100), plus High Economic Growth (IRS91a, growth rate +20%), plus Low Efficiency Scenario.

(2) Low Standard Scenario: Low Population Scenario (assumed by the World Bank (1991): 11.3 billion in 2100), plus Low Economic Growth (IRS91a, growth rate -20%), plus High Efficiency Scenario.

We also assume that $CO_2$ emissions are reduced and stabilized by the introduction of a carbon tax as one measure to limit global warming. In the emissions stabilization scenario, we assume a carbon tax that will halt the increase in emissions after 1990. The tax rate is assumed to be equal throughout the world. The rate depends greatly on the premise-based scenario. We calculate high and low tax rates that correspond to the two standard case scenarios and the resultant macroeconomic impacts. For the emission reduction scenario, we assume a reduction of 1%/year, with stabilization of atmospheric $CO_2$ concentrations by the end of the next century as a rough goal. The reference year is 1990. We also calculate two tax rates corresponding to the two scenarios of the standard case and the locus of the macroeconomic impacts over time.

To incorporate the effects of the missing sink and feedbacks fairly simply, we add the following allowances to the high and low standard cases. First, to the high estimate, we add: a 2% annual decline in the missing sink; positive feedback mechanisms – an increase in the rate of metabolism of terrestrial ecosystems, an increase in methane emissions from wetlands and increased destabilization of methane hydrates; and a change in ocean circulation patterns. To the low estimate, we add: a proportional increase in the missing sink as the atmospheric $CO_2$ concentration increases; and a negative feedback mechanism – the fertilization effect of $CO_2$.

# 4. Simulations Using the Asian-Pacific Integrated Model (AIM)

## 4.1. Summary of the models

In this examination we used the simulation model, Asian-Pacific Integrated Model (AIM). This model is being developed mainly to examine global warming response measures in the Asian-Pacific region, but it is linked to a World Model so that it is possible to make global estimates. The World Model is based on the Atmospheric Stabilization Framework (ASF) developed by U.S. EPA, while several submodels and input data have been added, replaced, or renewed (Matsuoka, 1992).

The AIM comprises four discrete but linked models: two main models – the GHG emission model (AIM/emission) and the global warming impact model (AIM/impact) – which are linked by two global physical models, the GHG cycle model and the climate change models. Figure 6 shows the relationships between these models. At present, three models have been completed: the global consistency and ROW model, the global GHG cycle model, and the global mean climate change model. Work is still in progress on the development of the AIM/emission and the AIM/impact models.

The AIM/emission model consists of Asian-Pacific country models integrated into a regional model. This in turn is linked to a Rest of the World (ROW) model (with six regions), which ensures that the interactions between these regional models are consistent. A variety of global and regional assumptions about such factors as population, economic trends, as well as government policies, are then entered into the model and interact with the regional and country models to provide estimates of energy consumption, land-use changes, etc., which ultimately provide predictions of GHG emissions.

In each country model, energy demand is calculated by multiplying the energy service (calculated by the Energy Service submodule) by an energy efficiency factor. This factor is calculated by the Energy Efficiency submodule, and is the product of assumptions made about the introduction of new technologies for energy conservation as influenced by energy prices. The Technology Selection submodule decides which technologies will be introduced.

When the AIM/emission model is finally completed, its outputs will be entered into the global GHG cycle model which will provide a variety of scenarios used in GCM experiments. Data from the GCM experiments will

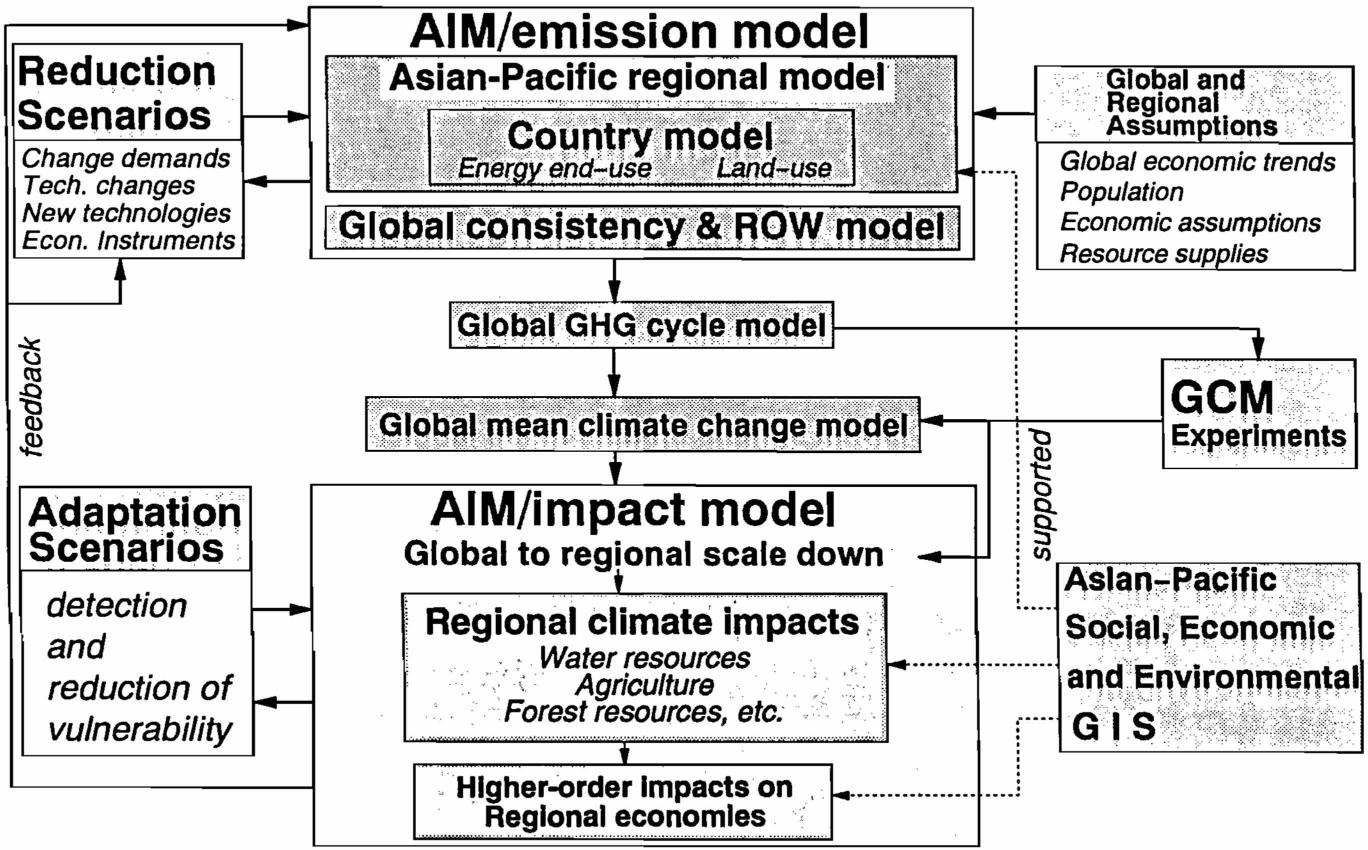


**Figure 6.** A summary of the Asian-Pacific Integrated Model (AIM).

be used as the basic assumptions for the AIM/impact model, and will reflect estimates of regional climatic impacts. The AIM/impact model will then calculate the impact on primary production (water supply, agricultural production, wood supplies, etc.), and will make predictions of higher-order impacts on the regional economy. To function properly, these models require a high-quality spatial database; we are currently developing an Asian-Pacific environmental, social, and economic geographical information system (GIS) in cooperation with the Center for Global Environmental Research, Japan. This GIS system has a spatial segmentation at the subcountry level. Information obtained from many international organizations, including the UNEP/GRID system, as well as individual governments, is integrated with our originally constructed data, and is then organized into a format that can be used by the AIM study. We are also planning to distribute the system via the UNEP/GRID system in Tsukuba in the near future.

When fully developed, the AIM will allow us to analyze the regional scenarios of GHG emissions, and to predict the impacts of global warming over the Asian-Pacific region. Over the last year or so, we have used the finalized global components of the AIM model to analyze global GHG emission scenarios and to predict global climatic changes. We have analyzed the uncertainties in both natural and socioeconomic systems, as well as the ranges of these uncertainties. The results are described in this paper, and show that even though the ranges of the uncertainties are large, the overall increase in global GHG emissions can be predicted, and, in fact, will be substantial.

## 4.2. Simulation results of global warming and policy scenarios

Assuming the above cases, we have estimated GHG emissions and temperature increases using the global component of the AIM (Morita *et al.*, 1993).

Figure 7 shows estimated $CO_2$ emissions from fossil fuel consumption using the above assumptions. Under the two standard scenarios, $CO_2$ emissions in 2025 are 1.4–2.4 times higher than in 1990, and those in 2100 are 2–7 times higher. As a result, emissions in 2100 reach 39.7 billion t C under the high standard scenario and 11.2 billion t C under the low scenario.

Figure 8 presents the tax rates required if a carbon tax were implemented to stabilize and to reduce emissions by 1% per year. The tax rate increases over time, and to stabilize emissions it would need to be \$180–440 per ton of carbon in 2025 and \$310–1,250 in 2100. The reduction in world GNP caused by the carbon tax is estimated to be between 1.5% and 2.8% in 2025 and 2.8% and 7.3% in 2100, as shown in Figure 9, if stabilization is to be

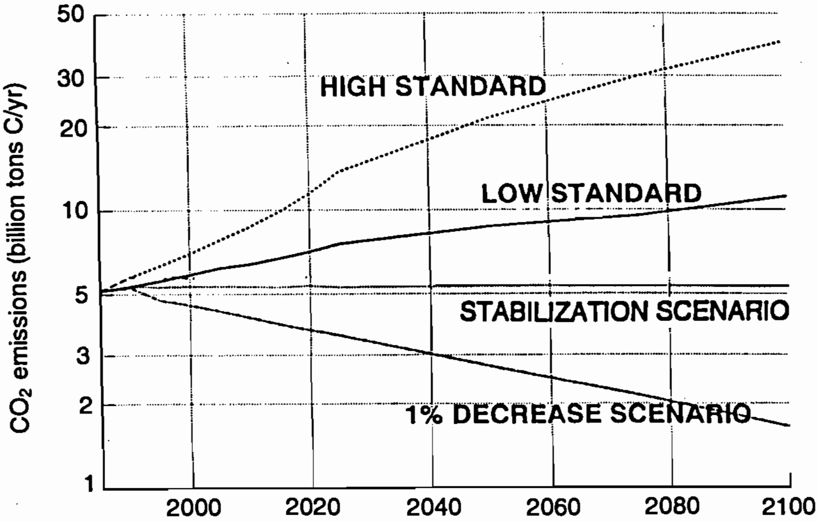


**Figure 7.** $CO_2$ emissions due to fossil fuel combustion.

achieved. It can be seen that the impacts on the world economy are not very large even under the high standard scenario and assuming that $CO_2$ emissions are stabilized by means of a carbon tax. However, stabilization of $CO_2$ emissions alone cannot prevent global warming. Much stricter responses need to be implemented. In the scenario that reduces emissions by 1% per annum, even with a carbon tax of more than $2,000 per ton of carbon by the end of the next century, the global temperature will continue to rise. These findings reinforce the view that comprehensive policy responses are needed, including long-term afforestation and substantial reductions in the costs of solar and biomass energy.

Figure 10 presents changes in GHG concentrations over time under the "business-as-usual" scenario. The dark shaded area denotes the range of uncertainties in the rates of economic growth, population growth and technological change. This figure also shows the range caused by uncertainties in the missing sink (MS), positive and negative feedback mechanisms, and the impact of oceanic $CO_2$ absorption. The range of the scenario becomes wider as these factors are added. The range of GHG concentrations, estimated as $CO_2$ equivalents, increases from 819–1,846 to 690–2,379 ppmv in the year 2100.

Similar changes can be seen in the range of temperature increases, as shown in Figure 11. The interesting feature here is the large influence of changes in ocean circulation. Figures 10 and 11 are based on a climate

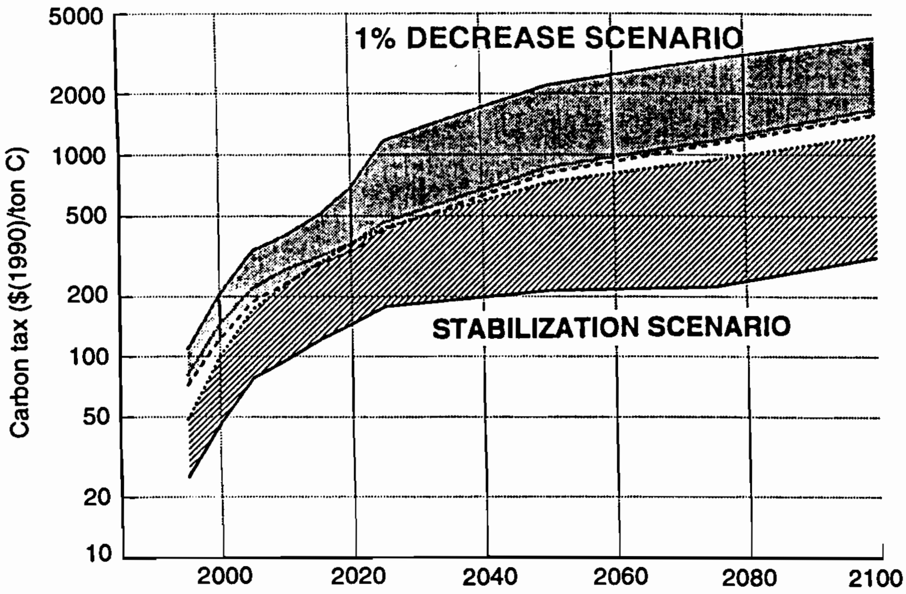


**Figure 8.** Changes in carbon tax rates. The shaded areas denote the ranges of the assumed scenarios.

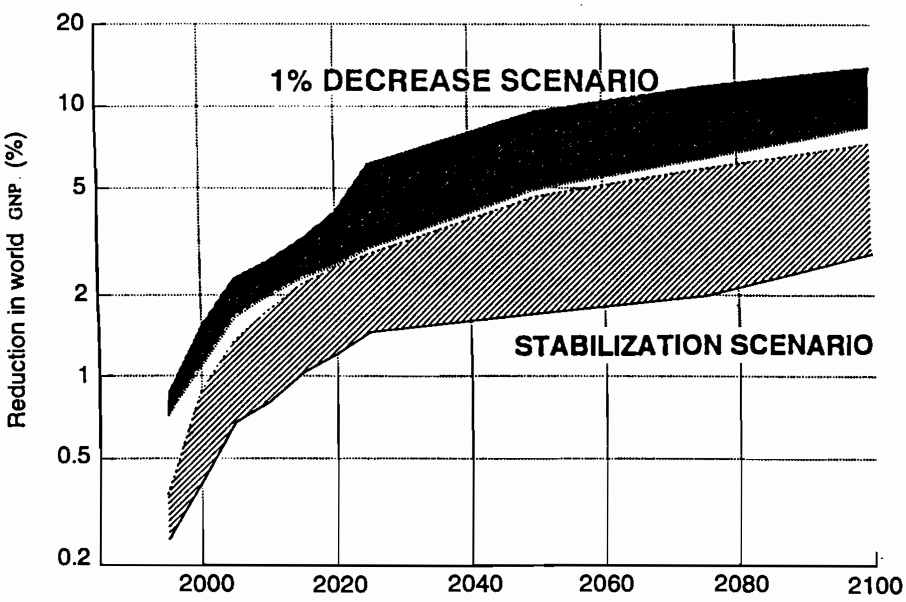


**Figure 9.** Reduction in the rates of world GNP. The shaded areas denote the ranges of difference between the assumed scenarios.

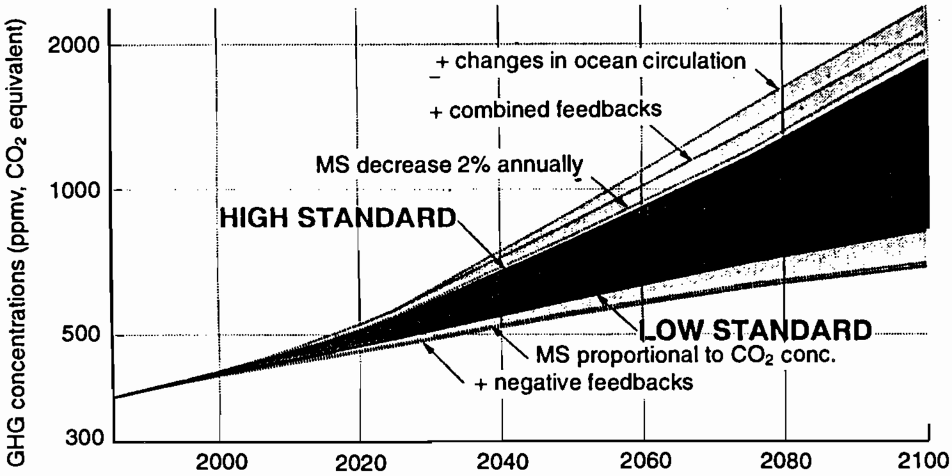


**Figure 10.** Changes in greenhouse gas concentrations with a climate sensitivity of 3°C. Business-as-usual scenario. Note: MS = missing sink.

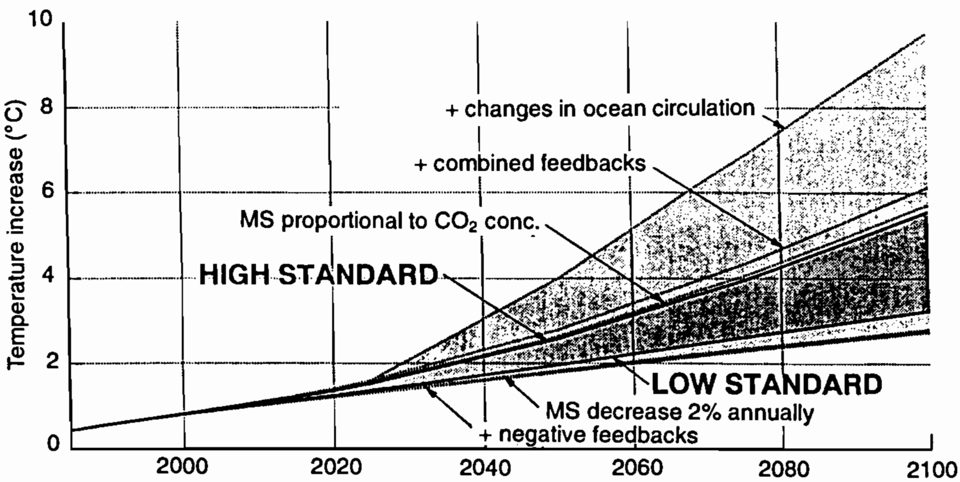


**Figure 11.** Temperature increase with a climate sensitivity of 3°C. Business-as-usual scenario.

sensitivity of 3°C, and Figure 12 illustrates the differences between the sensitivities of 2, 3, and 4°C. The highest and the lowest loci of all published cases are shown in this figure. The temperature increase would range from 1.5 to 10°C in 2080.

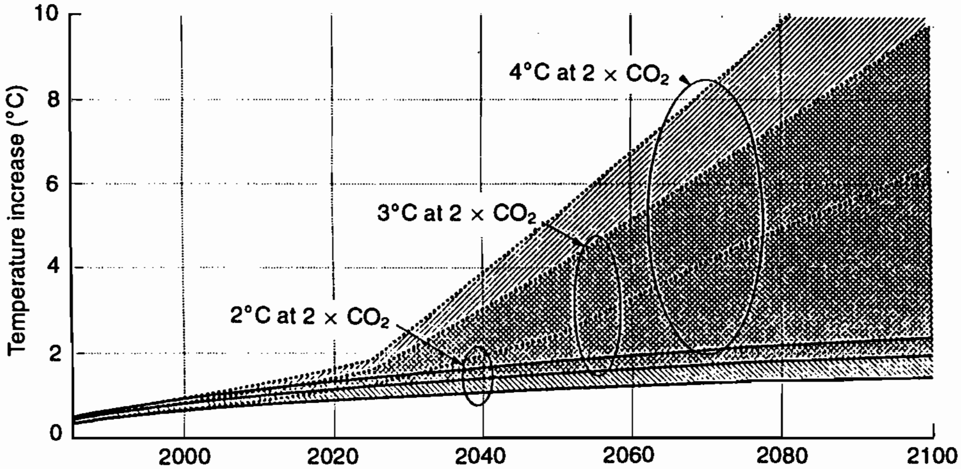


**Figure 12.** Temperature increase with climate sensitivities of 2–4°C. The standard, stabilization, and reduction by 1% per annum scenarios are shown.

Using the AIM/emission model, we have prepared preliminary estimates of regional GHG emissions for the year 2100. $CO_2$ emission intensities are shown in Figure 13, and when compared with the recent situation, the areas where major increases in $CO_2$ emissions will occur can be easily identified. They include Korea, China, Thailand, Malaysia, Indonesia, India, and Bangladesh.

## 4.3. Impact studies for the Asian-Pacific region

The other main component of the AIM is the AIM/impact model, which estimates the impacts of global warming in the Asian-Pacific region. This section of our work has not progressed far at this stage, but some preliminary modeling has been done.

We plan that the climate change scenarios to be used in AIM/impact will be mainly prepared by the Meteorological Research Institute (MRI) model of the Japan Meteorological Agency. The current MRI model is a coupled ocean–atmosphere model, and is expected to effectively simulate transient climate responses with a gradual increase in GHGs. As this experiment will be completed during the first half of 1994, we are performing preliminary impact studies using the results of general circulation model (GCM) experiments conducted at other institutions such as GISS (Goddard Institute for

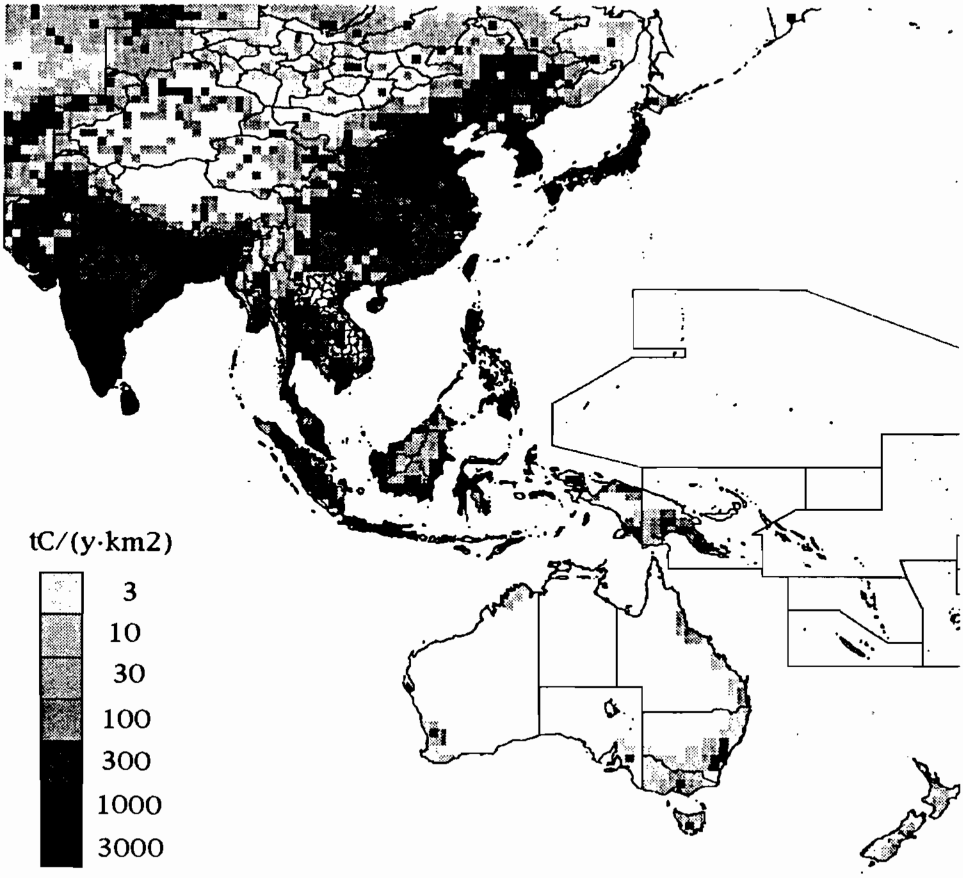


**Figure 13.** Estimates of $CO_2$ emission intensities in the Asian-Pacific region in the year 2100.

Space Studies), GFDL (Geophysical Fluid Dynamics Laboratory), and CCC (Canadian Climate Center).

In order to apply these GCM experiments, their outputs were normalized by dividing them by the difference between the global means of the equilibrium $2\times CO_2$ and $1\times CO_2$ experiments. This procedure eliminates the equilibrium sensitivities of different models, and also allows the normalized result to be applied to time-dependent scenarios of mean global warming produced by the AIM/emission model. These normalized patterns of climate change are basically prepared in the GCMs' spatial resolution, although they are subsequently interpolated to a finer grid in order to correspond with the regional impact models of each sector. As the subgrid interpolation of GCM outputs involves a number of problems, we are also intensively examining methods based on statistical relationships between broad-scale climatic data and small-scale observations from regional climate records.

Sectors on which the AIM/impact model has focused are water resources, vegetation, agriculture, and human health. Based on these primary impact estimates, we plan to estimate higher-order impacts on regional economies while taking into account the effects of international relations.

*Impacts on water resources*

Hydrological impacts are one of the most important aspects of future climate change. Changes in the magnitude, frequency, and duration of hydrological factors will influence the availability of water resources, flooding intensity, as well as agricultural and natural terrestrial ecosystems. A rainfall–runoff process submodel has been developed as one of the basic submodules of the AIM/impact model. This submodule consists of water balance and water transport components, and is intended to provide critical hydrological information to the impact models of other sectors. Specifically, it creates high-resolution datasets of surface runoff, soil moisture, evapotranspiration, and river discharges.

The inputs to the hydrological model are topography, soils, vegetation, as well as precipitation, temperature, and potential evapotranspiration. These last three parameters are endogenous variables of the total AIM system. Since the coupling of the total model system is not yet complete, we fixed soils, vegetation as well as topographical conditions to current situations.

The water balance component of the model is based primarily on the models of Thornthwaite and Mather (1955) and their successors. The water balance among precipitation, snowmelt, evapotranspiration, and streamflow is calculated for each grid cell in the simulated region. A number of climatological and geographical datasets were prepared from various sources; for example, precipitation and temperature data were taken from the interpolated results of a GCM experiment by the Geophysical Fluid Dynamics Laboratory (GFDL). Soil moisture capacities were estimated using current vegetation classes and soil textures (Vorosmarty *et al.*, 1989; Webb and Rosenzweig, 1993).

In the water transport component, the network topology of streams was determined from digital elevation data and modified with various hydrological maps of the analyzed regions. Modeling of surface water retention time in each cell followed the model of Vorosmarty *et al.* (1989). Figure 14 is a

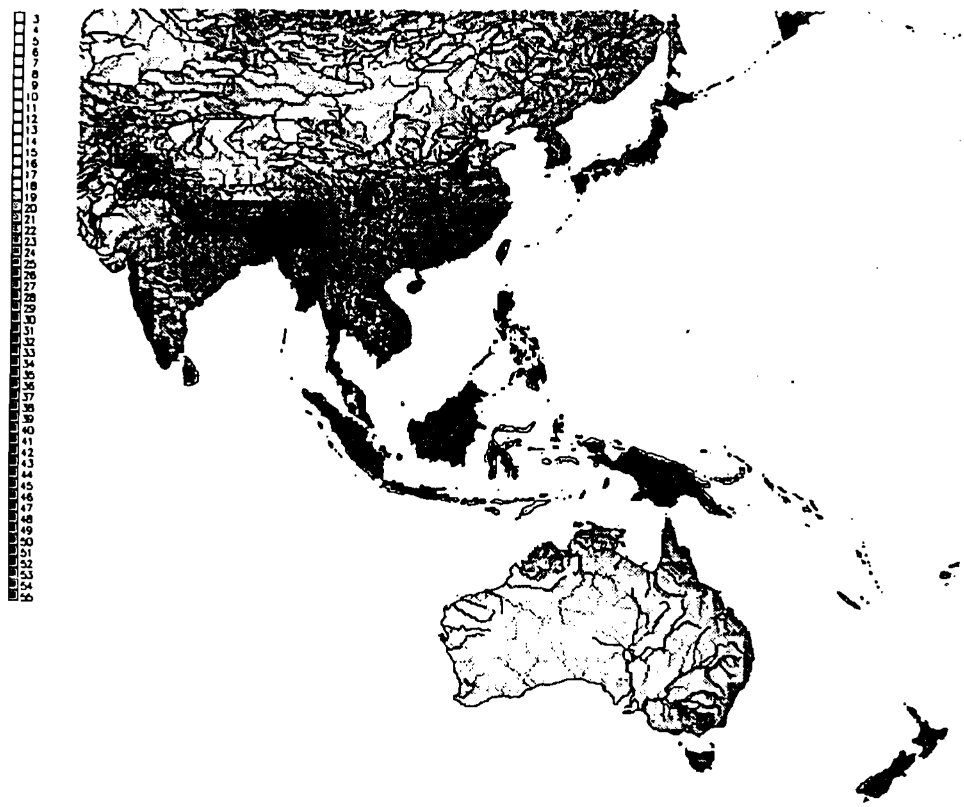

**Figure 14.** Estimates of current annual river flow intensity. Flow intensity refers to the mean surface water discharge transported downhill, divided by the unit work area (0.25° grid). The numbers in the legend are 10 log(flow intensity in mm/yr).

result of estimates the annually averaged accumulated runoff under current climate conditions. The calculation was conducted using 0.25° grid cells. Climatic data were taken from the monthly average datasets of Legates and Willmott (1989) with 0.5° resolution. The degree of shading in the figure expresses the intensity of discharge from one cell to the next downriver. Black indicates the areas of highest flow, and white those of lowest flow.

Using this model as the base condition, we then applied the outcomes of GCM experiments (the GFDL $Q$-flux experiment was used as the perturbed climate scenario), which provide precipitation, temperature, and soil

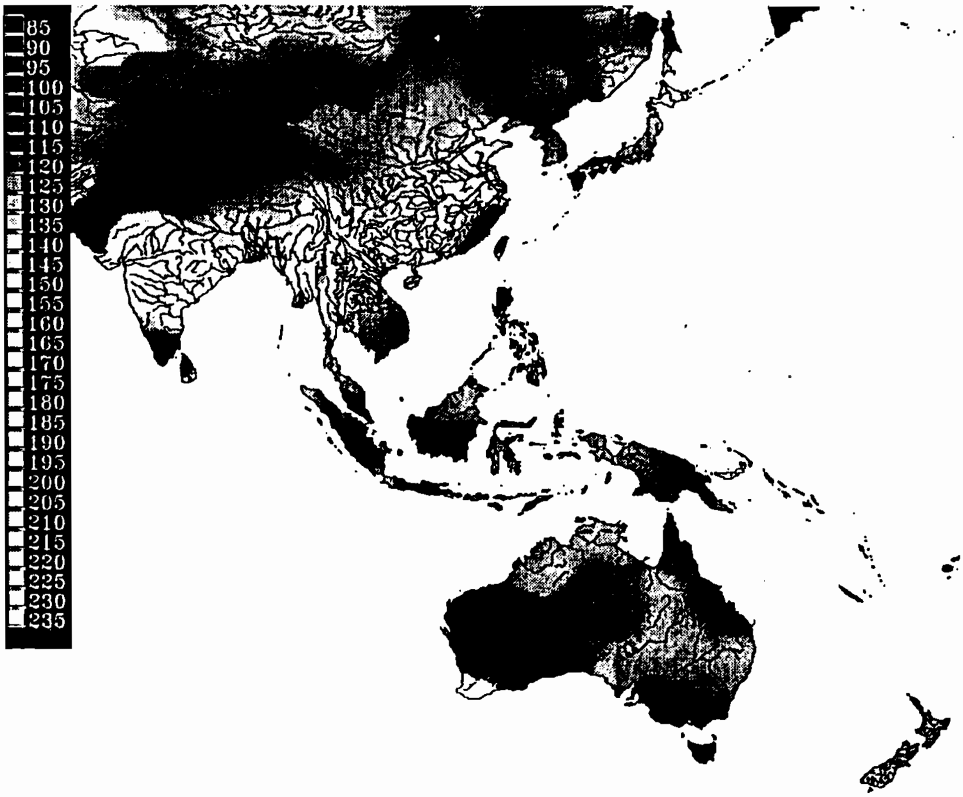


**Figure 15.** Predicted ratios of monthly high-flow discharges (% of $2\times CO_2/1\times CO_2$) over a ten-year return period. Based on the output of the GFDL climate model.

moisture data. These experiments were based on a future $CO_2$ level that is twice that of the pre-Industrial Revolution level. After interpolating the daily and monthly results of the GCM experiments, so that they could be overlaid with Legates' climatic pattern (which has a higher resolution than GCM outputs), these input conditions were used to prepare simulations of the variability in the water discharge of each river basin. These simulations were conducted for a ten-year period after a two-year initial simulation under each condition, and then the probability distributions of the monthly

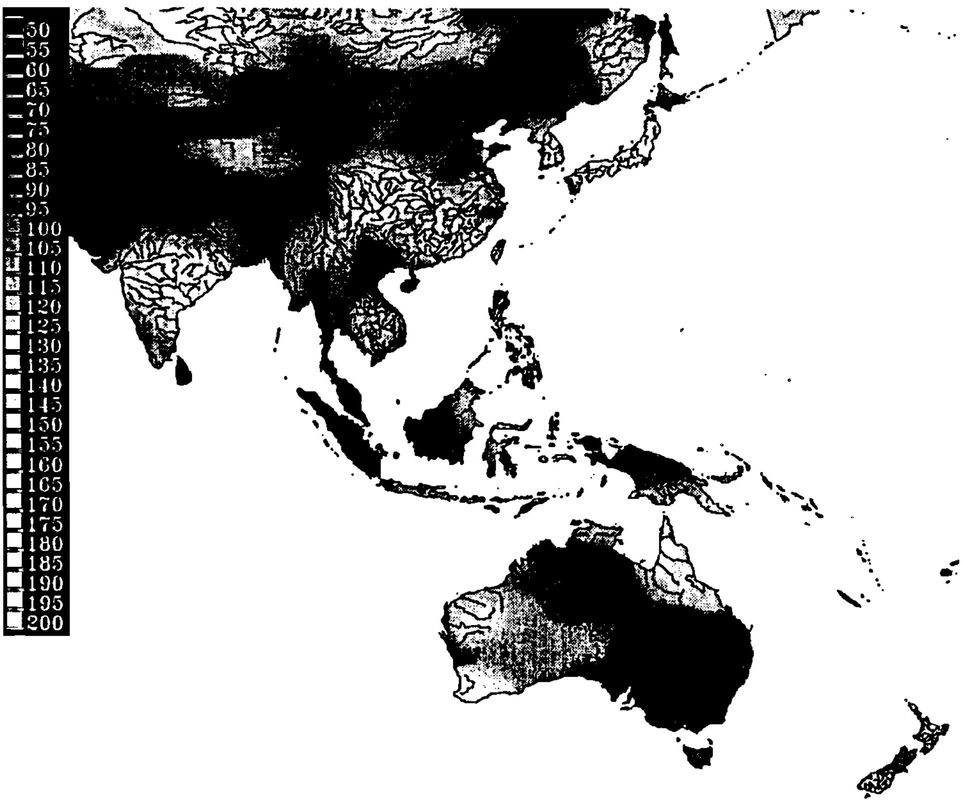


**Figure 16.** Predicted ratios of monthly low-flow discharges (% of $2\times CO_2/1\times CO_2$) over a ten-year return period. Based on the output of the GFDL $Q$-flux climate model.

simulated discharges were identified in each grid cell. Based on these distributions, we estimated flood and drought levels over a ten-year period under the $2\times CO_2$ condition.

Figure 15 shows the output of such a simulation for flood discharges. The light shading indicates the areas where the highest flow discharge levels for a ten-year return period may be expected to exceed twice the current level. Parts of India, China, and Japan could experience much higher levels of flooding. Figure 16 shows the changes in low-flow conditions over a ten-year period. The dark shading indicates the areas where the lowest flow levels could fall by 40 or 50%. As shown in the figure, large areas of the region are

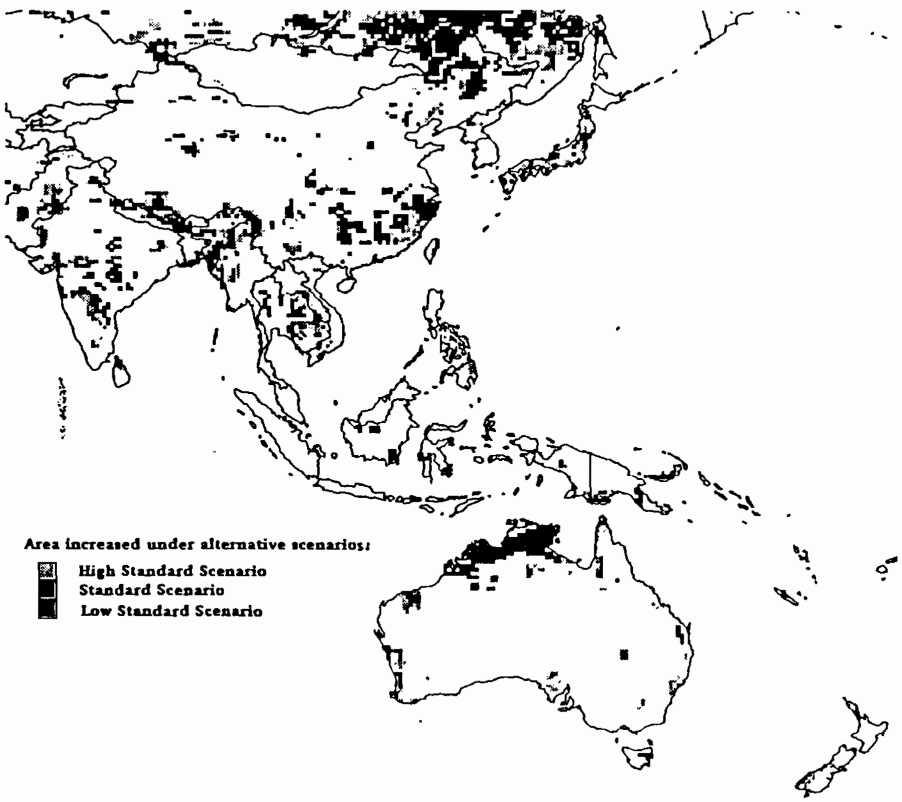


**Figure 17.** Potential changes in vegetation under various scenarios in the year 2100.

forecast to experience much drier conditions. The spatial pattern of influence was not sensitive to the selection of the return period. Intensification of flood discharges does not mean relief from drought, and in fact, an increase in the incidence of both events is anticipated for some regions.

In order to assess the direct impacts of hydrological changes from the human perspective, we have to consider the effect of water control and management devices, as well as the intensity and style of water consumption. So far, we have estimated only population-weighted average values of drought and flood intensities. Our model system is still too incomplete to comprehend the overall impacts of hydrological changes on human society. To clarify these impacts, we are now accumulating information on vulnerabilities to water-related factors at the regional and subcountry levels.

*Impacts on natural ecosystems*

The spatial distribution of natural vegetation is closely determined by climate. Future climate change is likely to have profound impacts on the distribution of vegetation patterns in the Asia-Pacific area. As a preliminary assessment of these impacts, we have established a simple model of global vegetation change caused by changes in related climatic elements. In this model, a vegetation type is assumed to change if any climatic element in its habitat exceeds the current global minimum or maximum level found in that vegetation habitat. As for the climatic elements, we used mean annual precipitation, mean annual temperature, coldest and hottest monthly temperatures, and degree-days above 5°C.

Figure 17 shows the potential changes in vegetation under the various scenarios of Figure 10, coupled with the results of the GFDL-R30 GCM experiment. Significant changes in northern China are observed, particularly in the boreal conifer forests and larch taiga. Tibetan and Himalayan alpine tundra would also be influenced. Evergreen–deciduous areas in southeast China, drought-deciduous forests in India, Indo-China, and Northern Australia would also be adversely affected by climate change. These changes should be considered as potential shifts under equilibrium assumptions, although the actual mechanisms of succession are far more complex and dynamic. For a preliminary analysis, the above method is useful, but we consider such a static model to be unsatisfactory and of limited use, so we are preparing dynamic population-based succession models.

## 5. Concluding Remarks

This paper has examined the issue of global warming, the uncertainties that surround it, and the prospects for limiting it, using simulation models to analyze various global warming scenarios. Our study is not yet complete, but the following tentative conclusions can be presented:

1. On the basis of current scientific knowledge and expectations of future economic development, it is extremely difficult to reject the global warming hypothesis. The range of uncertainties revealed here indicates that it is difficult to decide on suitable political options at this stage. The appropriate responses will be substantially different if the temperature

rises by 1.5°C or more than 5°C. Therefore, the basic foundations of policy development need to be prepared now. First, the wide range of political options that correspond to this range of uncertainties should be examined; second, efforts should continue to reduce the uncertainties; and third, measures should be adopted in preparation for the worst case scenario.

2. The main uncertainties in natural systems are climate sensitivity, the impacts of the oceans, and feedbacks. It is possible to reduce the level of these uncertainties through more research, but such research takes time, and even if it clarifies some issues, there will still be some phenomena that will not be clearly understood. As for socioeconomic factors, there are some for which the level of uncertainty can be reduced by population or economic policies, but it will be a long time before they have any noticeable effects.
3. Research on impact scenarios is lagging far behind that on global warming scenarios. This is because global warming scenarios themselves contain many uncertainties, and it is extremely difficult to estimate small changes in climate at regional levels. In this paper, some preliminary simulations have shown that parts of India, China, and Japan could experience much higher levels of flooding, and large areas of Southeast Asia and Australia are forecast to experience much drier conditions.
4. Integrating the above results, we can conclude that the best direction for policy development is to introduce preventive measures as soon as possible, beginning with those that will create the widest possible range of options for future generations, and those that will buy time to allow the degree and the range of uncertainties to be more accurately determined; and to examine the flexibility available within current socioeconomic systems as a precaution against the worst global warming scenario.

Finally, the problems that remain unresolved relating to this research should be described. First, although the premises and parameters used in this analysis have been based on the latest scientific knowledge and estimates of future conditions, the uncertainties related to solar variability, aerosols, and the introduction of innovative technology, such as non-carbon backstop technologies, have not been studied purely in order to limit the range of this analysis and to keep the logic simple. We are examining these issues separately. Also, even though it is necessary to consider the interrelationships between scenarios, such as population increases and economic growth when setting socioeconomic assumptions, here they were considered to be independent variables.

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# Part 3
# Cost and Benefit Studies

# The Economics of Stabilizing Atmospheric $CO_2$ Concentrations*

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## Abstract

This paper examines the economics of stabilizing atmospheric $CO_2$ concentrations. A particular concentrations target can be achieved in a variety of ways. It turns out that the choice of emissions time-path is as important as the concentrations level itself in determining the ultimate price-tag. Rather than choosing arbitrary emission trajectories, more attention needs to be devoted to identifying those paths that minimize the costs of achieving a specific target.

## 1. Introduction

The United Nations Framework Convention on Climate Change has as its ultimate objective the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." Under the terms of the Convention, the costs of the policies and measures for achieving the target are to be given little weight in establishing the level at which concentrations are to be stabilized. The level is to be based upon our understanding of the greenhouse effect and its potential consequences – not upon a balancing of benefits and costs.

Whereas economic considerations play little role in establishing the target, they play an important role in determining how the target is to be achieved. The Convention states that "policies and measures to deal with

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climate change should be cost-effective so as to ensure global benefits at the lowest possible cost." A particular concentrations target can be achieved in a variety of ways. Some will be more costly than others. Economic analysis is needed to identify emission paths that minimize the costs of achieving the desired concentrations level.

This paper addresses the issue of cost-effectiveness in the selection of an emissions time-path. The focus is on carbon dioxide, the most important anthropogenic greenhouse gas. A reduced form carbon cycle model is used to identify alternative emission paths for achieving a given $CO_2$ concentrations target. Using two widely-used energy–economy models, we then calculate how costs to the global economy vary with the choice of emissions trajectory. It turns out that the emissions time-path is as important as the concentrations level itself in determining the ultimate price-tag.

## 2. Carbon Emissions and Concentrations Under Business as Usual

We begin by examining how $CO_2$ emissions and atmospheric concentrations are apt to evolve under business as usual. That is, in the absence of explicit abatement measures. For purposes of the present analysis, emissions are divided into three categories: 1) fossil fuels, 2) net deforestation and land-use change, and 3) others.

The fossil fuel emissions baseline is established with the Global 2100 model of Manne and Richels (1992). Global 2100 is a dynamic nonlinear optimization model which divides the globe into five geopolitical regions: the US, the other OECD countries, the former Soviet Union, China, and the rest of the world. The model is designed to evaluate the options that are realistically available to each region as the world moves away from its heavy dependence on fossil fuels and toward a more diversified energy economy.

The model's key parameters are calibrated using the results of a recent expert survey (Manne and Richels, 1993).[1] Figure 1 reports the business-as-usual emissions path. For purposes of comparison, we also show the range of emissions scenarios contained in the recent supplement to the IPCC scientific

[1] A group of knowledgeable individuals were polled on their beliefs about five factors that are important to future $CO_2$ emissions. These are: 1) potential GDP growth rates, 2) the elasticity of price-induced substitution between energy and capital-labor, 3) the rate of autonomous energy efficiency improvements, 4) the availability of economically competitive carbon-free alternatives to coal-fired electricity and 5) the costs of a nonelectric backstop alternative to liquid fuels. The Global 2100 model runs reported here are based on the poll averages.

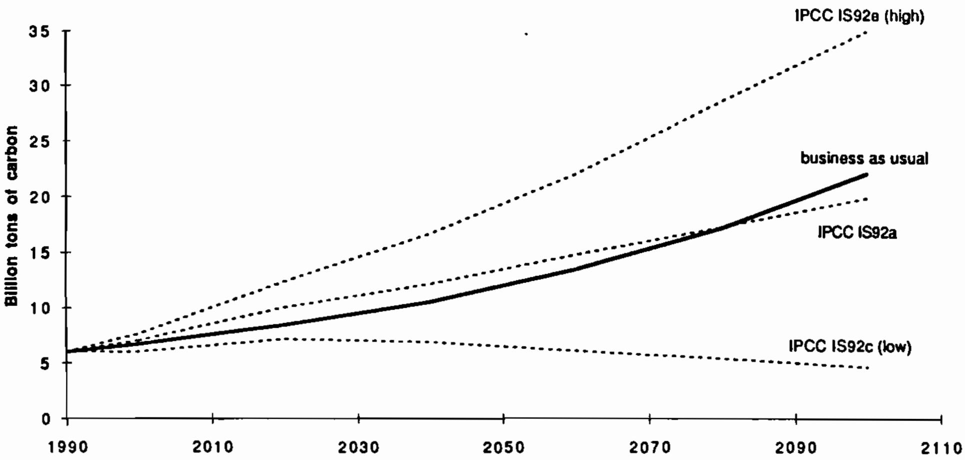


**Figure 1.** Global carbon emissions.

assessment (IPCC, 1992). Note that the results are quite similar to the IPCC's central case (IS92a).

For emissions from net deforestation and landuse change, we assume a "neutral biosphere". That is, the net biospheric input of $CO_2$ is exactly balanced by natural uptake mechanisms.[2] Further, we suppose that global cement production will contribute an additional 200 million tons of carbon to the atmosphere annually.

Ocean uptake of carbon is approximated by the impulse-response function of Maier-Reimer and Hasselmann (1987).[3] Figure 2 shows atmospheric concentrations under business as usual. According to our calculations, concentrations will be double pre-industrial levels in the middle of the next century and exceed 700 ppmv by the year 2100.

## 3. Stabilizing Atmospheric $CO_2$ Concentrations

The level at which "dangerous anthropogenic interference with the climate system" will occur has yet to be established. Indeed, the question of what constitutes an appropriate level is likely to remain the subject of intense discussion for some time. The present analysis makes no attempt to contribute

[2]This hypothesis is consistent with the post-World War II historical record (Post *et al.*, 1990).

[3]The model partitions carbon emissions into five classes, each with different atmospheric lifetimes. Parameters are least-square fitted to the computed response of a full ocean carbon cycle model.

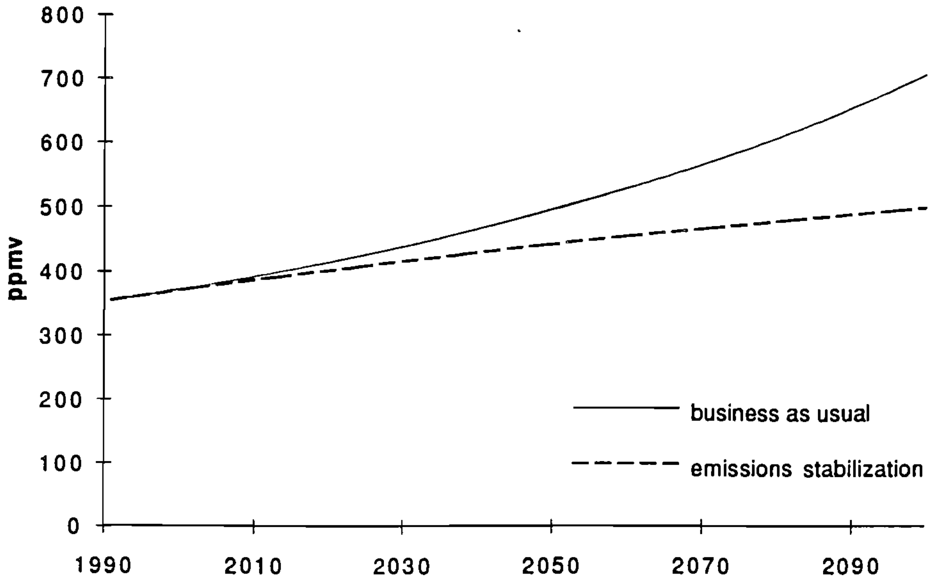


**Figure 2.** Atmospheric $CO_2$ concentrations – business as usual and emissions stabilization.

to this debate. Nor does it endorse any particular set of limits. Rather, we explore the economic implications of holding concentrations to a range of alternative levels.

It is noteworthy that most proposals for dealing with climate change have focused on emissions and not concentrations. For example, the Toronto Conference on "The Changing Atmosphere" called for a 20% worldwide reduction in $CO_2$ emissions by the year 2005 and the Hamburg Conference (November of 1988) called for a 30% reduction by the year 2000.

More recently, the focus of National Action Plans mandated by the Framework Convention has been to return emissions to their 1990 levels by the year 2000. This is seen as the first step in achieving the Convention's ultimate objective of stabilizing atmospheric concentrations. The second step, however, remains unclear. As a point of departure, we explore the implications of a policy which would permanently hold global emissions to 1990 levels.

Figure 2 shows the impact of such a policy upon atmospheric concentrations. The rate of increase has been considerably reduced. Atmospheric concentrations in 2100 are now only 500 ppmv. Stabilizing emissions, however, does not serve to stabilize concentrations. Although the rate of increase is slowing, the absolute level is still increasing.

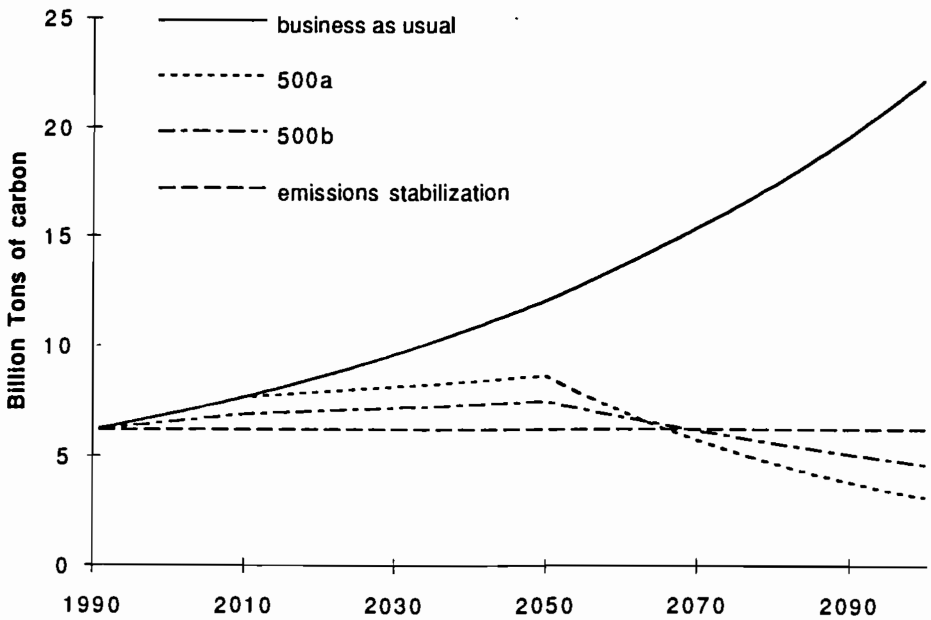


**Figure 3.** Global carbon emissions.

A particular concentrations target can be achieved in any of a number of ways. Figure 3 shows three alternative emission trajectories that would lead to 500 ppmv in 2100. The line labeled 500a represents a scenario in which emissions are allowed to follow the business-as-usual path through 2010; are reduced gradually between 2010–2050; and are reduced sharply thereafter. The line labeled 500b represents an emissions scenario which lies between the 500a and the emissions stabilization scenarios. Note that the areas under the lower three curves are approximately the same.

Figure 4 shows the corresponding curves for atmospheric concentrations. The 500a and 500b emission scenarios were chosen so as to stabilize concentrations at 500 ppmv by the end of the twenty-first century. This is in contrast to the emissions stabilization scenario where concentrations continue to rise into the twenty-second century.[4]

[4]The principal conclusions of our paper turn out to be independent of the choice of carbon cycle model. We performed the same exercise with the model of Wigley (1993) using a balanced carbon cycle model with feedbacks and the IS92a land-use emissions trajectory. While the atmospheric concentrations associated with stable 1990 fossil fuel carbon emissions are somewhat lower, 461 ppmv in 2100, cases 500a and 500b stabilize concentrations at 462 and 463 ppmv, respectively. Thus, the characteristic relationship between the time path of emissions and atmospheric concentrations holds.

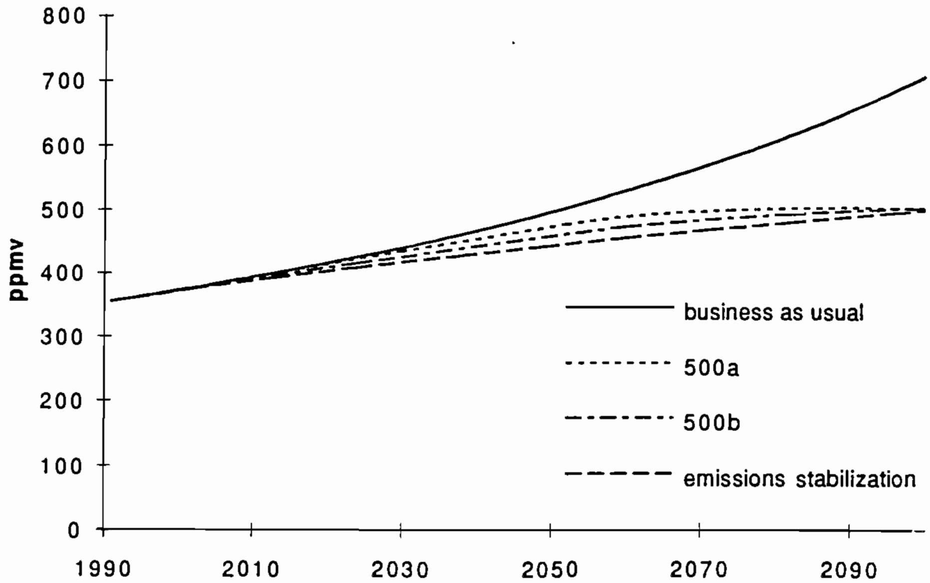


**Figure 4.** Atmospheric $CO_2$ concentrations.

The alternative concentration profiles have implications for temperature change. Emissions stabilization results in lower atmospheric concentrations prior to 2100. Hence, it is apt to produce slightly less temperature change during the next century. Over the longer-term, however, the scenarios which succeed in stabilizing concentrations are likely to be more effective in limiting temperature change.

## 4. The Economic Costs of Holding Concentrations to 500 ppmv

Next, we turn to the economics of holding concentrations to 500 ppmv in 2100.[5] Two models are used to quantify economic losses: Global 2100 and the Edmonds-Reilly-Barns Model (ERB). For a description of the latter, see Edmonds and Barns (1993). The models are alike in a number of respects. They are both long-term energy–economy models. They both provide relatively detailed representations of the energy system. And they both evaluate

[5]Nordhaus (1979) was the first to couple a carbon cycle model and an energy–economy model in order to explore cost-effective strategies for stabilizing atmospheric concentrations.

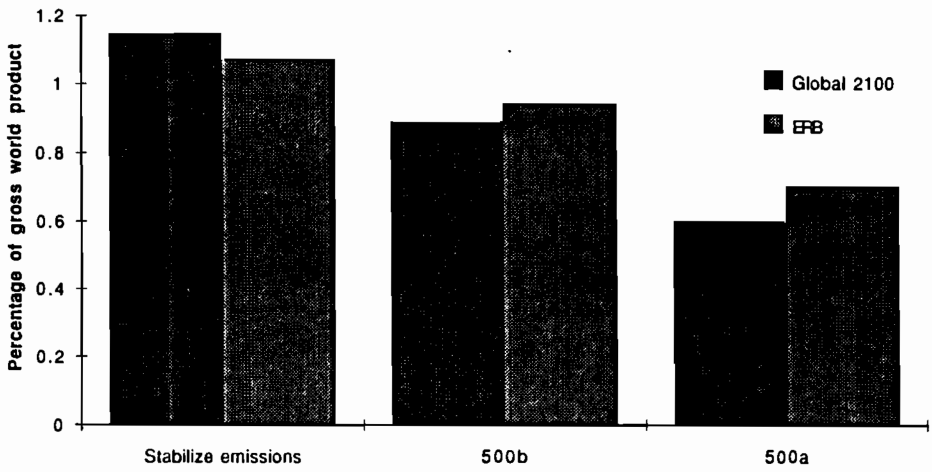


**Figure 5.** Costs of stabilizing atmospheric $CO_2$ concentrations at 500 ppmv by 2100.

the losses from a carbon constraint through the impacts on the price of energy.

The models differ, however, in a number of important ways. ERB is a recursive rather than an intertemporal optimization model. It employs a so-called "putty-putty" rather than a "putty-clay" approach to the vintaging of capital stocks. And it provides more regional disaggregation – nine versus five regions. (For a detailed model comparison, see Energy Modeling Forum, 1993).

The two models were chosen, more because of their differences, than their similarities. The application of alternative approaches can provide valuable insights into the robustness of a set of the results.

For the present analysis, the models were calibrated to the same emissions baseline. Independent cost analyses were then conducted to identify the least-cost strategy. From Figure 5, we see that the results are quite similar. Costs are evaluated through 2100 and presented as a percentage of gross world product. Stabilizing emissions at 1990 levels is by far the most costly strategy. Shifting the emission reductions into the outer years reduces costs by as much as fifty percent.

There are several reasons why a less restrictive near-term emissions path may turn out to be less expensive. First, the shift to a less carbon intensive economy cannot happen overnight. The time scale for large-scale deployment of new supply technologies is typically measured in decades. Widespread adoption of highly-efficient end-use technologies also takes time. Energy efficient systems are often embedded in long lived durable goods (autos, housing, equipment, structures), and these will not be replaced instantaneously. The process can be accelerated, but at a cost.

Secondly, there is apt to be a shortage of low-cost substitutes during the early decades of the 21st century. There are constraints on the rate at which new supply and end-use technologies can enter the marketplace. Having more time to manage the transition away from fossil fuels will be worth a great deal. We can emit more in the early years when the marginal cost of emissions abatement is high. The "pay back" can come in later years when low-cost technological alternatives are more plentiful.

Finally, scenarios 500a and 500b are less expensive because of the time value of money. With a positive discount rate, a dollar in the future is worth less than a dollar today. Even if the cost of reducing a ton of carbon were the same in all years, we would still prefer to make the expenditures later on. Doing so will result in a lower discounted present value.[6]

## 5. The Economic Costs of Stabilizing Concentrations at Alternative Levels

The focus thus far has been on holding concentrations to 500 ppmv. As noted earlier, our selection of a particular target was arbitrary. The goal was to explore the sensitivity of compliance costs to the choice of emissions trajectory. Costs are also a function of the target itself. To explore the nature of this relationship, we examine the costs of holding concentrations at alternative levels. For each target, we have attempted to identify an emissions path close to the least-cost solution. That is, we have selected paths which provide the greatest degree of near-term flexibility.

Figure 6 shows emission trajectories for stabilizing concentrations at 400, 450 and 500 ppmv. Figure 7 presents the corresponding time profiles for atmospheric concentrations. In the case of the most stringent target, there is little alternative but to reduce near-term emissions. In 1990, concentrations

[6] It is important to distinguish between the rate of time preference and the marginal productivity of capital. The above discussion relates to the latter. We have assumed a net real rate of return on capital of 5% per year. For purposes of illustration, suppose that it costs \$100 to remove a ton of carbon – regardless of the year in which the reduction occurs. If we were to remove a ton today, it would cost \$100. Alternatively, we could invest \$25 today to have the resources to remove a ton of carbon in 2020. Hence, if the focus is on the cumulative total rather than year-by-year emissions, we will prefer strategies which shift reductions into the outer years.

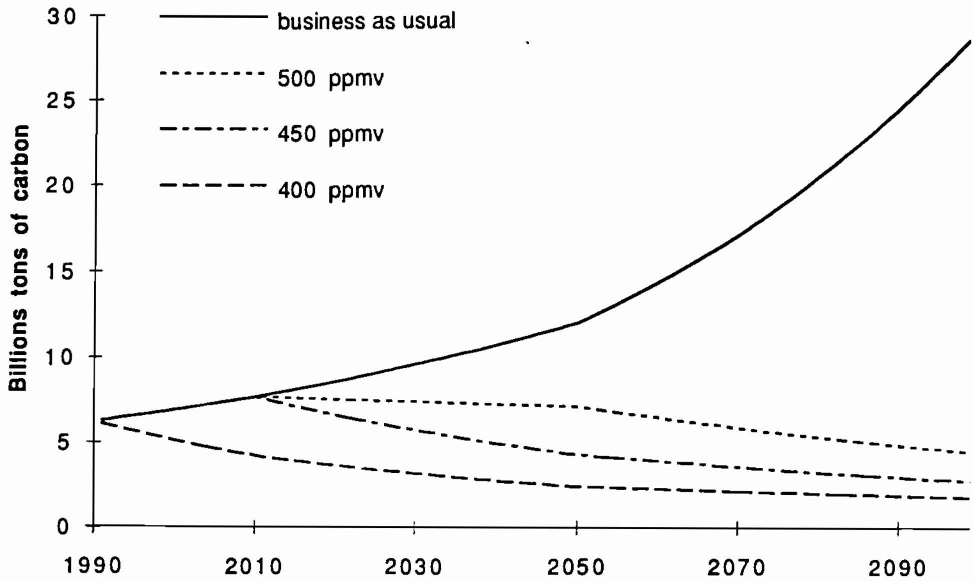


**Figure 6.** Global carbon emissions associated with alternative concentration levels.

were already at 353 ppmv. Limiting concentrations to 400 ppmv will require an early and rapid departure from the business-as-usual trajectory.

As the concentrations limit is relaxed, we gain in degrees of freedom. Stabilizing concentrations at 450 ppmv allows for some growth in near-term emissions. Stabilization at 500 ppmv allows for more growth still.

Figure 8 shows abatement costs for the alternative targets. The figure highlights the importance of flexibility in the early years. This is when the marginal cost of emissions abatement is likely to be highest. Concentration targets requiring sharp reductions in near-term emissions will be particularly costly.[7]

## 6. Final Comments

The economic costs of stabilizing concentrations will depend upon both the target and the manner in which the target is achieved. Under the terms of the UN Framework Convention on Climate Change, implementation costs

[7]The explanation for why the two cost estimates differ so markedly for the 400 ppmv case is straightforward. Unlike ERB, Global 2100 keeps track of the economic lifetime of the existing capital stock. As a result, its price responsiveness is lower in the short run than over the long run.

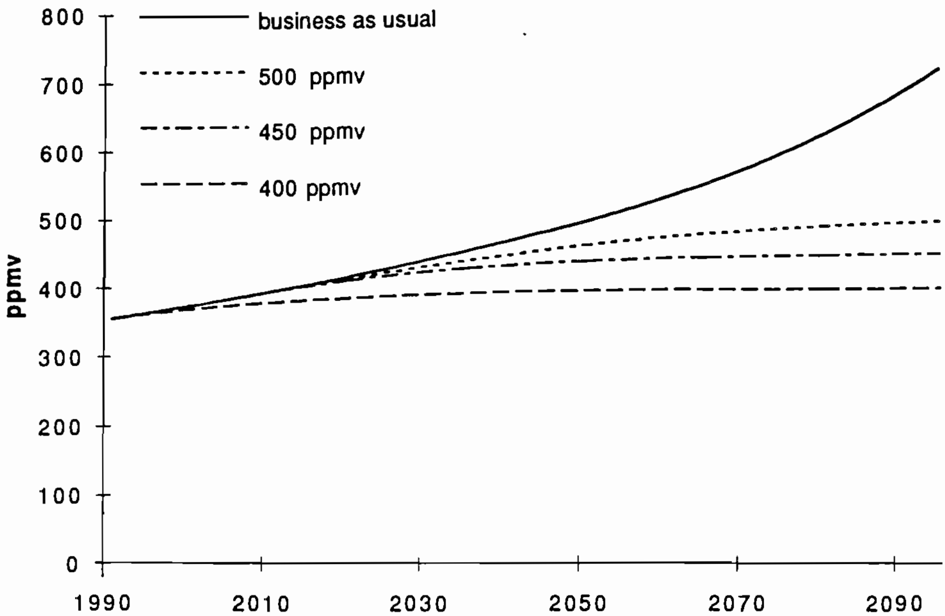


**Figure 7.** Alternative concentration levels.

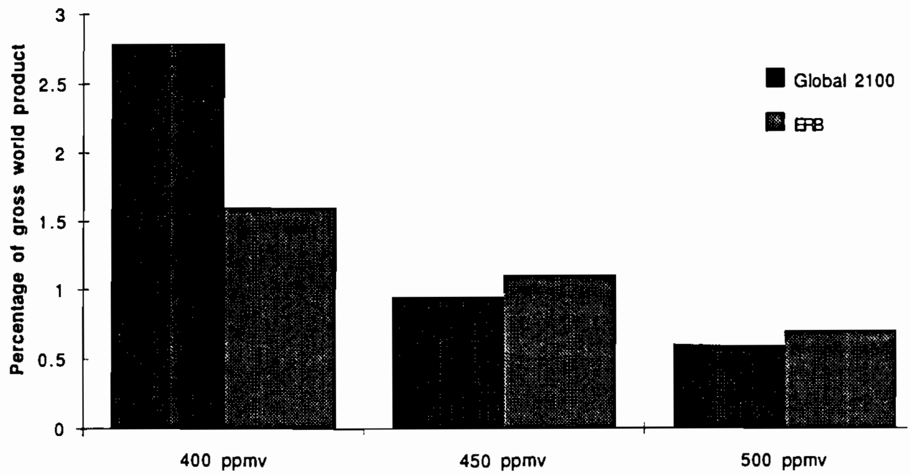


**Figure 8.** Costs of stabilizing atmospheric $CO_2$ concentration at alternative levels.

are not a principal consideration in the choice of a concentrations limit. The decision is to be based on a scientific assessment of what constitutes "dangerous anthropogenic interference with the climate system." Nevertheless, international negotiators would do well to recognize the nonlinear relationship between concentration levels and implementation costs. The perceived price tag will undoubtedly influence the willingness of nations to abide by the treaty.

One way to increase political acceptability is to ensure that benefits are attained at the lowest possible cost. A particular target can be achieved in a variety of ways. The analysis has shown that the emissions time-path may be as important as the target itself in determining economic losses. Rather than choosing arbitrary emission trajectories, more attention needs to be devoted to identifying those paths that minimize the costs of achieving a particular target.

The analysis also points to the importance of research and development. Currently, more than ninety percent of the world's commercial energy is derived from fossil fuels. The transition to a low-carbon economy will likely involve significant costs, but there are steps we can take to reduce the size of the ultimate bill. The key will be timing. Time is needed both for an economical turnover of the existing capital stock and to develop ample supplies of low-cost substitutes.

There are a number of promising carbon-free options – both on the supply and demand sides of the energy sector. New technologies, however, take many years for market penetration. A sustained research effort is needed to clarify their potential role and to ensure that cost-effective options are available to the greatest extent possible.

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# Toward a Fossil Free Future: The Technical and Economic Feasibility of Phasing out Global Fossil Fuel Use

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## Abstract

The environmental impacts of utilizing fossil fuels are severe. The paper assesses the likely carbon dioxide ($CO_2$) and climatic impacts of the global energy system in the absence of new policies. On the basis of the precautionary principle and analyses on possible ecological limits for greenhouse gas emissions, it then assesses the technical, economic, and policy feasibility of phasing out fossil fuels over the next century by developing a Fossil Free Energy Scenario (FFES). The likely climatic benefits that would follow are assessed. It draws out the crucial role of renewable energy, in combination with greatly improved energy efficiency. Some validation of the assumptions utilized in the FFES is provided through a series of case studies on successful energy efficiency and renewable energy technologies and programs.

## 1. The Environmental Impacts of Fossil Fuels

Fossil fuel combustion is the major source of greenhouse gas (GHG) emissions, largely in the form of carbon dioxide ($CO_2$), accounting for 85% of current net anthropogenic $CO_2$ emissions (Subak *et al.*, 1991). Over the past 50 years, fossil fuel consumption has increased fivefold, from approximately 57 exajoules in 1937 to around 282 exajoules in 1988 (Fulkerson *et al.*, 1990). Predominant among these fuels is the use of coal and oil, though natural gas use is projected to increase rapidly over the next few decades (IEA, 1991;

*The author acknowledges the detailed technical analysis carried out by Mike Lazarus and colleagues at the Stockholm Environment Institute – Boston in developing the FFES. In addition, climate modeling and additional economic analysis was carried out by Paul Waide. Detailed transport sector analysis was carried out by Michael Walsh. Roger Kayes developed supporting carbon sequestration analysis. This paper is heavily based on the above analysis, with the exception of the Policy Section and Section 7.3.

Stern, 1991). If fossil fuel consumption continues to grow, a doubling of pre-industrial $CO_2$ concentrations could occur as early as 2030, leading to a projected increase in the global average equilibrium temperature of 1.5 to 4.5°C (IPCC, 1990, 1992). Increasing concentrations of the other greenhouse gases would add to this increase.

In the past three years, a major international study under the auspices of the Intergovernmental Panel on Climate Change (IPCC, 1990, 1992) has largely confirmed the previous findings of a range of scientific assessments that a continuation of current fossil fuel and deforestation trends will likely increase global temperatures to unprecedented levels. The IPCC calculated that it would take a reduction in global $CO_2$ emissions by 60% to stabilize atmospheric concentrations. Given the likely increase in emissions from industrializing nations, this implies a near fossil fuel phase-out in OECD countries. The reduction in greenhouse gas (GHG) emissions, and particularly gases such as carbon dioxide which are linked to fossil fuel combustion, provided the basis for a study commissioned by Greenpeace International (1993a).

## 2. The Fossil Free Energy Study

The Stockholm Environmental Institute – Boston (SEI-B) and other independent consultants (see acknowledgements) carried out the bulk of the analysis for the Greenpeace study. The main objective of the study was to assess the technical, economic, and policy implications of moving toward a fossil free energy system. The study considered the world in terms of ten separate regions, reflecting, to the extent possible, varying patterns of economic activity, personal consumption, energy use, and energy resources. These regions are listed in Table 1.

The time frame for this study extends to the year 2100. This is an end year common to a number of global studies. The long time frame is necessary, as the climate effects of GHG emissions are expected to lag substantially behind the emissions themselves. Given the speculative nature of such long-range scenarios, greater emphasis should be placed on the time period between now and 2030. In fact, the next 40 years present the most challenging period if we are to reverse the trend of rising emissions of carbon dioxide, and develop policies that enable humankind to meet climate stabilization targets.

**Table 1.** Regional disaggregation for this study (based on the Edmonds–Reilly model).

| Abbrev. | Region |
|---|---|
| AFR | Africa |
| CPA | Centrally planned Asia (China, Laos, Cambodia, Vietnam, N. Korea) |
| EE | Central and Eastern Europe |
| JANZ | JANZ/OECD Pacific (Japan, Australia, New Zealand, Fiji) |
| LA | Latin America |
| ME | Middle East (Asia East to Afghanistan) |
| SEA | South and East Asia (All other Asian countries) |
| US | United States |
| USSR[a] | Former USSR, now CIS and adjoining states |
| WE[b] | Western Europe and Canada |

[a]In contrast to the Edmonds–Reilly model, we consider separately the former USSR and Eastern Europe.
[b]This region was only chosen to be compatible with the Edmonds–Reilly model of regional breakdown.

### 2.1. Computer modeling approach

The overall Greenpeace study utilized three computer models to assess the climate, technical, economic, and policy implications of moving toward a "fossil free" energy system over the next century. A main fossil free energy scenario (FFES), with variations, was developed. The computer models were used (a) to develop climate targets which the energy modelers used as limits in order to bring climate impacts down to manageable levels; (b) to assess the climate impact of the fossil free energy scenarios developed; (c) to develop a disaggregated, sectoral global energy scenario which was based on high levels of energy efficiency and an increasing quantity of renewable energy sources; (d) to assess the pricing and overall cost implications of the scenario; and (e) to inform the evolution of policies which would be needed to achieve the scenario. The three models were as follows:

1. The end-use global energy model called LEAP – Long Range Energy Alternative Planning system. LEAP is linked to Environmental Data Bases (EDB) compiled from international data sources, that was used here to estimate future greenhouse gas emissions. The model allows assessment of regional and energy sector end-uses, energy resources and technologies applied to a world which, for the purpose of the study, was divided into ten regions.
2. A model called Atmospheric Stabilization Framework (ASF), developed for the US Environmental Protection Agency. The energy component

is based on the widely used Edmonds-Reilly (ER) model. This takes account of price and income factors to a greater extent than LEAP. Linked to the results from LEAP, it was used to give additional cost information to the project.

3. The Sea-level and Temperature change Under the Greenhouse Effect climate model (STUGE), developed by the Climatic Research Unit at the University of East Anglia in the UK. This was employed to develop climate targets and assess the climate impacts of the FFES and its variants.

In addition, a range of projections for carbon emissions from biogenic sources was developed.

## 2.2. Assumptions for the study

A number of assumptions were made to guide the modeling exercise by SEI–Boston and the other analysts. It should be noted that these are not necessarily Greenpeace policy, but were used in order to make the study comparable with other studies:

1. Fossil fuel combustion was to be eliminated by the year 2100. This outcome was a scenario "constraint", and did not result from an economic cost-benefit or modeling analysis of the value of substituting for every energy use of fossil fuels.
2. Carbon removal technologies were not considered.
3. Nuclear power was eliminated by 2010. Nuclear power is not regarded by Greenpeace as an attractive substitute for fossil fuels, because of the significant risk factors from catastrophic accidents and proliferation, the high costs of generating nuclear electricity in many countries, plus the environmental concerns of solid and liquid radioactive wastes.
4. New renewable and other resources were subject to environmental restrictions. Concerns about the construction of new, large hydro facilities were reflected in a downgrading of the global technical/economic potential of hydropower by 35%. No municipal waste incineration was considered. Restraints on biomass plantations were intended to reflect the need to develop more sustainable, albeit lower yield, ecosystems.
5. Conventional assumptions for GDP and population were made, with one exception, that relating to equity. This does not signify acceptance by Greenpeace of such assumptions, but to allow cross-comparison of the FFES with other policy scenarios. World population grows to over 11 billion by the year 2100, with over five-fold growth in Africa from

560 million to almost 3 billion (Bulatao *et al.*, 1989). Total global GDP grows more than 14 times. In the FFES analysis an approach to regional income equity was proposed wherein the ratio of highest to lowest average regional income drops to 2:1 by 2100, compared with the projected ratio of over 14:1. This is not true equity, of which GDP is only a very crude and inadequate measure anyway, but the gap continues to narrow after the year 2100. GDP is redistributed among regions to achieve the same total world GDP as the IPCC forecast does in 2100: 258 trillion ECUs or 23,028 ECUs per capita [$213 trillion or $19,000 per capita (1985 US $)].

6. Structural Change. The concept of structural change in economies is fundamental to the FFES. With the rapid GDP growth rates for the South embodied in our scenarios, SEI–Boston anticipated the general transition among sectors that has accompanied the industrialization process in the North: from agricultural and other primary production to a period of greater industrial activity, and finally to the ascendancy of the service sector. The specific path for future economic development in the industrializing countries of the South is impossible to predict; the model of the currently industrialized countries is used as one possible option. Once again this is not Greenpeace policy.
7. Economic Criteria. It was sought, where possible, to ensure that measures undertaken over the near and medium term (to 2030) yielded net economic benefits or were unlikely to incur significant costs. The emphasis here is on proven or near market technologies that have been shown to be either cost-effective or cost-competitive with other options. The economic analysis utilizing the ASF model addresses this issue in greater detail (Waide and Boyle, 1993). Any cost estimates for the period beyond 2030 are inherently speculative; for this period, the scenarios reflect what currently appears credible and achievable.

## 3. Business-as-Usual Scenarios

Many researchers have constructed forecasts into the early or mid 21st century. The far smaller number that have attempted to forecast to the year 2100 have done so primarily for the purpose of $CO_2$ projections and climate studies. Two reference case projections were selected for comparison with the results of the FFES, an IPCC projection and an average of EPA's Rapidly and Slowly Changing World cases.

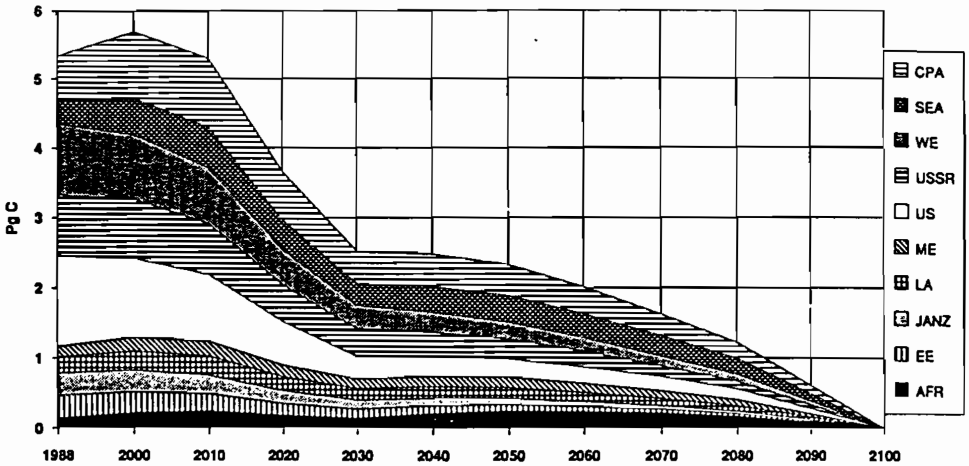


**Figure 1.** Carbon dioxide emissions under FFES by region (PgC).

### 3.1. The climate implications of a business-as-usual scenario

The climatic consequences of these scenarios were assessed using STUGE. By 2100, the global-mean induced radiative forcing exceeds 10 W/m$^2$, while under a 2.5°C climate sensitivity, global mean temperature is forecast to exceed 4°C above pre-industrial times. Even if emissions were held static or cut, the long atmospheric residence time of GHGs would ensure that global mean temperatures continue to rise beyond 2100. Sea level is projected to increase from 35 to 115 cm (depending on climate sensitivity), while rates of temperature increase are between 0.2 and 0.6°C per decade.

## 4. Results of the Fossil Free Energy Scenario (FFES)

The findings of the Fossil Free Energy Scenario (FFES) indicate that a combination of efficiency improvements, renewable energy technologies, and fuel switching could achieve significant long-term reductions in $CO_2$ emissions. As shown in Figure 1, annual $CO_2$ emissions peak around the year 2000, and decline to 48% and 29% of current global levels by 2030 and 2075, respectively, before reaching the fossil-fuel target of zero net $CO_2$ emissions by 2100.

The initial rise in $CO_2$ emissions reflects the momentum of current energy use patterns, the embedded stock of energy-inefficient equipment, and

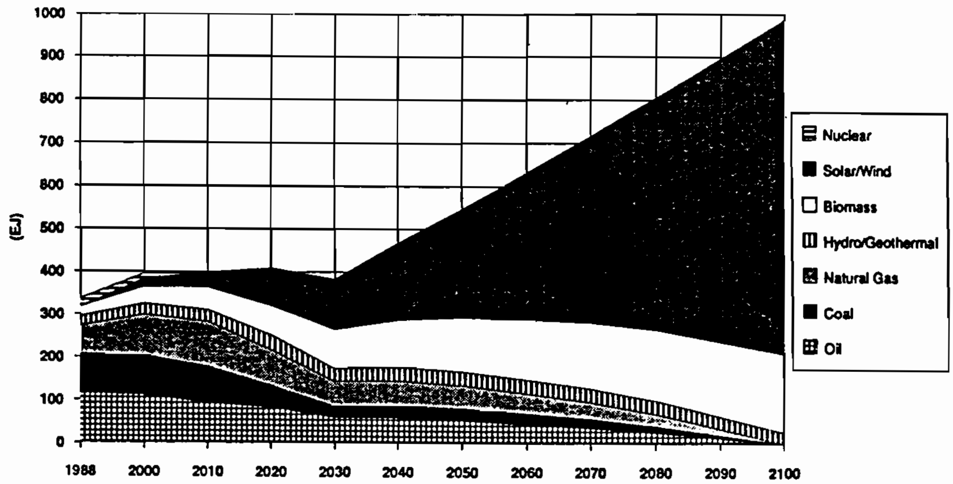


**Figure 2.** Primary energy supply mix under FFES: 1988–2100. Solar, wind, hydro, geothermal, and nuclear energy converted from electricity to primary energy using then-current average fossil/biomass plant efficiencies.

the time required to effect of large shifts in fuel and technology choices throughout the world.

The scenario roughly achieves a 20% reduction by 2005 among industrial countries. These reductions do not reflect Greenpeace policy, as higher individual national targets would be expected. In the scenario reported here, $CO_2$ emissions from 1988 to 2000 decline by 3–12% in industrialized regions, while increases in developing regions range from 21% in Latin America to 55% in South and East Asia. This leads to a 6% overall increase in global $CO_2$ emissions.

Between 2000 and 2010, the effects of technology improvements begin to outweigh the underlying forces of economic and population growth, and global $CO_2$ levels begin to decline. Reductions in the industrialized regions offset continued increases in the South. Beyond 2010, emission levels decline in all regions, as the current stock of energy consumption and production equipment turns over, and high efficiency end-use and electricity generation technologies are widely implemented. Reduced dependence on coal and modest levels of renewable fuels and electricity further contribute to $CO_2$ savings. The contribution of fuels to primary energy is shown in Figure 2.

By 2030, a new generation of lower cost renewable supply technologies provide a cleaner, low-$CO_2$ mix of fuels and electricity. In the shorter term, biomass technologies, windpower and a limited expansion of hydropower provide the bulk of the renewables contribution. Over the longer term, a solar energy system (solar PV, solar thermal power and solar water and space heating) linked to hydrogen predominates, providing 80 per cent of supplies in 2100.

Renewables currently provide nearly 14% of total global energy supplies. This comes mainly from hydropower and biomass. From just over 20% of total energy demand in 2000, renewable sources grow to 26% in 2010, and over 60% in 2030. The projections are based upon technical potentials, assessed in a range of countries and taking account of electricity storage and load management issues. They are also based on the growing experience of some significant renewable technologies in a few countries. This transition to a solar and biomass-based energy system leads to the complete reduction of fossil fuel carbon dioxide emissions by 2100. Though the FFES is a global study, different penetration levels for the various types of renewable technologies were assumed, taking account of resources (i.e., greater wind potential in Europe, than Africa, and vice versa for solar-electric, extensive use of biomass in Latin America).

The costs of renewable technologies have been falling significantly in recent years. Based on analyses by a range of research organizations, cost projections were assumed which show renewables currently becoming competitive with conventional fossil fuels from now to within 20–30 years, depending on the technology and circumstance.

Many renewable technologies tend to have higher capital costs and lower running costs than competing fossil fuel options. The assumed cost of capital and payback periods (discount rates) can thus make a very big difference to apparent costs. Where lower discount rates are used (8% or less), windpower, solar thermal, biomass combustion, passive solar energy in buildings, hydropower, and geothermal energy technologies are already cost-competitive with fossil fuels in many countries. For remote locations, solar electric cells are currently cheaper than diesel-generated electricity, and are projected to be cost-effective against fossil fuel power stations in 2010–2015. Costs have been falling. The price of electricity from windpower has dropped 70% in less than a decade in the USA and Denmark. Solar thermal power costs have fallen 75% since 1980, with a further fall of 25% projected by the year 2000.

Estimated cumulative global $CO_2$ emissions from 1988 to 2100 amount to 314 (Pg C), as shown in Table 2. Emissions from the 5 industrialized regions account for 53% (165 Pg C) of these cumulative emissions.

Improved end-use energy efficiency in residential, industrial, transport, and service sectors accounts for the major source of emission reductions

**Table 2.** Carbon dioxide emissions by region: 1988–2100 (PgC).

| | 1988 | 2000 | 2010 | 2020 | 2030 | 2040 | 2050 | 2075 | 2100 | Est-Cum 1988 to 2100 |
|---|---|---|---|---|---|---|---|---|---|---|
| AFR | 0.16 | 0.23 | 0.26 | 0.19 | 0.16 | 0.22 | 0.26 | 0.22 | 0.00 | 22 |
| CPA | 0.65 | 0.98 | 1.00 | 0.69 | 0.46 | 0.46 | 0.43 | 0.28 | 0.00 | 55 |
| EE | 0.31 | 0.29 | 0.24 | 0.16 | 0.12 | 0.10 | 0.09 | 0.04 | 0.00 | 14 |
| JANZ | 0.32 | 0.30 | 0.25 | 0.18 | 0.13 | 0.11 | 0.09 | 0.04 | 0.00 | 14 |
| LA | 0.22 | 0.27 | 0.28 | 0.20 | 0.17 | 0.17 | 0.15 | 0.10 | 0.00 | 18 |
| ME | 0.16 | 0.20 | 0.21 | 0.17 | 0.14 | 0.15 | 0.15 | 0.11 | 0.00 | 15 |
| SEA | 0.34 | 0.53 | 0.59 | 0.44 | 0.32 | 0.37 | 0.38 | 0.29 | 0.00 | 39 |
| US | 1.28 | 1.13 | 0.97 | 0.65 | 0.33 | 0.30 | 0.28 | 0.21 | 0.00 | 53 |
| USSR | 0.88 | 0.85 | 0.73 | 0.52 | 0.40 | 0.34 | 0.28 | 0.14 | 0.00 | 43 |
| WE | 1.01 | 0.90 | 0.74 | 0.50 | 0.33 | 0.28 | 0.24 | 0.12 | 0.00 | 42 |
| Total | 5.34 | 5.68 | 5.26 | 3.69 | 2.55 | 2.50 | 2.35 | 1.56 | 0.00 | 314 |
| North | 3.81 | 3.47 | 2.92 | 2.01 | 1.31 | 1.14 | 0.97 | 0.55 | 0.00 | 165 |
| South | 1.53 | 2.21 | 2.33 | 1.69 | 1.24 | 1.36 | 1.38 | 1.01 | 0.00 | 148 |

between now and 2030. On average, the rate of improvement in energy intensities (through energy efficiency and structural change) is 2.5% per year. For the period beyond 2030, smaller improvements are assumed. The dip in energy use from 2010 to 2030, followed by a subsequent rise for the remainder of the scenario, largely results from strong efficiency improvements prior to 2030 that outweigh the dual forces of growing economies and population for a brief period of time. Beyond 2030, much slower rates of efficiency improvement and structural change of 0.5% per year were assumed.

The levels of end-use efficiency improvements included in this scenario are based upon current assessments of economic and technical potential: levels based on market or near market technologies that can be implemented within 40 years.

Improved efficiency on the supply side, including the more efficient use of fossil fuels for electricity production (e.g., combined cycle and fuel cell systems), provide important contributions to reducing emissions over the next 40 years. This also includes the overall efficiency gains offered by on-site and centralized combined heat and power generation (cogeneration). After 2030, approximately 20% of global electricity demand is supplied from centralized and on-site cogeneration.

Fuel switching from coal and oil to natural gas also plays an important role in reducing emissions in the near and medium term (to 2030). Estimates were made for each region regarding the ability to switch to lower carbon

**Table 3.** Primary energy supply, 1988–2100.

| Source | 1988 | | 2000 | | 2010 | | 2030 | | 2100 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Oil | 116 | 34% | 112 | 28% | 93 | 23% | 59 | 15% | 0 | – |
| Coal | 93 | 27% | 93 | 23% | 85 | 21% | 28 | 7% | 0 | – |
| Natural gas | 65 | 19% | 96 | 24% | 105 | 26% | 57 | 15% | 0 | – |
| Hydro/geothermal[a] | 23 | 7% | 26 | 7% | 28 | 7% | 3 | 8% | 28 | 3% |
| Biomass[b] | 22 | 7% | 38 | 10% | 52 | 13% | 91 | 24% | 181 | 18% |
| Solar/wind[a] | 0 | – | 20 | 5% | 36 | 9% | 118 | 31% | 778 | 79% |
| Nuclear[a] | 19 | 6% | 12 | 3% | 0 | – | 0 | – | 0 | – |
| Total | 338 | | 396 | | 400 | | 384 | | 987 | |

[a]Solar, wind, hydro, geothermal, and nuclear energy converted from electricity to primary energy using then-current average fossil/biomass plant efficiencies.
[b]Note that 1988 biomass figures reflect UN estimates (UN, 1990) and may be low by a factor of 2.

fuels, based on the availability of fossil fuel supplies, particularly natural gas, and end-use considerations. The resulting primary energy shares are shown in Table 3. The cumulative global consumption of natural gas and oil in the FFES is 6200 EJ and 6600 EJ, respectively.

For regions heavily dependent on coal, with limited supplies of natural gas and other fuels, coal continues to account for an important but declining share of primary supply. For example, in Centrally Planned Asia, coal use drops from 72% of primary energy in 1988, to 51% in 2010, and to 22% in 2030.

### 4.1. Land use implications of the FFES

Figures 3a and 3b summarize the land-use implications of the FFES. Due to the trade-off between biomass yields and the need for sustainable plantation and forestry systems, the land requirements are quite large, i.e., more than 8% of global arable/pasture/forest and woodland (6% of total global land area). This also reflects the modeling assumptions for GDP and population. Additional sensitivities were carried out on these and biomass/solar yields and productivities which had the effect of reducing the proportion of total global land area to between 2 and 3% (see Section 8.2). The potential land-use problems for solar/wind are much less. Using non-productive land (deserts and degraded areas) plus roof tops can alleviate potential problems. Wind parks allow farming to continue largely unaffected. Any discussion over land use also needs to acknowledge the land-use requirements of fossil fuels. One analysis suggests that coal fired electricity, including coal mining,

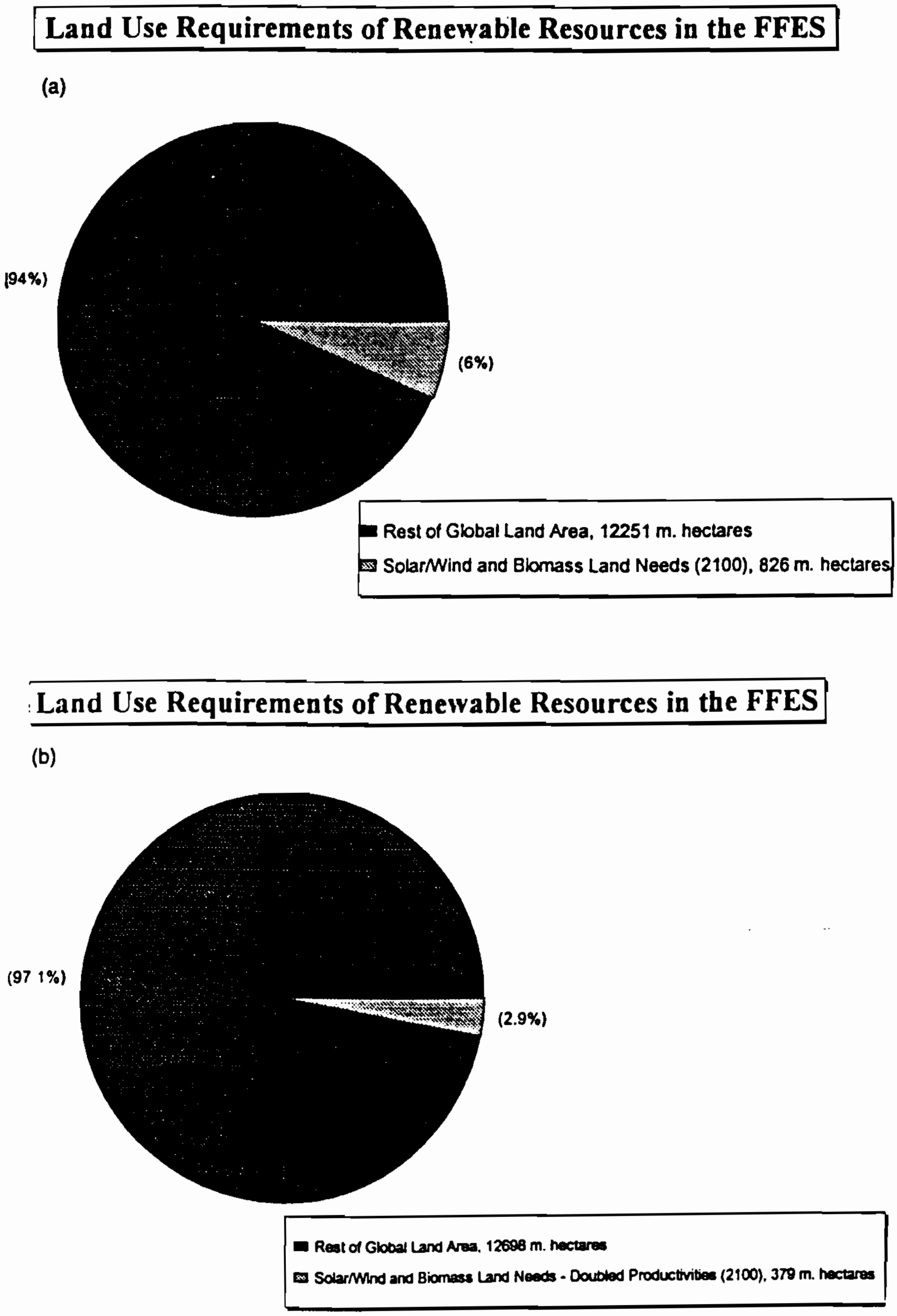


**Figure 3.** Land use requirements of renewable resources in the FFES.

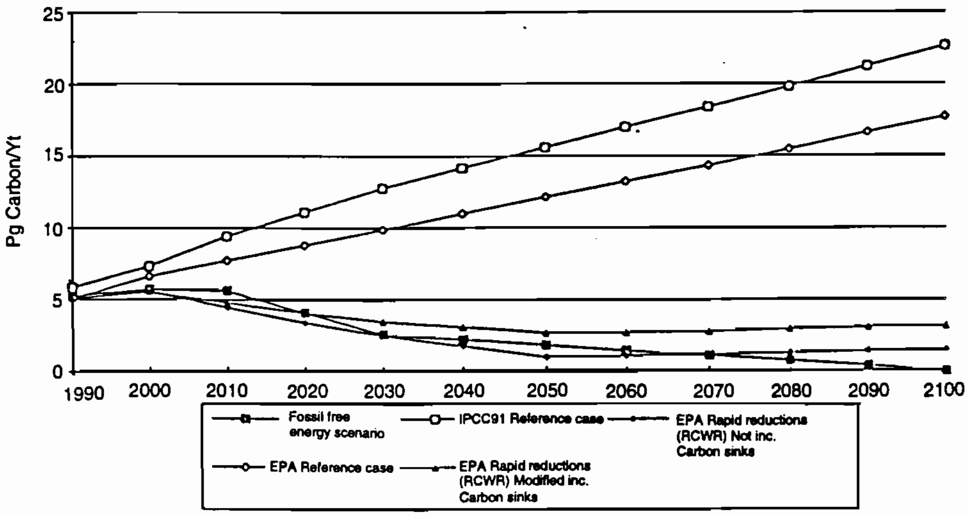


**Figure 4.** Summary comparison results of FFES and variants of IPCC/US EPA reference scenarios.

takes up a similar amount of land as solar, and a greater amount than wind (Pasqualetti and Muller, 1984).

## 5. Comparison of FFES Results with Other Scenarios

Figure 4 compares the results of the Fossil Free Energy Scenario (FFES) with one of the IPCC's and the US EPA's reference case scenarios, and the EPA's lowest policy $CO_2$ emission scenario, Rapidly Changing World with Rapid Reductions (RCWR) (US EPA, 1990). The contrast in fossil fuel usage between the FFES, the business-as-usual scenarios, and other policy scenarios is stark. Even in one of the more radical policy scenarios produced by the US EPA (RCWR), overall oil usage increases over the period. Though oil use falls rapidly to a similar level as the FFES in 2030, oil from polluting synthetic fuels increases rapidly. This is double the level found in the FFES in 2030, and it increases throughout the remainder of the century.

# 6. The Climate Benefits of the FFES

## 6.1. Other greenhouse gases

The dominant GHG is $CO_2$ accounting for 61% of the global warming impact of all GHG emissions in 1990, followed by methane ($CH_4$) at 15%, halocarbons (CFCs and HCFCs) with 11%, and nitrous oxide ($N_2O$) at 4% (Shine *et al.*, 1990). The 1992 IPCC scientific assessment of climate change indicated that CFCs may provide only a small net radiative forcing effect. Other changes, such as the impact of sulfate aerosols, have also been estimated by Wigley. Given the attendant uncertainties, these were not incorporated in the climate modeling analysis. If they had been, the role of $CO_2$ would have increased in relative terms. Given the rapid phase-out of CFCs and other halocarbons, the net effect on the climate results would also have been small. To complete the climate analysis, assumptions were made for the other GHGs which effectively stabilized emissions at current levels.

## 6.2. Climate modeling results

Modeling the results of FFES using STUGE demonstrates that it significantly reduces the risks of climate change (Waide, 1993). Based on the FFES total emission of 314 Gt carbon, carbon dioxide concentrations in the atmosphere are kept to below 400 ppm, in contrast to well over 750 ppm in both business-as-usual (BAU) scenarios. Under a climate sensitivity of 2.5°C for a doubling of pre-industrial carbon concentrations, global average temperature increases are kept from increasing above 1.5°C within the time period, in contrast to more than 4°C under BAU. Temperatures are actually falling from the year 2050 onwards in the scenario. Rates of temperature increase are brought to below 0.1°C per decade around the year 2020. Sea level increases are kept between 10 and 35 cm, in contrast to between 35 to 115 cm in the BAU (depending on climate sensitivity).

# 7. The Economic Implications of the FFES

The costs of a scenario developed over a time period of more than a century are necessarily speculative. The projected costs of future energy systems crucially depend on assumed costs for the various fuels, the costs of implementing policies for energy efficiency and renewable energy, the type of computer model used, assumptions about the current energy market and the business-as-usual scenario. A number of authors have commented on the wide range of cost estimates for carbon dioxide abatement (Grubb, 1990; Boyle, 1992). A major difference in cost estimates emerges between those developed using "top-down" macro-economic models, and those using "bottom-up" end-use models. The latter are less reliant on price alone as a policy lever, hence costs tend to be lower. A common criticism of this type of end-use study is that the penetration rates for more efficient technology may be overly optimistic (Manne and Richels, 1990). This partly reflects current market failures such as the very high discount rates applied by private consumers in contrast to large utilities (30 to 50% is common among private consumers, as against 5 to 12% for utilities). The FFES has responded to such criticism in two ways: by scaling back some of the technical potential for energy efficiency and implicitly assuming that such barriers will be tackled by policy changes. The FFES utilized both types of models to give some indication of the costs.

Considerable evidence suggests that implementation of the measures in this scenario could be achieved at modest cost or even at net economic benefit relative to a business-as-usual world. Projections of renewable energy supply costs indicate that solar, wind, and biomass technologies could be close enough to those of fossil fuels to enable a transition to occur without major economic penalties (Ogden and Williams, 1989; Johansson *et al.*, 1993; Nitsch *et al.*, 1990). Major economic benefits in avoided electric capacity, roads infrastructure, and fossil fuel supply requirements would result from investments in efficient end-use technologies.

A full cost–benefit analysis would include the avoided costs and capital requirements (e.g., dikes to stem coastal flooding) that would otherwise be needed to mitigate the impacts of global warming, if the world were to continue its current dependence on fossil fuels.

### 7.1. Other cost studies

The FFES was based on data supplied from a wide range of sources. It also utilized more than 100 national, regional, and global reports on carbon dioxide reductions which have been produced in the past two years. Several provided significant input to the development of the scenario. These include studies by Levine *et al.* (1991), Johansson *et al.* (1993), UCS *et al.* (1991), and Krause *et al.* (1992). These show that estimating the costs of $CO_2$ reduction over such long periods is difficult, but that the findings of the FFES are not unusual. A number of regional studies have indicated that there are enormous savings to be made from energy efficiency and renewable energy.

1. In the US, "America's Energy Choices" (UCS *et al.*, 1991) showed a cut of 70% in $CO_2$ emissions to be possible between now and 2030, producing savings of $2.3 trillion.
2. A US study: "Energy Efficiency, Developing Nations, and Eastern Europe" (Levine *et al.*, 1991) concluded that improved energy efficiency up to 2025 could reduce cumulative capital requirements in Eastern Europe and the South from $4657 billion to $2320 billion, and globally from $7785 to $4111 billion.
3. "Western Europe, Energy and Climate Change" (Krause *et al.*, 1992) studied the five largest countries, and projected $CO_2$ cuts of up to 58% by 2020, at a saving to consumers of between 2 and 27%, compared to present-day energy costs.

## 7.2. ASF economic modeling

The ASF model was used to gain additional information on the pricing implications of the FFES (Waide and Boyle, 1993). This is a partial equilibrium model commonly used throughout the world. By feeding in a range of fuel costs for renewable and fossil fuels, using US EPA figures in the main, the relative costs of the business-as-usual scenario and the FFES could be compared.

## 7.3. Preliminary economic conclusions for FFES

The results are shown in Figures 5 and 6. They indicate that, accepting the assumed costs for fossil fuels and renewable energy, the costs of secondary energy consumption as paid by the consumer for the FFES are considerably lower than under BAU. In a world where there is a significant shift away from fossil fuels, fossil fuel companies may offer such fuel at very low prices – the price equilibrium effect. To deal with this potential problem, the fuel share weightings were controlled in the model. This was intended to simulate policies such as $CO_2$ emission controls and strict international compliance of $CO_2$ reduction Protocols.

What the results do not show are the additional costs of the end-use efficiency equipment needed to achieve the FFES demand profile. A related Greenpeace project (Greenpeace International, 1993a) gives some indication of these likely costs.

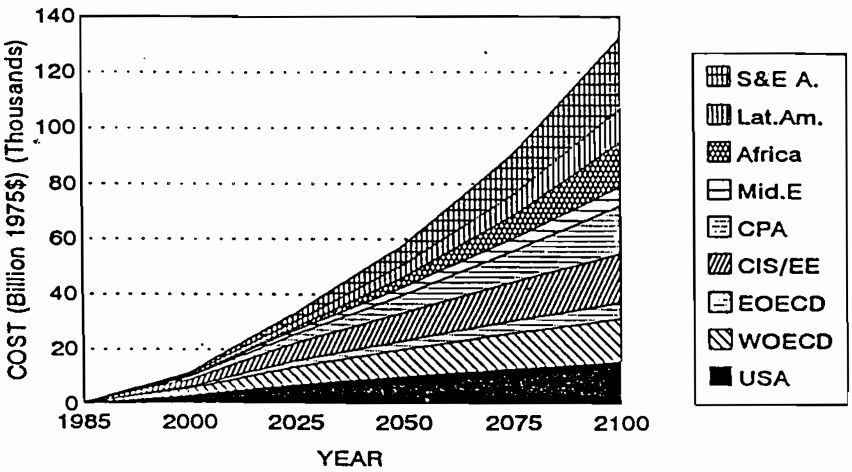


**Figure 5.** Cumulative costs of secondary energy consumption for scenario 1. Very low carbon tax of \$17.20/ton of carbon introduced over a 65-year period.

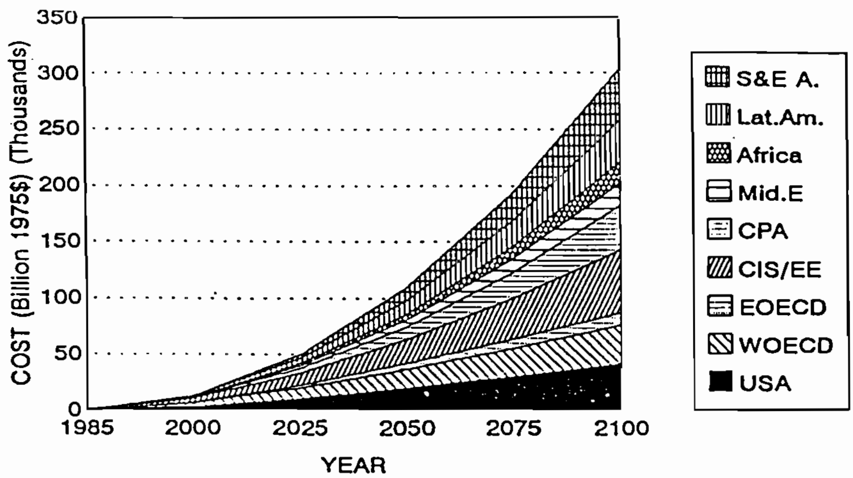


**Figure 6.** Cumulative costs of secondary energy consumption for US EPA slowly changing world scenario.

## 7.4. Case studies in successful energy efficiency and renewable energy technologies, policies and programs

A report by Greenpeace International (1993b) assessed a number of "best-practice" case studies for energy efficiency and renewable energy throughout the OECD over the past 15–20 years. Of particular interest is the extent to which successes might be replicated in other countries and regions. Failures are also of interest in this process, as a great deal can be learned and considerable resources saved.

The report provides some validation as to whether the expected performance and costs of energy efficiency and renewable energy assumed in the FFES could be realised. This is an issue of some debate among economists and policymakers. The following are some of the highlights of the report.

1. Efficiency.
   The FFES assumes a reduction in energy intensity (both through energy efficiency and structural changes) of around 2.5% per annum between 1990 and 2030. It also assumes that much of this accelerated energy efficiency improvement can be obtained at a cost generally less than new supply. How valid are these assumptions?
   (a) Costs of demand side management (DSM). A number of the early DSM programs in the USA and Canada were not as cost-effective as predicted. This reflected the learning curve of a new approach by utilities, plus a range of initial problems, including poor administration, lack of interest by the utility, and the learning curve of trying out new marketing techniques. However, lessons have been learned (Nadel, 1992), and many of the better DSM programs are proving to be extremely cost-effective, able to be replicated, and with a high uptake of participants. Of 50 recent DSM programs across the USA assessed by IRT, the average cost was 2.8c/kWh, with many below 1c/kWh (IRT, 1993). Among the more aggressive utilities investing in DSM in the USA, projected peak demand savings by the year 2000 range from 8 to 19% (MW) and from 2% to 19% (GWh) of total demand. An assessment of 50 efficient lighting programs throughout Europe revealed a total societal cost of 2.1c/kWh (Mills, 1993).
   (b) There are a number of key lessons from DSM experience in North America and Europe. These include the need for good initial design, innovative marketing, strong financial incentives and a resulting commitment to DSM from the utility, regular review of progress, flexibility of programs allowing changes to be made on a regular basis, and the involvement of customers (Nadel, 1992). Good programs are now being replicated throughout the USA, and are beginning to be utilized by some utilities in Europe.
   (c) Super-efficient buildings, both new and retrofit, have been shown to be cost-effective throughout the world (with examples in UK,

Canada, USA, Germany, Netherlands, Spain). Additional costs are often offset by savings on the heating and cooling systems. There are a wide range of buildings throughout the OECD with additional capital costs of 1 to 5% compared to standard buildings, and which have paybacks of less than 5 years (Doggart, 1993). Simplicity of design and use by occupants are key elements of success.

(d) Significant efficiency improvements in appliances have already been achieved at a 7% additional cost (Sweden) or less than 1% additional costs (USA). Between 1991 and 1994, model ranges of the top ten most efficient appliances in Sweden improved their average efficiency by 25%, while average costs increased 7% from 7291 SK to 7805 SK (Nilsson, 1993). In the USA, which introduced mandatory minimum efficiency standards for appliances in 1987, significant improvements in efficiencies have occurred. For refrigerators and freezers, these have improved in two stages so far, by approximately 40% compared to pre-1990 levels. A further 25-35% efficiency improvement for 1997 has been proposed. The 1993 standards, a 25-30% improvement on 1990 standards, led to a 1% increase in the costs of appliances to the consumer (Turiel, 1993), without any reduction in total sales or the range of models. These rates of energy efficiency improvement are considerably in excess of 2.5% per annum.

2. Renewable Energy.

(a) Major reductions in costs have occurred in a number of the technologies, particularly wind, solar thermal, solar photovoltaic, and biomass (World Bank, 1993; Johansson *et al.*, 1993).

(b) Successes include windpower development in Denmark and California. Approaches in these countries have varied. A high level of initial subsidies in the USA, leading to a high fallout of manufacturers as poor quality machines fell by the wayside, may have been less economically efficient, but a dynamic and cost-effective industry has emerged. This has had positive global implications for the technology and was a factor in the successful development of the Danish and Netherlands wind industries since they achieved significant exports to the US market in their formative stages. The Danish approach started with small capacity machines and built up an industry with an integrated set of polices (fiscal and non-fiscal), a challenging target for wind (10% of total electricity supplies by the period 2000–2005), and supportive planning legislation. Costs have fallen in both countries by 70–75% (Rashkin, 1991; Madsen, 1993; Cavallo *et al.*, 1993). Prospects of a further 25% reduction in costs through R&D look high (EPRI, 1992).

(c) Solar thermal power generating costs fell by 75% between 1984 and 1991. Financing and long-term supply contracts were critical elements in this development. Technical prospects for further improvements and reductions in cost of at least 25% in the next 4 years look high (Ven, 1993; Keepin and Mills, 1993).

(d) Solar PV costs have fallen more than 90% in the past ten years. Applications have moved from space, through consumer electronics, to remote power use, and recently to peak load shedding. A number of additional technical advances will be needed to make the breakthrough into central grid applications, particularly with thin-film cells. Key ingredients behind this progress include long-term R&D with a series of applications in the market place as costs fall. Large scale systems using hydrogen as a carrier are still to be tested.

(e) There is widespread use of solar water heating in a relatively small number of countries (e.g., Japan, Israel, Greece, and Cyprus). The high uptake in Israel (65% of all domestic dwellings) and Cyprus (c. 90% of domestic dwellings and 30% of commercial buildings) have been mainly due to building codes which make it mandatory to include solar heating, standard setting (e.g., guaranteed performance), affordable and simple financing, and good marketing (Gregory, 1993). Solar water heating in certain climates is cost-effective relative to oil and gas, including hybrid (solar-gas) systems in Australia and water heating in most Mediterranean countries.

## 8. Sensitivity Testing

A wide range of sensitivity tests were carried out on the FFES. These included the following, relative to the central assumptions of the FFES:

(a) Lower levels of economic growth (as measured by GDP) to assess the impact of "lifestyle" changes and alternative development models.
(b) Lower levels of population. Though higher levels of population are conceivable, this was not tested in the sensitivities.
(c) Less intensive use of materials and resources.
(d) The impact of higher efficiencies of solar and biomass technologies.
(e) The impact of lower rates of improvement in energy efficiency.

(f) Variations in the absolute and relative costs assumed for fossil fuels and solar technology.

## 8.1. Slower penetration of improved energy efficiency

This sensitivity underscores the importance of achieving the technical and economic potential for improved efficiency. In this scenario, energy efficiency improvements are scaled back by one-third through 2030. From 2030 to 2100, a 0.5% per year efficiency improvement rate was assumed, as in the FFES. The result of this sensitivity is a substantial increase in $CO_2$ emissions over the next 40 years relative to the FFES scenario. Projected annual emissions increase from 5.3 to 6.1 Pg C in 2010 and from 2.6 to 3.8 Pg C by 2030. Cumulative emissions rise to nearly 400 Pg C, a 27% increase.

## 8.2. The impact of higher efficiencies of solar and biomass efficiencies

The main impact is to considerably reduce the land area requirements for renewable energy, particularly biomass. By doubling solar/wind efficiencies, doubling the baseline biomass productivities, and assuming a 25% recovery of biomass residues, land-use requirements fall to 379 million hectares, or 4% of global arable/forest/pasture/wood land. If this were linked to other sensitivities where global GDP is reduced by one-third and the population is lower, the land-use requirements fall to as little as 2% of total global land-use.

## 8.3. The impact of higher solar costs

Sensitivities were developed whereby unit solar costs were 30 and 50% higher than the main FFES scenario. The impact is to delay the transition to a fossil-free energy economy and/or require a larger level of carbon/energy taxation, plus other policy measures (e.g., $CO_2$ emission standards), to maintain the contribution of the technologies. In contrast to the US EPA's RCW, and SCW global scenarios, unit costs increase by 7 to 9.5% in 2025 and 17.5 to 26% in the year 2050. This leads to a nominal loss of output compared to global GDP of less than 0.03% in the year 2025 and 0.06% in the year 2050. It should be noted, however, that primary energy demand is considerably less in the FFES than either the RCW or SCW scenarios in the periods concerned.

### 8.4. Other sensitivity test results

A somewhat surprising result of the sensitivity testing is that annual carbon dioxide emissions are little altered from the main FFES, with the exception of slower energy efficiency improvement rates. This does not lead to a conclusion that population and GDP levels have no impact on the results; in fact they significantly reduce global fuel needs. It mainly reflects the already low levels of carbon emissions achieved in the main scenario. What the sensitivity tests show above all is the need to make an early start on measures to improve energy efficiency throughout society.

## 9. Policy Implications of the FFES

Historically, it has taken new fuels some 50 years to capture 10% of the global energy market (Marchetti, 1989). In the period 1973–1986, a number of OECD countries reduced energy intensities 2-3% per annum. The FFES assumes an average level of reduction of 2.5% per annum. In the FFES, renewable energy sources increase from their current 14% of total energy supplies, some of which is based on inefficient traditional biofuels, to 60% within the next 40 years. Strong policies will clearly be needed to reach those targets.

A detailed consideration of the policy implications of achieving a fossil free energy future is beyond the focus of this paper. However, a number of key policy points have been developed by Greenpeace.

### 9.1. Pricing policies

A perfect energy market requires full knowledge of all market elements and alternatives, equal access to capital, and free competition. The perfect energy market does not exist as government and industry interfere with the market in numerous ways. In the last fifty years, legislation, pricing, and institutions have developed to favor fossil fuels and nuclear power. These now form market barriers, preventing producers and consumers from using new technologies to save money and utilize cleaner and sustainable energy systems.

Realistic energy pricing will not on its own solve global warming. As part of a wider strategy, however, it is important in sending the correct signals for investment choices and removing subsidies. Policies should include the introduction of energy taxes to reflect the full environmental costs of fossil fuels and nuclear power; the introduction of tax credits for renewable energy developers; and removing the financial incentives for utilities to sell increasing quantities of gas or electricity.

## 9.2. Intervening in the market

In addition to realistic energy pricing, regulation is needed to prevent cartels forming and the market from being manipulated. Policies should include new mandatory efficiency standards for appliances, vehicles, buildings, industrial motors, and other technologies; government support for public transport; planning regulations which discourage major new road-building and urban sprawl; integrated resource planning (IRP) and Demand Side Management (DSM) programs could be encouraged. DSM expenditure is doubling from 3.6 billion ECUs per year in 1992 ($3 billion) in the USA to a projected 8.4 billion ECUs ($7 billion) by 2000 (Krier and Goodman, 1992). An expenditure of 12–24 billion ECUs ($10–20) per year could be justified (Prindle, 1990). The role of externalities pricing within IRP or renewables credits are important policy tools to encourage the development of renewables.

## 9.3. Research and development

There are a number of reasons why certain technologies achieve success and capture a large portion of the energy market. Improving efficiencies and reducing costs are important objectives for accelerating the impact of renewable energy technologies. Enhanced research, development, and deployment (R,D&D) can assist in this. One study has estimated that an expenditure of some 3.6 billion ECUs ($3 billion) in the USA over the next few decades could double the projected contribution of renewable energy over that period (Solar Energy Research Institute *et al.*, 1990).

A new approach toward energy Research and Development is needed. International Energy Agency governments energy R&D budgets are currently heavily skewed toward fossil fuels and nuclear power. Only 12.5% of the total budget of 9.3 billion ECUs ($7,675 million) is allocated to renewables and energy conservation; over 70% is allocated to fossil fuels and nuclear power (Greenpeace International, 1992).

## 9.4. Changing institutions

None of the current energy institutions are guided by environmental concerns. At the international level, organizations exist to promote and develop oil use (OPEC), coal (the International Energy Agency), and nuclear power (the International Atomic Energy Agency). Transnational corporations promote and lobby for oil, coal, gas, and nuclear power. No international organizations exist for energy efficiency and renewable energy.

A major reassessment of energy institutions is needed if global energy policies are to change. New lending criteria for power sector loans, which encourage energy efficiency investments, would be a start. The creation of a new international agency for the development and promotion of technologies for renewables and energy efficiency (TREEs) has been proposed by Greenpeace and others.

A TREEs agency could provide a focus for energy funding, R&D collaboration, technology transfer, education, and information supply.

## 9.5. International climate protection policies

One hundred and fifty four nations signed the International Climate Convention at the Earth Summit in June, 1992. Article 2 of the Convention commits signatories to the stabilization of concentrations of greenhouse gases at a level which will prevent dangerous anthropogenic change. Achieving this will require a range of strong protocols or modifications to the Convention itself, and tough international compliance, complimented with tough national and regional $CO_2$ reduction targets. A priority follow-up protocol to the Convention could be an Energy Efficiency Protocol committing signatory countries to achieving annual improvements in energy efficiency over the next few decades. A challenging target would be an average of 2.5% per year over the next forty years. Other options which could be linked to global $CO_2$ targets might include renewable energy and transport protocols (covering energy efficiency and alternative fuels).

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# Russia – Energy-Related Greenhouse Gas Emissions: Present and Future

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## Abstract

In many long-term world energy and greenhouse gas (GHG) emission models, the former USSR was one of the most important and most difficult regions to model. Now that the former USSR has been split into 15 newly independent states (NIS), the modeling process has become even more difficult. On the one hand, collecting energy and economic data has always been a nightmare, and even more so now. On the other, economic policies of the NIS countries are different, and so are the times they will need to manage the transition to market economies.

Russia is the largest contributor to GHG emissions among the NIS countries. This paper presents major results for present and future energy-related GHG emissions in Russia, and the results of a GHG emissions inventory for 1990. The level, structure, and costs of GHG emissions reductions due to economic crisis in 1990–1995 are evaluated, and a basic scenario for determination of future mitigation strategies for 1995–2015 is presented. Different strategies for economic and energy development with minimum GHG emissions are analyzed and evaluated, and the effectiveness of a carbon tax is assessed.

## 1. Starting Point: GHG Emissions in Russia in 1990

The first results of 1990 energy-related GHG emissions inventory for Russia were presented in Bashmakov (1993). Since then these results have been slightly revised, but not finally. Much more data are needed to improve the estimates, especially for $CH_4$, CO, and $NO_x$[1] emissions. It is a challenge to predict the future of any country, but in Russia it is even a greater challenge to collect the data necessary for a proper description of the past. Based

[1] $NO_x = NO + NO_2$ (reactive odd nitrogen) throughout this paper.

on intensive work using various statistical data sources, the 1990 Russian energy balance has been updated and presented in more detail (see Table 1). The main features of the Russian energy balance are as follows:

- Russia is one of the world's largest energy exporters; net exports in 1990 were 434 mtoe, or 33.5% of energy production;
- the share of natural gas in primary energy consumption is very high: 43% compared with the world average of 19%;
- the share of the residential and commercial sectors in final energy consumption is relatively low: 25% compared with the world average of 34%;
- the share of district heating in final energy consumption is unusually high: 31.4%;
- Russia has a much higher energy intensity than Western countries: the energy intensity of GDP is 2–3 times those of the USA or Western Europe.

Based on these revised energy balance data and the methodology of GHG emissions inventory developed by the OECD (Bashmakov, 1992 and 1993), revised emissions estimates have been made, as shown in Table 2.

Only emissions released by production, storage, transformation, transportation, distribution, and consumption of fossil fuels, and only emission of four principal greenhouse gases – $CO_2$, $CH_4$, CO, and $NO_x$ – are considered in this paper. Emission factors for $N_2O$ releases in energy related activities are unknown, therefore only total $NO_x$ emissions are presented here.

*$CO_2$*. Total $CO_2$ emissions in Russia in 1990 were 622 Mt C, or approximately 10% of the global energy-related $CO_2$ emissions. Russia was the third largest emitter after the USA and China. With per capita emissions of 4.2 tons, Russia occupied fifth place after the former East Germany (5.4 tons), the USA (5.3 tons), Canada (4.6 tons), and the former Czechoslovakia (4.4 tons). The main sources of $CO_2$ emissions include the energy sector, industry and agriculture, residential and commercial, and transportation, with 59, 21, 10, and 10%, respectively (see Table 2). The leading sources by fuel type are natural gas, oil, coal, and other solid fuels. The carbon contribution to the total emissions of the four major greenhouse gases totals 78%.

*$CH_4$*. Methane emissions in 1990 are estimated to be 16.7 Mt (see Table 2). The major source of methane emissions is the gas supply system (76%), followed by coal production (23.8%). Studies of methane leakages as part

**Table 1.** Energy balance, Russia 1990.

| Sectors | Coal | Other solid fuels | Oil | Gas | Nuclear | Hydro | Electri- city- | Heat | Total |
|---|---|---|---|---|---|---|---|---|---|
| Production | 276.10 | 27.50 | 742.50 | 736.70 | 44.90 | 20.40 | | | 1848.10 |
| Import | 28.60 | 0.00 | 35.20 | 29.00 | | | 4.31 | | 97.11 |
| Export | 53.10 | 0.00 | 415.60 | 243.80 | | | 5.33 | | 717.83 |
| Changes in stocks | 0.00 | 0.00 | | –3.70 | | | | | –3.70 |
| Consumption | 251.60 | 27.50 | 362.10 | 525.60 | 44.90 | 20.40 | –1.02 | | 1231.08 |
| Stat. diff. | 8.93 | 0.07 | 3.43 | –2.43 | | | –0.09 | 0.34 | 10.25 |
| El. generation | –74.19 | –0.80 | –26.69 | –60.80 | –44.00 | –20.40 | 90.10 | | –136.78 |
| CHP | –40.56 | –1.17 | –23.94 | –158.87 | | | 42.90 | 136.42 | –45.22 |
| Boilers | –31.33 | –5.80 | –40.08 | –95.91 | –0.90 | | | 144.86 | –29.16 |
| Rec. waste heat | 0.00 | 0.00 | 0.00 | 0.00 | | | | 14.73 | 14.73 |
| Own use and losses | –0.42 | –0.04 | –12.23 | –80.14 | | | –34.64 | –20.13 | –147.60 |
| Final consumption | 96.17 | 19.62 | 255.73 | 132.31 | 0.00 | 0.00 | 97.43 | 275.54 | 876.80 |
| Industry | 50.56 | 0.78 | 30.50 | 60.78 | | | 53.44 | 139.83 | 335.89 |
| Iron and steel | 45.51 | 0.00 | 4.29 | 26.34 | | | 8.94 | 9.95 | 95.03 |
| Non-ferrous | 0.13 | 0.00 | 3.79 | 2.46 | | | 11.98 | 5.95 | 24.31 |
| Chemical | 0.01 | 0.00 | 5.18 | 4.46 | | | 8.50 | 39.91 | 58.06 |
| Machinery | 0.32 | 0.00 | 3.23 | 6.10 | | | 11.41 | 31.92 | 52.98 |
| Wood and pulp and paper | 0.10 | 0.54 | 2.21 | 0.37 | | | 3.01 | 16.03 | 22.26 |
| Building material | 3.23 | 0.10 | 6.57 | 15.62 | | | 3.65 | 12.28 | 41.45 |
| Construction | 0.43 | 0.00 | 0.00 | 3.75 | | | 2.31 | 5.96 | 12.45 |
| Light | 0.02 | 0.00 | 0.05 | 0.05 | | | 1.82 | 5.78 | 7.72 |
| Food | 0.81 | 0.14 | 5.18 | 1.63 | | | 1.82 | 12.05 | 21.63 |
| Transport | 0.31 | 0.01 | 108.48 | 0.50 | | | 7.63 | 5.43 | 122.36 |
| Agriculture | 2.28 | 0.97 | 23.99 | 1.40 | | | 8.28 | 10.93 | 47.85 |
| Commercial | 22.94 | 6.30 | 8.36 | 13.59 | | | 10.84 | 32.86 | 94.89 |
| Residential | 16.62 | 4.67 | 9.73 | 18.86 | | | 10.54 | 66.37 | 126.79 |
| Others | 1.84 | 0.75 | 10.16 | 4.16 | | | 6.70 | 20.12 | 43.73 |
| Non-energy use | 1.62 | 6.14 | 64.51 | 33.02 | | | | | 105.29 |

Source: Bashmakov *et al.*, 1994.

**Table 2.** Russia: Revised estimates of energy-related GHG emissions, 1990.

| Energy process | Fuel types | $CO_2$ (Mt C) | $CH_4$ (Mt) | CO ($10^3$ t) | $NO_x$ ($10^3$ t) | GHGs (Mt $CO_2$ eq.) |
|---|---|---|---|---|---|---|
| Electricity generation | Total[a] | 102.5 | | 45.3 | 896.9 | 411.7 |
| | Coal | 58.5 | | 37.0 | 519.3 | 235.3 |
| | Oil | 16.3 | | 8.0 | 160.1 | 66.0 |
| | Gas | 27.0 | | | 212.8 | 107.0 |
| District heating | Total | 96.3 | | 181.3 | 610.7 | 378.1 |
| | Coal | 24.3 | | 156.7 | 141.0 | 95.3 |
| | Oil | 24.5 | 0.02 | 12.0 | 168.3 | 97.0 |
| | Gas | 42.6 | | | 278.1 | 167.0 |
| CHP | Total | 117.5 | | 27.7 | 868.6 | 465.1 |
| | Coal | 31.3 | | 20.3 | 223.1 | 123.8 |
| | Oil | 14.7 | | 7.18 | 119.7 | 59.0 |
| | Gas | 70.5 | | | 508.4 | 279.0 |
| Own use and losses | Total | 43.4 | | 3.9 | 236.0 | 168.6 |
| | Coal | 0.3 | | 0.2 | 1.3 | 1.2 |
| | Oil | 7.5 | | 3.7 | 34.2 | 29.0 |
| | Gas | 35.6 | | | 200.4 | 138.0 |
| Industry | Total | 92.8 | | 4115.3 | 437.5 | 370.1 |
| | Coal | 38.8 | | 3668.0 | 157.2 | 159.5 |
| | Oil | 23.9 | | 447.3 | 113.9 | 94.0 |
| | Gas | 28.8 | | | 162.3 | 112.0 |
| Agriculture | Total | 16.9 | | 152.5 | 68.3 | 65.1 |
| | Coal | 1.7 | | 114.0 | 5.7 | 6.9 |
| | Oil | 13.7 | | 24.0 | 57.6 | 53.0 |
| | Gas | 0.6 | | | 2.8 | 2.0 |
| Transportation | Total | 61.0 | | 18839.0 | 2390.6 | 376.0 |
| | Coal | | | | | |
| | Oil | 60.9 | | 18767.0 | 2386.6 | 375.0 |
| | Gas | 0.2 | | 72.0 | 4.0 | 1.0 |
| Residential and commercial | Total | 63.4 | 0.004 | 2160.6 | 257.3 | 249.4 |
| | Coal | 30.1 | | 1978.0 | 114.7 | 121.1 |
| | Oil | 10.3 | | 18.1 | 47.0 | 40.0 |
| | Gas | 14.4 | | | 68.2 | 56.0 |
| Non-energy use | Total | 23.4 | | | | 86.0 |
| | Coal | | | | | |
| | Oil | 13.6 | | | | 50.0 |
| | Gas | 9.8 | | | | 36.0 |
| Energy production and transportation | Total | 4.9 | 16.74 | | | 369.6 |
| | Coal | | 3.98 | | | 83.6 |
| | Oil | 4.9 | 0.1 | | | 20.0 |
| | Gas | | 12.66 | | | 266.0 |
| Total | Total | 622.1 | 16.75 | 25525.8 | 5754.0 | 2939.3 |
| | Coal | 185.1 | 3.98 | 5974.2 | 1162.2 | 826.6 |
| | Oil | 190.3 | 0.1 | 19287.3 | 3087.4 | 881.0 |
| | Gas | 229.1 | 12.66 | 72.0 | 1436.9 | |

[a]Total includes other solid fuels.

of the global warming problem are at a very early stage in Russia. Little information is available, especially regarding the losses from the gas supply system. Many more measurements and studies in this area are needed to provide more reliable information. Methane is the second most important greenhouse gas, contributing 12% to the total emissions.

*CO.* CO emissions in 1990 were 25.3 Mt. The main sources of these emissions were petroleum consumption by transport (74%) and industry (16%). The contribution of CO to total GHG emissions is estimated at about 2.6%.

*$NO_x$.* $NO_x$ emissions in 1990 were 5.8 Mt $NO_x$. Among the major contributors are transport, electricity, and heat generation. $NO_x$ contributes 7.8% to total emissions of greenhouse gases.

The emission estimates for $NO_x$ and CO are much less reliable than that for $CO_2$ (Bashmakov, 1991). This uncertainty is largely due to the dependence of emission coefficients on a number of factors, including: fuel characteristics; combustion conditions; control equipment efficiency; and combustion technology type, size, vintage, maintenance, and operation. Depending on these factors, emissions could vary by several orders of magnitude (OECD, 1991). The OECD methodology suggests a set of coefficients that can be used for nations without national CO and $NO_x$ emissions inventories. Results for the former USSR for CO and $NO_x$ using this set of coefficients in combination with national statistical data illustrate how crude estimates based on such external coefficients can be (Bashmakov, 1992).

*GHG.* Total energy-related GHG emissions in 1990 were 2,939 Mt $CO_2$ equivalent.

## 2. Economic Crisis as a Mitigation Strategy

### 2.1. Land of crisis[2]

Russia is a land in crisis, as is demonstrated by the following litany of ills:

- The Russian GDP declined by 18.5% in 1992. Economic activity in 1993 was lower than in 1985: industry by 39%; agriculture by 13%; construction by 59%; and trade by 45%.

[2]This section is based on Bashmakov *et al.* (1993).

**Table 3.** Indices of economic activity in Russia (1985=100).

| | 1989 | 1990 | 1991 | 1992 | 1993[a] |
|---|---|---|---|---|---|
| National income | 110 | 109 | 94 | 75 | 61 |
| Industry | 110 | 108 | 101 | 81 | 64 |
| Agriculture | 114 | 102 | 100 | 95 | 87 |
| Construction | 136 | 130 | 114 | 59 | 41 |
| Transport/Communications | 102 | 96 | 89 | 71 | 51 |
| Trade and others | 99 | 90 | 66 | 40 | 56 |
| Public transport | 111 | 113 | 107 | 94 | 77 |
| Residential (living area) | 111 | 113 | 116 | 116 | 116 |
| Commercial (floor area) | 129 | 138 | 143 | 147 | 149 |

[a]Preliminary estimates based on eight months of economic activity.
Sources: Calculated based on: "Rossiyskaya Federatsiya v Tsifrakh v 1992 godu," Moscow, 1992; "O Razvitii Economicheskikh Reform v Regionakh Rossiyskoy Federatsii," Moscow, September 1993; "Narodnoye Khozyaistvo RSFSR in 1991," Statistics Yearbook.

- Inflation is running at over 25% per month, or 2000% per year; average monthly wages were about \$40 in September 1993; unemployment is low, less than 1%.
- Standards of living are falling; in June 1993 private consumption in real terms was only 34% of the December 1990 level.
- The energy intensity of the already inefficient economy increased by more than 40–42% in 1990–1993.
- Russian oil production in 1993 was 48% below the 1988 level.

The public is unsettled and the government faltering. Production is slumping, inflation is accelerating. Many activities in the industrial and energy sectors have been crippled by mismanagement, power struggles, increasing production costs, and diminishing government subsidies (see Table 3). Despite – and because of – the high energy and materials intensity, the level of goods and services available to consumers is extremely low and the standard of living is still unacceptable.

Russia has begun a transition to democracy and a market system. Although there are disagreements both within the government and between the government and the current legislature on the pace and mechanism of reform, fledgling democratic relations and signs of market economics are beginning to take shape. Economic measures such as price reforms and privatization have resulted in some semblance of market-type activity.

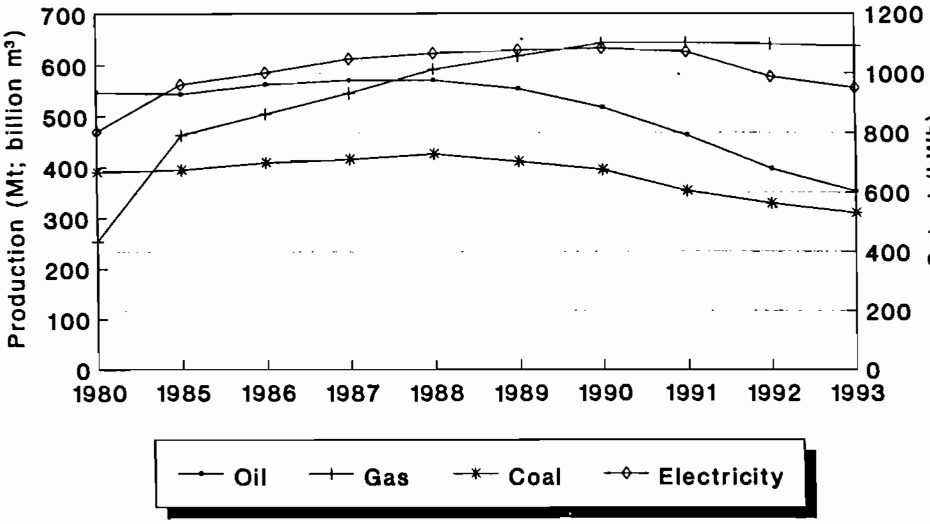


**Figure 1.** Energy production in Russia, 1980–1993.

## 2.2. 1992 energy balance

Based on available data, the Russian energy balance for 1992 has been reconstructed (see Table 4). Against the background of economic change, the evolution of the energy balance in 1990–1992 is not impressive:

- Primary energy production declined by 13%, and primary energy consumption declined even more slowly, by just 6%.
- The greatest decline was in coal and oil production, while natural gas, hydro, and nuclear power production remained almost constant (see Figure 1). As a result, the contribution natural gas to energy production grew to 46%. Natural gas produced in Russia was able to cover 64% of the country's primary energy demand.
- While in all sectors energy consumption shrank, consumption in the residential and commercial sectors was higher than in 1990.

## 2.3. Sharp growth of energy intensity

It is the energy intensity of national income that has been really surprising. By the end of 1993 it is expected to be 40–42% above the 1990 level (see Figure 2). A number of structural factors have contributed negatively to the energy intensity (see Figure 3):

**Table 4.** Energy balance, Russia 1992.

| Sectors | Coal | Other solid fuels | Oil | Gas | Nuclear | Hydro | Electri-city- | Heat | Total |
|---|---|---|---|---|---|---|---|---|---|
| Production | 210.00 | 28.50 | 572.00 | 735.00 | 44.80 | 21.00 | | | 1611.30 |
| Import | 22.90 | 0.00 | 29.70 | 10.00 | | | 4.31 | | 66.91 |
| Export | 22.60 | 0.00 | 273.00 | 223.45 | | | 5.33 | | 524.38 |
| Change in stocks | 0.00 | 0.00 | 1.00 | -1.10 | | | | | -0.10 |
| Consumption | 210.30 | 28.50 | 327.70 | 522.65 | 44.80 | 21.00 | -1.02 | | 1153.93 |
| Stat. diff. | 1.53 | -0.14 | 11.93 | 7.33 | | | 3.21 | 3.74 | 27.59 |
| El. generation | -61.20 | -1.04 | -28.00 | -62.60 | -44.00 | -21.00 | 81.80 | 1.29 | -134.75 |
| CHP | -33.00 | -1.40 | -23.40 | -162.00 | | | 42.20 | 137.28 | -40.32 |
| Boilers | -29.50 | -5.90 | -37.50 | -96.00 | -0.80 | | | 136.71 | -32.99 |
| Rec. waste heat | 0.00 | 0.00 | 0.00 | 0.00 | | | | 14.01 | 14.01 |
| Own use and losses | -0.42 | -0.05 | -13.00 | -80.04 | | | -21.97 | -19.20 | -134.68 |
| Final consumption | 84.65 | 20.25 | 213.87 | 114.68 | 0.00 | 0.00 | 97.80 | 266.35 | 797.60 |
| Industry | 38.56 | 0.81 | 24.64 | 48.54 | | | 53.03 | 130.64 | 296.21 |
| Iron and steel | 34.98 | 0.00 | 3.63 | 22.06 | | | 8.84 | 8.72 | 78.23 |
| Non-ferrous | 0.09 | 0.00 | 2.81 | 1.80 | | | 11.20 | 5.77 | 21.67 |
| Chemical | 0.01 | 0.00 | 4.17 | 3.56 | | | 8.64 | 38.61 | 54.99 |
| Machinery | 0.25 | 0.00 | 2.73 | 5.11 | | | 11.46 | 31.17 | 50.72 |
| Wood and pulp and paper | 0.08 | 0.55 | 1.88 | 0.31 | | | 3.45 | 14.30 | 20.57 |
| Building material | 2.37 | 0.10 | 5.31 | 12.51 | | | 3.44 | 10.89 | 34.63 |
| Construction | 0.20 | 0.00 | 0.00 | 1.86 | | | 2.12 | 4.79 | 8.97 |
| Light | 0.01 | 0.00 | 0.04 | 0.04 | | | 1.73 | 5.29 | 7.11 |
| Food | 0.58 | 0.16 | 4.07 | 1.27 | | | 2.16 | 11.10 | 19.34 |
| Transport | 0.23 | 0.10 | 94.00 | 0.40 | | | 10.98 | 5.43 | 111.14 |
| Agriculture | 2.03 | 1.00 | 21.00 | 1.50 | | | 6.15 | 10.93 | 42.61 |
| Commercial | 24.32 | 6.50 | 9.00 | 15.70 | | | 10.84 | 32.86 | 99.22 |
| Residential | 16.95 | 5.00 | 10.00 | 20.97 | | | 11.55 | 66.37 | 130.84 |
| Others | 1.38 | 0.70 | 8.00 | 3.40 | | | 5.25 | 20.12 | 38.85 |
| Non-energy use | 1.19 | 6.14 | 47.23 | 24.18 | | | | | 78.73 |

Source: Calculated on the basis of "Rossiyskaya Federatsiya v Tsifrakh v 1992 godu," Moscow, 1992; "O Razvitii Economicheskikh Reform v Regionakh Rossiyskoy Federatsii," Moscow, September 1993; "Narodnoye Khozyaistvo RSFSR in 1991," Statistics Yearbook.

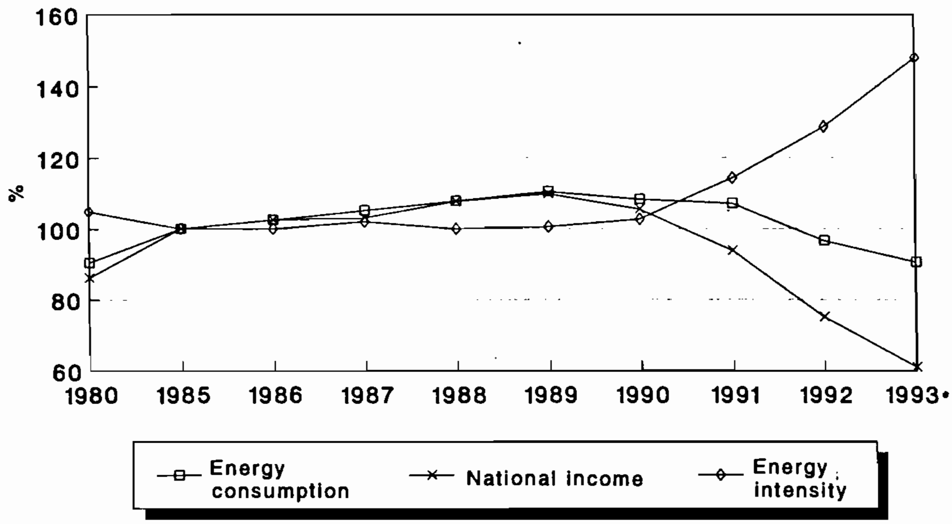


**Figure 2.** Energy consumption, national income, and energy intensity: 1985=100. (*Preliminary estimates based on eight months of economic activity.)

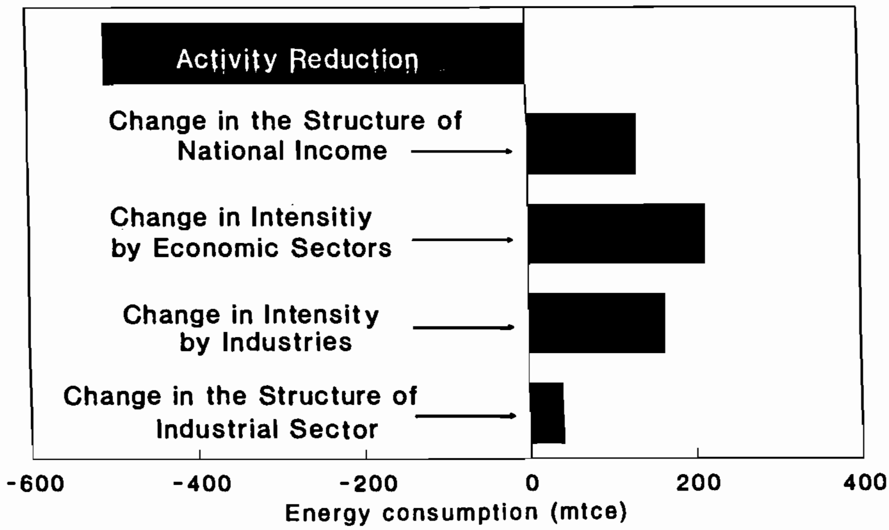


**Figure 3.** Factors in the evolution of energy intensity, 1990–1993.

- Economic output declined against the background of stable and even growing energy consumption in the residential and commercial sectors.

**Table 5.** GHG emissions, 1990–1995.

| Years | $CO_2$ (Mt C) | $CH_4$ (Mt) | CO (Mt) | $NO_x$ (Mt) | GHGs (Mt $CO_2$ eq.) |
|---|---|---|---|---|---|
| 1990 | 622.1 | 16.75 | 26.27 | 5.75 | 2939 |
| 1991 | 590.5 | 15.68 | 23.20 | 5.44 | 2782 |
| 1992 | 570.8 | 15.63 | 21.89 | 5.20 | 2695 |
| 1993 | 534.2 | 14.60 | 21.32 | 4.67 | 2516 |
| 1994 | 518.2 | 14.98 | 20.71 | 4.52 | 2458 |
| 1995 | 528.1 | 15.21 | 21.10 | 4.62 | 2504 |

Note: Total GHG emissions are estimated on the basis of the global warming potential concept with $CO_2$ equivalent coefficients: 21 for $CH_4$; 3 for CO; 40 for $NO_x$.

This relatively stable consumption, in relation to the reduced national income, has contributed negatively to energy intensity.

- Negative structural changes in the industrial sector (at the two-digit level) also contributed to the reduction of energy efficiency in Russia. Structural changes reduced the shares of less energy intensive industries; the share of energy consumption related to the volume of production decreased and a larger share of energy is consumed regardless of plant throughput.

## 2.4. GHG emissions reductions

Russia is one of the a few nations who at present is not only speaking of the necessity of reducing GHG emissions, but is also actively moving in this direction. In 1990–1992 $CO_2$ and CO emissions declined by 8%, $CH_4$ emissions by 7%, and $NO_x$ emissions by 5% (see Table 5). In 1993 and 1994 more significant reductions are expected – $CO_2$ emissions in 1993 are expected to be 90 Mt C, or 14% lower than the 1990 level. It is clear that the economic crisis is a major driving force behind this reduction. It is also clear that due to the specific nature of this crisis, the GHG emissions reduction was not as great as the economic decline.

We could speculate with several "ifs". For example, what would happen if the energy intensity in 1990–1992 had remained stable? In 1990–1993 national income declined by 44%. If the energy intensity had not changed, primary energy consumption would be (861 mtoe $\times$ 0.56 =) 482 mtoe. That means that in addition to the hydro, nuclear, and natural gas consumed in 1992, there would have been an additional demand for only 92 mtoe of oil. In this scenario $CO_2$ emissions would have been only 296 Mt C in 1992, or 48% of the 1990 level (a decline of 52%) (see Figure 4). $CH_4$ emissions would

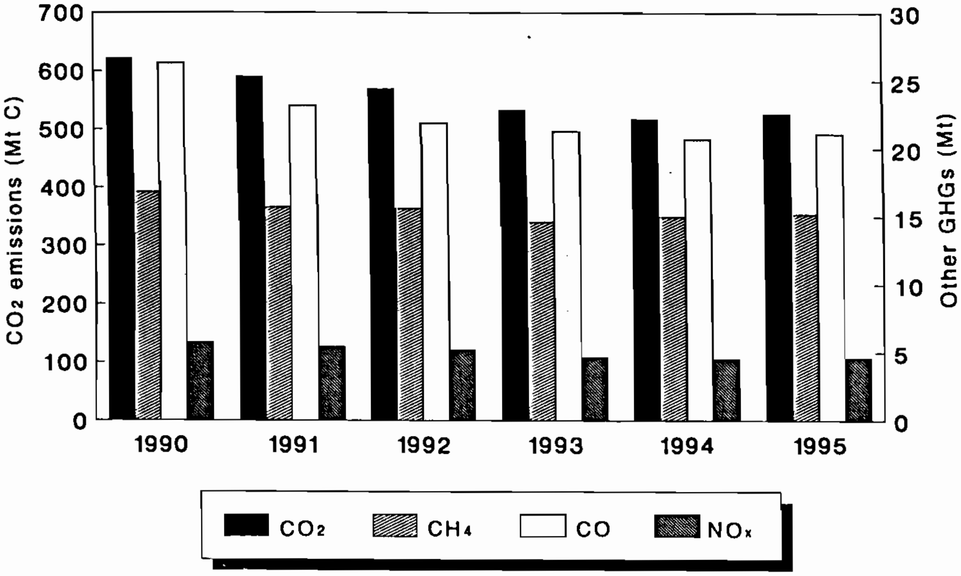


**Figure 4.** GHG emissions, 1990-1995.

also have been 25% lower (equivalent to an additional 23 Mt C) due to a complete halt on coal mining.

If the fuel mix had stabilized as well as energy intensity, then $CO_2$ emissions in 1992 would have declined by 44%, to 348 Mt C. Unfortunately, none of these "ifs" happened, and the decline in GHG emissions in Russia was much more moderate.

The economic crisis in Russia will continue for some time to come. Because of the significant political component, predicting the length and shape of this crisis in future is not an easy task.

Predictions for 1993–1995 were based on the assumptions that the decline in GDP will continue in 1994 (4%), and that 1995 will be the first year of the easing of the crisis (7% GDP growth). These optimistic assumptions, as well as other exogenous variables such as energy price evolution and structural changes in the economy, were used as inputs to a variant of the RUSEB model, adjusted for crisis conditions. The Russian energy balances for 1993–1995 were estimated by this model and the results were inputs in CO2RUS, CH4RUS, CORUS, NOXRUS, and GHGRUS models.

Aggregated GHG emissions estimates taken from these models for 1993–1995 are presented in Table 5. According to these results, GHG emissions will continue to decline in 1993–1994, with some slight growth after 1995.

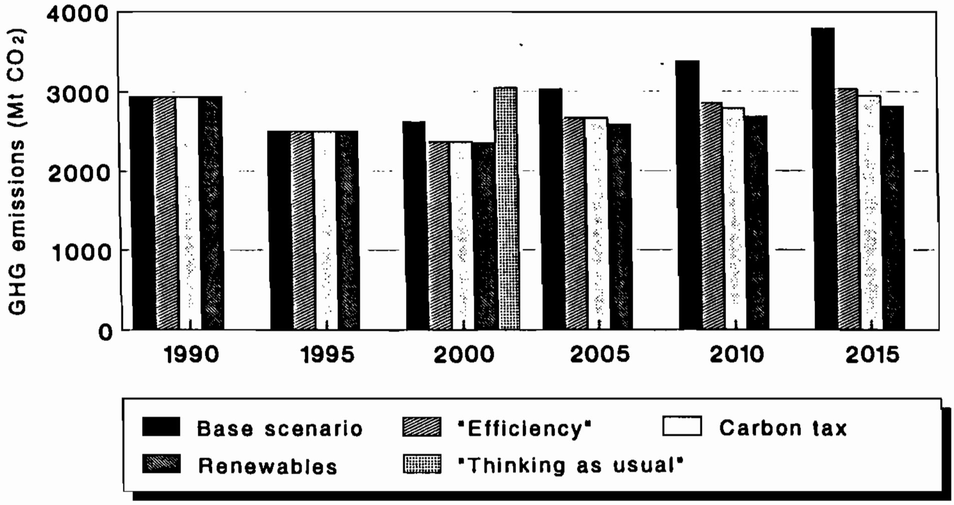


**Figure 5.** GHG emissions scenarios for Russia, 1990–2015.

## 2.5. How expensive is crisis as a mitigation strategy?

The Russian GDP losses in 1991–1995 are estimated to be $2,023 billion (1980).[3] The cumulative GHG emissions reduction in 1991–1995 is estimated to be 474 Mt C. In other words, the cost of every ton of carbon reduced is $4,260 (1980) of GDP loss. In the case of stable energy intensity and a stable fuel mix, the cumulative GHG reductions would be 1,427 Mt C, and the GDP loss per ton would be $1,417 (1980). In the case where priority is given to the replacement of carbon-intensive fuels, the cumulative reduction would be 1570 Mt C, and therefore the GDP loss per ton of carbon reduced would be $1,288. In any case, the price of GHG mitigation through economic crisis is extremely high.

To conclude this section, we would like to comment that *the cumulative reduction of total GHG emissions in 1990–1995 will be 474 Mt C, and should be considered as an emission credit for Russia in the years to come.* Russia has already paid heavily to prevent the release of this amount of carbon to the atmosphere. If an international agreement on tradable carbon emission rights is negotiated, it should allow countries to trade emission credits received as a result of economic crisis. If the price of carbon were $50 per ton (which is much less than the proposed carbon tax rate of $200 per ton), Russia would receive for these emissions a credit of $23.7 billion.

[3]Estimate based on PPP data (Summers and Heston, 1988).

# 3. "Business as Usual" with Very Unusual Business

## 3.1. "Thinking as usual"

The painful process of transition in Russia is actually several simultaneous transitions. The monolithic, top-down government must be transformed into a bottom-up system of regional authority and decision making. The centrally planned system must be recast for the economy to develop market-based interactions. Emphasis on military production and heavy industry must be reduced in favor of consumer goods and light industry. Isolationism must give way to international trade and participation in foreign markets. And the people must alter their way of thinking – and working – in order to survive in a competitive world.

In other words, there is not too much room left for Russians to do "business as usual", but "thinking as usual" still remains. This thinking is represented in two recent government programs on energy sector development. The first is the "Concept of Russia's Energy Policy under New Economic Conditions", which has been criticized for its old style of thinking by a group of Russian experts.[4] Second, based on this "Concept", the State Program "Fuel and Energy" was developed and approved by the Council of Ministers in July 1993.[5]

The major weaknesses of these two documents include:

- Only one scenario was developed for the very uncertain future of the economy and energy system.
- A practically exclusive orientation on supply-side options to cover energy demand.
- The maintenance of centralized control over the energy sector even for a long-range future.
- The levels of energy production proposed by both documents are close to upper potential capacities, and the program is very capital intensive.

The "Fuel and Energy" program was developed about a year after the "Concept", when some quantitative targets were revised. The data presented

[4] Conclusion by a team of experts on "The Concept of Russia's Energy Policy under New Economic Conditions", *Energeticheskoe Stroitelstvo*, No. 6, 1993. The members of the expert group included I. Bashmakov, Yu. Bokserman, O. Braginsky, S. Chernavský, I. Grisevich, V. Laslennikov, and N. Roddatis. The work was coordinated by L. Popova and V. Nemenchinsky.

[5] *Decision of the Presidium of the Council of Ministers on the State Program "Fuel and Energy"*, 22 July 1993, Government of the Russian Federation.

**Table 6.** Main indicators of the "Fuel and Energy" program (mtce).

| Indices | 1990 | 1992 | 1993 | 1995 | 2000 |
|---|---|---|---|---|---|
| National income | 100 | 66.5 | 63.4 | 64.9 | 75.2 |
| Energy intensity | 100 | 138.1 | 144.4 | 139.2 | 129.1 |
| Primary energy consumption | 1272 | 1174 | 1122 | 1100 | 1230 |
| (1990=100) | 100 | 92.3 | 88.2 | 86.5 | 96.7 |
| Coal | 250 | 212 | 221 | 210 | 220 |
| Oil | 429 | 369 | 362 | 326 | 358 |
| Natural gas | 533 | 526 | 525 | 536 | 590 |
| Primary energy production | 1852 | 1625 | 1546 | 1500 | 1670–1730 |
| Coal (Mt) | 369 | 337 | 315 | 325–350 | 340–375 |
| Oil (Mt) | 516 | 400 | 351 | 325 | 330–360 |
| Natural gas (billion $m^3$) | 641 | 640 | 635 | 665 | 735–753 |
| Electricity (billion kWh) | 1082 | 1010 | 975 | 990 | 1070–1100 |
| Hydro | 166 | 172 | 165 | 165 | 167–170 |
| Nuclear | 118 | 120 | 117 | 125 | 115–121 |

Source: State Program "Fuel and Energy", Government of the Russian Federation, July 1993.

in Table 6 are taken from the program. Several comments can be made on these data:

- The energy intensity remains very high until 2000 (it is 29% above the 1990 level in 2000). This means that neither the structural changes due to the predicted revival of the Russian economy, nor the aggressive energy efficiency improvement policy declared in both documents, will achieve meaningful results in terms of improvements in economic productivity in general, and energy efficiency in particular.
- Emphasis is given to providing capital resources for the maintenance and growth of energy supply.

With this "thinking as usual" scenario, $CO_2$ emissions in the year 2000 are estimated to be about 640 Mt C, or 3.5% higher than in 1990 with national income 25% below the 1990 level. In other words, the carbon intensity of national income in the year 2000 would be 38% above the 1990 level.

## 3.2. Base scenario

Many different methodologies and models for energy system evolution projections were developed in the former USSR. Most of these are no longer valid and should be replaced, for at least two reasons:

**Table 7.** Results of the base scenario of the RUSEB model.

| | 1995 | 2000 | 2005 | 2010 | 2015 |
|---|---|---|---|---|---|
| GDP (1995=100) | 100 | 134 | 171 | 208 | 253 |
| Primary energy consumption (mtce) | 1047 | 1100 | 1273 | 1424 | 1600 |
| Energy intensity (1995=100) | 100 | 79 | 71 | 66 | 61 |
| $CO_2$ (Mt C) | 528 | 561 | 649 | 726 | 816 |
| $CH_4$ (Mt) | 15.2 | 15.4 | 17.8 | 19.5 | 21.5 |
| CO (Mt) | 21.3 | 19.5 | 22.2 | 23.7 | 25.4 |
| $NO_x$ (Mt) | 4.6 | 4.7 | 5.4 | 5.9 | 6.6 |
| GHG emissions (Mt $CO_2$ eq.) | 2503 | 2628 | 3036 | 3382 | 3786 |
| (1995=100) | 100 | 105 | 121 | 135 | 151 |

- The system of decision making is under significant evolution and models tuned to a command-administrative economy with no incorporation of market parameters fail to predict the behavior and responses of final energy consumers and energy producers to market signals.
- All models were developed to simulate the growth of the energy system; insufficient information is available to describe the energy system during periods of rapid economic decline or revival.

For those who are trying to incorporate market variables in their models, there is another significant challenge: the absence of more or less reliable information based on which parameters of energy producers' and consumers' reactions to market signals can be calibrated.

The perspectives for the evolution of the Russian energy balance in 1995–2015 have been estimated using the RUSEB model. This model was developed by the author as an energy demand model for five final energy consumption sectors and four energy transformation sectors, which transform eight primary energy resources to six secondary energy carriers. The model includes an energy prices and taxes block and allows the simulation of different energy pricing and tax policies. RUSEB includes about 400 equations that describe, among others, the price competition between fossil fuels. The results of the base scenario are summarized in Table 7.

The base scenario was built on the following major assumptions:

- The Russian GDP will increase by 7% in 1995–2000, by 5% in 2000–2005, and by 4% in 2005–2015.
- The share of services in GDP will grow, and average rates of growth in the industrial sector (excluding the energy sector) will be 90% of those for GDP; in agriculture – 70 % and in transport – 50%.

**Table 8.** Evolution of energy intensity in the Russian cycle.

| | Conditional years | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| GDP | 100 | 50 | 80 |
| GDP-related energy consumption | 60 | 30 | 40 |
| Non-GDP-related energy consumption | 20 | 20 | 15 |
| Residential and commercial | 20 | 20 | 20 |
| Final energy consumption | 100 | 70 | 75 |
| Energy sector | 50 | 35 | 37.5 |
| Primary energy consumption | 150 | 105 | 112.5 |
| Energy intensity | 1.5 | 2.1 | 1.4 |
| Industrial sector | | +0.2 | −0.31 |
| Residential & commercial sectors | | +0.2 | −0.15 |
| Energy sector | | +0.2 | −0.23 |

- Energy prices will remain stable for all energy carriers other than natural gas and coal, and for these two real prices in 2000 will grow to 1990 levels.
- No special programs to promote energy efficiency will be undertaken.
- Energy intensity in 1995–2000 will be reduced by 5% per year because of the reverse effect of structural changes during the economic revival: a higher capacity utilization will reduce intensities due to the lower share of energy consumption, independent of the volume of production; faster growth of less energy intensive industries (manufacturing, for example) will also contribute.
- Autonomous technical progress will bring about a decline in energy intensity by 1% per year in all final energy consumption sectors in 2000–2015.
- The level of nuclear and hydro power production will not change until 1995.

Proposals for the rates of economic growth should be viewed as overoptimistic. In the case of very slow growth rates, mitigation strategies are unlikely to be needed for Russia because GHG emissions would not grow significantly above the 1990 level (see Figure 5).

Some clarification of the declining rates of energy intensity is required. A schematic explanation of the approach taken is given in Table 8. The sharp growth in energy intensity during the very sharp decline in economic activity could be explained by the equal contributions of three major factors: stable energy consumption in the residential and commercial sectors; stable consumption in non-GDP-related sector activities (HVAC systems, etc.); and

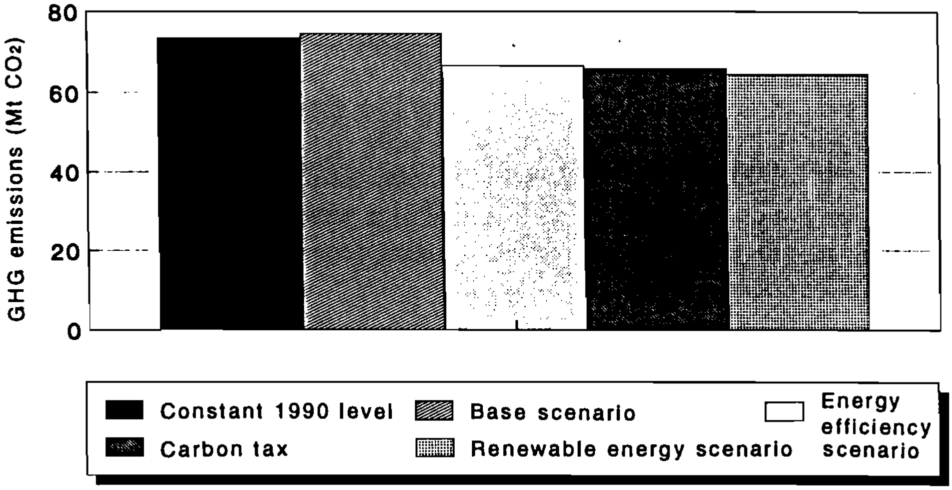


**Figure 6.** Cumulative GHG emissions in Russia, 1990–2015.

finally by increased energy consumption in the energy sector to produce and deliver energy to meet these two demands.

When it happens against the background of a sharp (50%) decline in GDP its energy intensity grows sharply. When the economy revives (say from 50 to 80% of the first year), then if the residential/commercial and HVAC consumption remain constant, and with the closure of factories that produce goods for which there is no demand, not only could the present level of energy intensity be restored, but it could even be reduced below the level of the first year.

Therefore, economic revival could be accompanied by a dynamic reduction in energy intensity. Average rates of GDP decline in 1990–1993 were 13% per year and average rates of energy intensity increase were 12% per year. In 1995–2000, lower rates of growth are projected, as well as lower rates of energy intensity decline compared to the rates of growth in 1990–1993. GDP growth by 2.5 times is accompanied by a 1.5-fold growth in both primary energy consumption and in GHG emissions. In this scenario, the cumulative GHG emissions for 1990–2015 are 74,549 Mt $CO_2$ equivalent, or slightly higher than the cumulative emissions in the case with the stable 1990 level for all 25 years ($2{,}939 \times 25 = 73{,}475$ Mt $CO_2$) (see Figure 6). If the stabilization target is set in the right way for cumulative emissions for the given amount of time, irrespective of the time profile of these emissions, we could state that in 1991–2015 Russia will stabilize average annual cumulative emissions at the 1990 level even in the base case. This means some of the emissions credits accumulated in 1991–1995 would be consumed by Russia itself in the coming years. This result is important for several reasons:

- Russia can accept an obligation to stabilize average annual GHG emissions at the 1990 level at least before 2005.
- Even in the case of faster rates of economic growth and no efficiency improvements, some GHG credits would still accumulate during the years of economic crisis left to cover the extra (compared to the base case) GHG emissions.

As a modification of the base scenario, we assumed that rates of economic growth are 1% lower for every year in 1996–2015. In this case $CO_2$ emissions would increase to 711 Mt C in 2015 (compared to 816 Mt C in the base case). This means that an additional 1% GDP growth will give rise to emissions of about 100 Mt C.

# 4. Business as Unusual

## 4.1. Energy efficiency scenario

Improvement of energy efficiency is not yet usual business in Russia. The tendency for energy intensity to decline is a long-term historical phenomenon (OECD, 1990). There is no definite evidence that this trend ever existed in Russia under the centrally planned economy; according to Kononov (1992), in 1930–1990 the energy intensity of the Russian GDP approximately doubled. If this is indeed the case, the trend observed in Russia was opposite to the general trend elsewhere.

The need for an energy conservation policy is increasingly being considered by the Russian government. As recently as 18 June 1993, the Presidium of the Council of Ministers of the Russian Federation (Cabinet) considered the "Energy Conservation Program for Russia", submitted by the Fuel and Energy Ministry. The potential for improving energy efficiency in Russia is large by any scale (see Table 9). But knowledge of this potential, and even willingness to promote particular technologies through government programs will be of limited use unless new market-based mechanisms are developed that will enable this potential to be realized. The problem is not simply one of inefficient equipment, but also concerns the highly inefficient practices and policies that serve to discourage improvements. Thus the problem should be addressed not just with equipment and technologies in mind, but also with proper institutional infrastructure, management and planning tools,

**Table 9.** Energy savings potential in the Russian Federation in 2010.

| Sector | Natural gas (bill. $m^3$) | Petroleum products (Mt) | Coke & coal (Mt) | Electr. (bill. kWh) | Heat (mill. Gcal) | Total (mtce) |
|---|---|---|---|---|---|---|
| *Fuel and energy complex* | 45–60 | 15–17 | 33–39 | 40 | 160–180 | 150–180 |
| Oil production | 5–10 | | | | | 6–12 |
| Coal production | 3–4 | | | 10 | | 3.5–4.5 |
| Transportation of energy carriers | 8–9 | | 7–8 | 30 | 150–170 | 52–59 |
| Electricity and thermal energy | 32–42 | 10–12 | 26–31 | | | 80–96 |
| Oil refining | | 4.7–5 | | | 9–10 | 8–9 |
| *Residential and commercial sector* | 10 | 0.6–0.8 | 21–23 | 90–105 | 120–145 | 85–95 |
| *Agriculture* | 1.4–1.5 | 35–41 | 1.5–1.7 | 8–10 | 4 | 54–64 |
| *Transportation* | | 29–34 | | | | 42–50 |
| *Industry* | 32–42 | 6–7 | 12 | 140–175 | 75–100 | 71–89 |
| General measures | 10–13 | 0.5 | | | | |
| Metallurgy | 12–15 | 2 | 10–11 | 20-24 | 5–6 | 34–39 |
| Machinery manufacture | 3–4 | 0.5 | | 55–60 | | 14–17 |
| Construction materials | 10–11.5 | 1.7–2 | 2–2.5 | 8.5–10 | 40–45 | 20–23 |
| Chemicals and petrochemicals | 5–6 | | | 4–5 | 12–15 | 9–10 |
| Timber and paper | 0.3–0.7 | 1–2 | | | 35–40 | 8–10 |
| Total | 90–100 | 85–100 | 70–80 | 350–420 | 450–540 | 480–570 |

Source: *Innovacionnaya Investicionnaya "Programma Energosberezenia Rossii" (Strategia Pervoocherednie Meri)*, Draft, Ministry of Fuel and Energy of Russian Federation, June 1993.

efficient legislation and regulatory systems, financial incentives, education and training, standards, data and information needs.

In the "energy efficiency" scenario it was assumed that a very strong energy efficiency policy will be implemented. It is difficult to relate directly the level of efforts to promote energy efficiency and the effectiveness of those efforts. Nevertheless, it was assumed that these activities will lead to the growth of rates of autonomous energy efficiency improvements by 2% per year in all sectors. To provide the financial resources for such a large-scale efficiency program, the funds received from the sale of emissions credits accumulated in 1991–1995 could be used.

**Table 10.** Results of the energy efficiency scenario.

| | 1995 | 2000 | 2005 | 2010 | 2015 |
|---|---|---|---|---|---|
| GDP (1995=100) | 100 | 134 | 171 | 208 | 253 |
| Primary energy consumption (mtce) | 1047 | 995 | 1110 | 1187 | 1274 |
| Energy intensity (1995=100) | 100 | 71 | 62 | 55 | 43 |
| $CO_2$ (Mt C) | 528 | 503 | 571 | 610 | 655 |
| $CH_4$ (Mt) | 15.2 | 13.6 | 14.7 | 15.4 | 16.2 |
| CO (Mt) | 21.3 | 19.1 | 20.9 | 21.4 | 22.0 |
| $NO_x$ (Mt) | 4.6 | 4.3 | 4.8 | 5.0 | 5.3 |
| GHG emissions (Mt $CO_2$ eq.) | 2503 | 2372 | 2667 | 2857 | 3032 |
| (1995=100) | 100 | 95 | 106 | 113 | 121 |

It was also assumed in this scenario that energy prices in 2000 would approach 80% of the world export price level and then stabilize for 2001–2015. This combination of an aggressive energy efficiency policy with price growth would contribute significantly to the reduction of GHG emissions (see Table 10).

In this scenario, GHG emissions grow by 21% in 1995–2015, but would be just 3% above the 1990 level. Cumulative GHG emissions for 1991–2015 are 66,552 Mt $CO_2$ equivalent, or 6,923 Mt lower than the cumulative emissions at the average 1990 level for 25 years. In other words, in the energy efficiency scenario Russia will have accumulated emissions credits equal to about 7 Gt of $CO_2$ equivalent even in the year 2015.

*Energy efficiency improvements are the cheapest and the most effective way to halt further environmental degradation in Russia, and would also contribute to the solution of the global climate stabilization problem.*

## 4.2. Carbon tax scenario

In the previous scenario, energy prices were kept stable in the years 2001–2015. To continue the effect of price growth on energy demand, carbon taxes (per ton of carbon) of $10 for 2005, $50 for 2010, and $100 in 2015 were introduced in RUSEB, keeping all other variables the same as in the energy efficiency scenario. In 2015, the introduction of a carbon tax would reduce GHG emissions by an additional 83 Mt $CO_2$ equivalent, and would lower the 2015 emissions to about the 1990 level (see Table 11). Cumulative emission credits would grow to 7,522 Mt $CO_2$.

Of course, the efficiency of a carbon taxation policy depends to a great extent on price elasticities. In RUSEB, medium-term price elasticities are

**Table 11.** Results of the carbon tax scenario.

| | 1995 | 2000 | 2005 | 2010 | 2015 |
|---|---|---|---|---|---|
| GDP (1995=100) | 100 | 134 | 171 | 208 | 253 |
| Primary energy consumption (mtce) | 1047 | 995 | 1110 | 1187 | 1274 |
| Energy intensity (1995=100) | 100 | 71 | 62 | 55 | 43 |
| $CO_2$ (Mt C) | 528 | 503 | 571 | 603 | 640 |
| $CH_4$ (Mt) | 15.2 | 13.6 | 14.7 | 15.2 | 16.0 |
| CO (Mt) | 21.3 | 19.1 | 20.9 | 20.7 | 20.8 |
| $NO_x$ (Mt) | 4.6 | 4.3 | 4.8 | 4.9 | 5.2 |
| GHG emissions (Mt $CO_2$ eq.) | 2503 | 2372 | 2667 | 2790 | 2949 |
| (1995=100) | 100 | 95 | 106 | 111 | 118 |

**Table 12.** Results of the renewable resources scenario.

| | 1995 | 2000 | 2005 | 2010 | 2015 |
|---|---|---|---|---|---|
| GDP (1995=100) | 100 | 134 | 171 | 208 | 253 |
| Primary energy consumption (mtce) | 1047 | 992 | 1037 | 1159 | 1231 |
| Energy intensity (1995=100) | 100 | 71 | 62 | 55 | 43 |
| $CO_2$ (Mt C) | 528 | 500 | 552 | 576 | 605 |
| $CH_4$ (Mt) | 15.2 | 13.6 | 14.7 | 15.2 | 16.0 |
| CO (Mt) | 21.3 | 19.1 | 20.9 | 20.7 | 20.8 |
| $NO_x$ (Mt) | 4.6 | 4.3 | 4.8 | 4.9 | 5.2 |
| GHG emissions (Mt $CO_2$ eq.) | 2503 | 2372 | 2667 | 2790 | 2949 |
| (1995=100) | 100 | 95 | 106 | 111 | 118 |

equal to −0.1 in all sectors, with the exception of the residential and commercial sectors, where it is −0.05. Real elasticities for the Russian economy at the beginning of the next century are difficult, if possible, to predict. Thus the presented results of the effects of a carbon tax should be viewed as very crude preliminary estimates.

### 4.3. Renewable resources scenario

In the final scenario, it was assumed that the growth of energy prices and the introduction of a carbon tax will make renewable resources cost effective in Russia. Their contribution to the energy balance will grow by 2 mtce in 2000, 10 mtce in 2005, 15 mtce in 2010, and 20 mtce in 2015. There are some signs that this development may occur in reality, although it is difficult to say how large this contribution would be.

The growth of the contribution of renewable resources will drive GHG emissions even below the 1990 level (see Table 12). The GHG credits accumulated over 25 years with this scenario will be 8,930 Mt $CO_2$ equivalent, or equal to three years of GHG emissions at the 1990 level.

Many other energy-related strategies were left unexplored, including reductions in methane losses, and in specific CO and $NO_x$ emissions due to energy consumption and production processes, etc. If such strategies were introduced to supplement the policies described in this paper, the conclusion that Russia has a potential to maintain emissions of GHG gases below the 1990 level would receive additional support.

## 5. Conclusions

Total $CO_2$ emissions in Russia in 1990 were 622 Mt C, or approximately 10% of the global energy-related $CO_2$ emissions. Russia was the third largest emitter after the USA and China. At present Russia is one of the few nations who is not only speaking of the necessity of reducing GHG emissions, but is also actively moving in this direction. In 1993, $CO_2$ emissions were by 90 Mt C or 14% lower than in 1990. The economic crisis was the major driving force behind this reduction.

The cumulative reduction in total GHG emissions in the period 1990–1995 will be around 474 Mt C and should be considered as an emission credit for Russia in the years to come.

The Russian GDP losses in 1991–1995 are estimated to be $2,023 billion (1980). Thus the cost of each ton of carbon reduced is $4,260 (1980) in GDP loss. The price for GHG mitigation through economic crisis is extremely high.

If the emissions stabilization target is set for cumulative emissions in a specified time period irrespective of the temporal distribution of the emissions, the conclusion is that in 1991–2015 Russia could stabilize average annual cumulative emission at 1990 level.

If the stabilization target is set for a given time point, then:

- In the base scenario, GHG emissions in 2015 will exceed the 1990 level by 28%.
- The combination of aggressive energy efficiency policy and price increases contributes significantly to the reduction of GHG emissions which grow only by 3 percent in 1990–2015.

- Introducing a carbon tax brings additional GHG emissions reductions and lowers the 2015 emission to the level of the 1990 emissions.
- Growth of renewable resources contribution drives GHG emission even below the 1990 level.

The general conclusion is that Russia will be able to keep GHG emissions below the 1990 level even if the stabilization target is set for a given point in time.

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# Impacts of Economic Reforms in Russia on Greenhouse Gas Emissions, Mitigation and Adaptation

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## Abstract

The high energy intensity of the Russian economy has made it one of the world's largest emitters of atmospheric carbon. The costs of reducing $CO_2$ emission would be high. Successful economic reforms rather than special abatement measures will provide opportunity for emissions mitigation and adaptation strategies to climate change.

Russia has not yet taken steps to reduce $CO_2$ emissions by the beginning of the next century. This is explained by two reasons: the existing theory on the positive effects of global warming for Russia, and the extremely difficult economic situation in the country.

As far as is known to the author, the real economic costs of global warming have not been estimated in Russia, but an attempt to do so is presented in Table 1. Taking into account the conditional nature of these calculations, it is assumed that global warming will increase yields in Siberia, have a positive effect on the forestry sector, reduce fuel consumption for space heating (by at least 20 million tons of coal equivalent, mtce), and improve conditions for navigation on the Siberian rivers and along the northern shipping route. On the whole, however, the negative consequences of global warming will exceed the positive ones. But the damage could be as low as 0.2% of GNP, i.e., seven to eight times lower than the world average.

Russia is the world's third largest contributor (after the USA and China) to increased greenhouse gas (GHG) concentrations in the atmosphere. A deep and lingering economic crisis which has not yet reached its bottom interrupted the growth in GNP: in 1992 it was 10% lower than in 1990. At present, Russia is in the transition to a market economy. The rate of this transition and the character and success of economic reforms will strongly influence GHG emissions.

**Table 1.** Damage due to a doubling of $CO_2$ ($ billion).

| | Former USSR[a] | Russia[b] |
|---|---|---|
| Coastal defense and land loss | 2.4 | 2.0 |
| Special loss | 2.6 | 1.5 |
| Agriculture | 6.2 | –1.0 |
| Forestry | –2.9 | –2.8 |
| Water | 3.0 | 1.5 |
| Energy and amenity | –0.7 | –1.2 |
| Life/morbidity | 3.9 | 2.0 |
| Air pollution | 2.1 | 1.0 |
| Migration | 0.2 | 0.1 |
| Navigation | – | –0.4 |
| Total | 16.8 | 2.7 |
| (% of GNP, 1988) | (0.7) | (0.2) |

[a]Compiled from Fankhauser, 1993.
[b]Author's evaluation using initial data from Fankhauser.

Three possible scenarios of economic development in Russia have been considered (see Figure 1). The first (optimistic) scenario assumes that the decline in production will stop in 1994 and the economy will develop at a mean annual rate of 5–7% over the period 1995–2000 and 3.5–4% in subsequent years. According to the second (realistic) scenario, stabilization will be achieved only in 1995 and the economy will develop at moderate rates (3–4%). In the third (pessimistic) scenario, the economic situation is expected to improve only after 1997–1998, basically due to large foreign investments and the rapid development of the oil and gas industries.

According to these calculations, the energy-related GHG emissions will start to increase after 1995 and will exceed the 1990 level by 2010 only in the optimistic scenario (Figure 2). In this case, the following changes in the GHG emission structure will take place: $CO_2$ emissions will increase from 74.7% in 1990 to 75.8% in 2010, $CH_4$ emissions will decrease from 18.6% to 17.4%, and $N_2O$ emissions will increase from 6.7% to 6.8%.

Note that the difference between the scenarios in terms of GHG emissions (9% in 2010) is lower than in terms of the GNP value (30%). This is explained by the fact that a more rapid decrease in the energy consumption–GNP ratio (Figure 3) and a more rapid decarbonization of energy consumption (Figure 4) correspond to higher economic growth rates. As a result, GHG emissions per unit of GNP in the optimistic scenario will be 16% lower

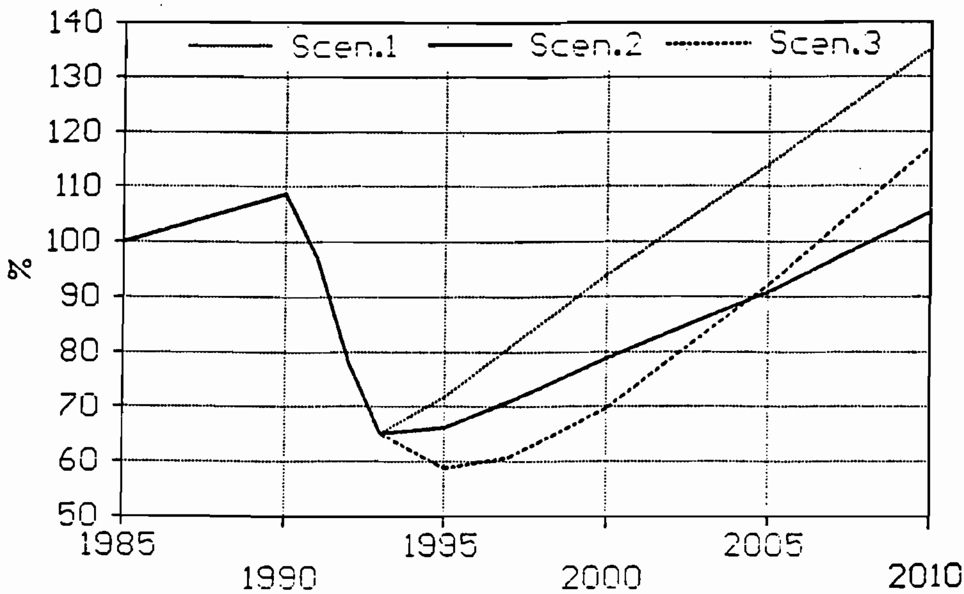


**Figure 1.** Russian GNP dynamics.

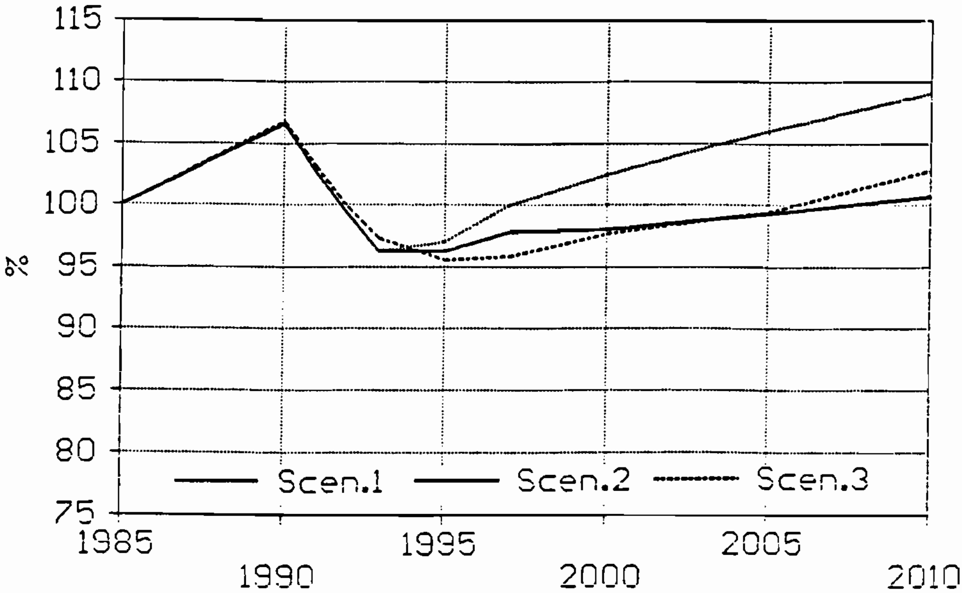


**Figure 2.** Energy-related GHG emissions.

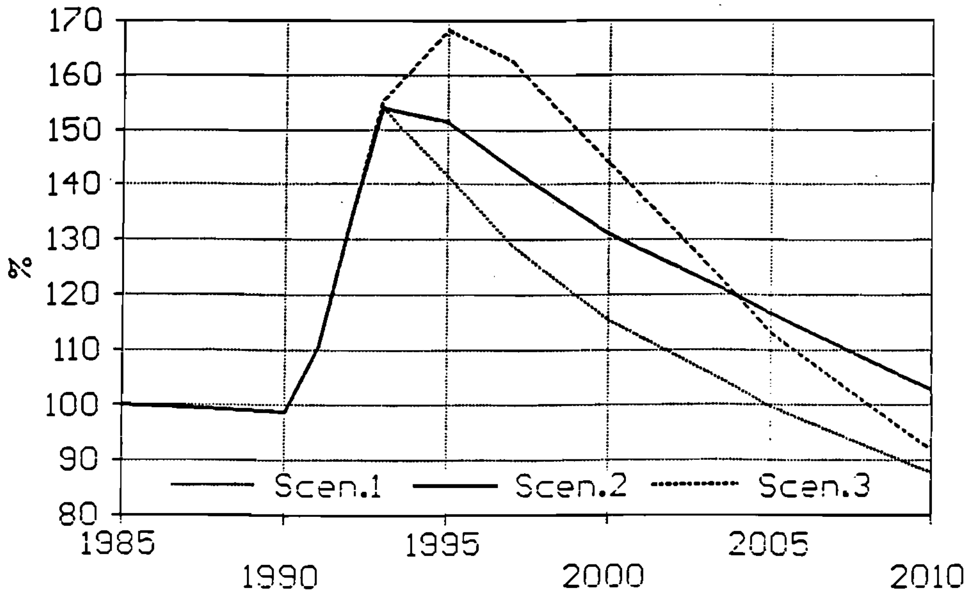


**Figure 3.** Energy/GNP index dynamics.

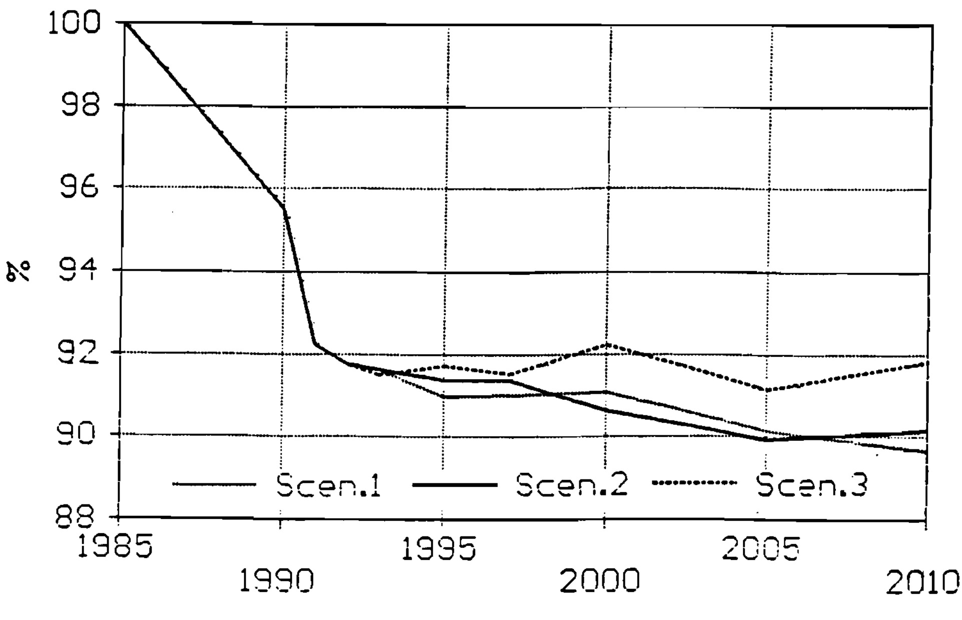


**Figure 4.** $CO_2$/energy index dynamics.

**Table 2.** Characteristics of some GHG mitigation strategies in Russia.[a]

| Strategy | Possible emission decrease (Mt C/yr) | Net capital cost ($/t C) |
|---|---|---|
| Additional energy conservation | | |
| Moderate | 40–80 | 40–100 |
| Large | 110–160 | 150–350 |
| Maximum | 200–250 | 700–1100 |
| $CH_4$ leakage reductions | 40–50 | 90–150 |
| Substitution of gas for coal | 30–55 | 180–290 |
| Replacement of fuel-fired power plants by: | | |
| Nuclear power | 30–40 | 100–185 |
| Hydro power | 6–7 | 240–395 |

[a]In addition to the realistic scenario.

by the year 2010 than in the pessimistic scenario and 27% lower than in 1990 (Figure 5).

These scenarios do not foresee special measures for GHG emission reductions, although the natural processes taking place in the economy and energy systems which promote this reduction (energy conservation, increases in the share of natural gas, and leakage reductions from 4% to 3%, etc.) were taken into consideration.

Additional GHG emissions reductions are possible at net capital costs of $100/t C and higher (Table 2). The abatement costs in this case are a nonlinear function of the decrease in GNP (Figure 6).

The cost of reducing GHG emissions by another 100 Mt C (about 10%) will be $7–10 billion, and to achieve reductions of 200 Mt C (about 20%), over $30 billion will be required.

The social cost of GHG control strategies can be measured by changes in living conditions. This is especially important for Russia, where there is an acute housing shortage. If a 10% emissions reduction is to be realized, it will be necessary to divert capital investments from housing construction to GHG emission control strategies, which will mean that the average floor space per capita in the year 2010 will be 2–3 $m^2$ lower than planned, and even 6 $m^2$ per capita lower in the case of a 20% emissions reduction.

In conclusion, GHG emissions in Russia will depend to a large extent on the rates of economic development rather than on special abatement measures. Economic reforms and the subsequent deterioration and elimination of old structures will lead to younger capital vintage structures and to a less energy- and emission-intensive economy.

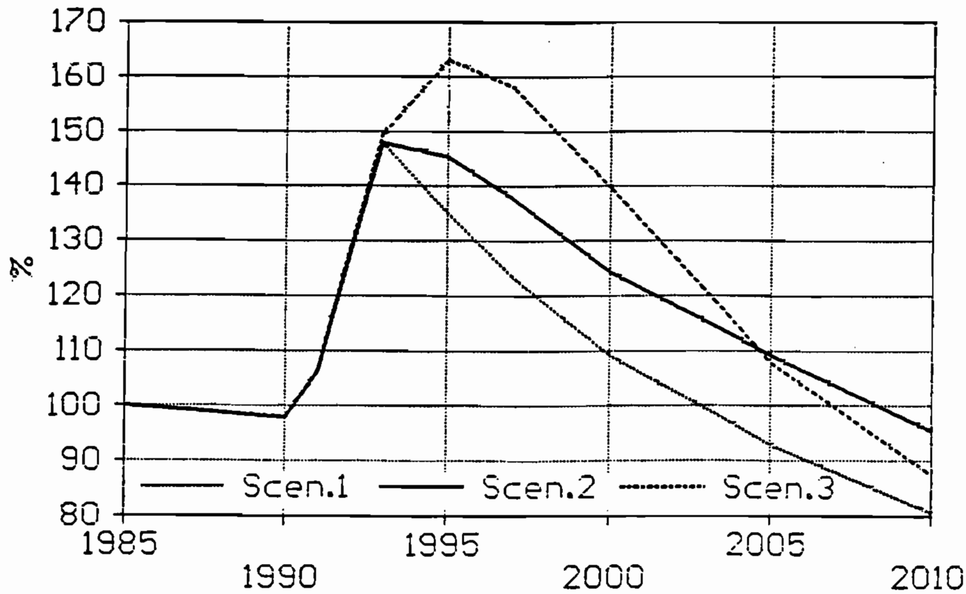


**Figure 5.** GHG emissions/GNP index dynamics.

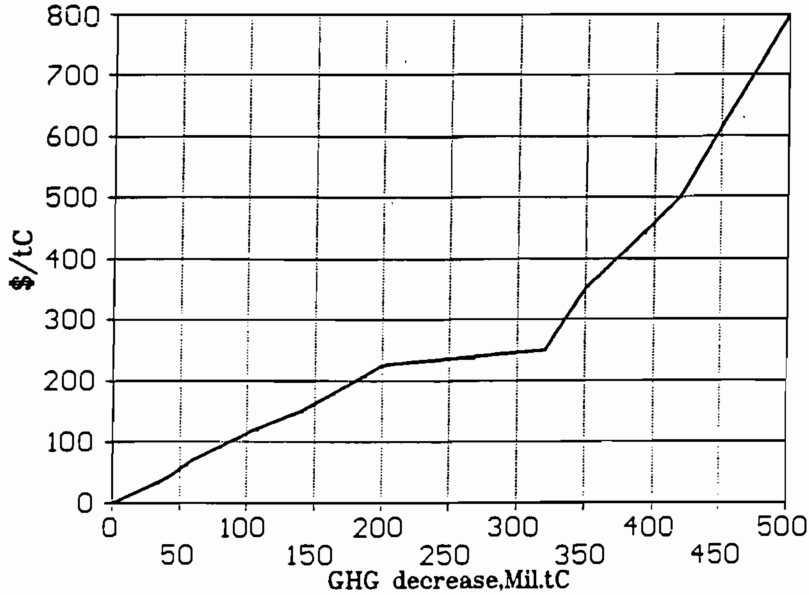


**Figure 6.** Net capital costs of GHG mitigation.

Successful economic reforms in Russia will provide the best (and, in the near term of 10–15 years, perhaps the only) opportunity for emissions mitigation and adaptation strategies to climate change.

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# Climate Change and the Technical and Institutional Adaptations: China's Perspective

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## Abstract

The paper presents a preliminary analysis of the possible impacts of global climate change on China's agricultural production and water resources, and of sea level rise caused by global warming on the economic development in Eastern China's well-developed regions. In order to reduce energy-related $CO_2$ emissions, major response policies and mitigation measures available for China are analyzed, and the costs and benefits of energy technologies for improving energy efficiency, substituting fossil fuels, and sequestering $CO_2$ emissions are assessed. Furthermore, institutional adaptation will be an important challenge, besides setting up energy technological options. Therefore it is analyzed in the fields of international and internal affairs, such as international cooperation, population control, economic development and environmental protection, economic and price reform, and energy legislation, with a view to improving the global environment.

## 1. Introduction

Besides its concerns for the common fate of global human beings, China is also paying special attention to climate change due to following factors:

1. China has a population of 1.2 billion, who are dependent on domestic rather than foreign food supplies, while Chinese agriculture is basically called "eating depending on the weather" which is affected by natural environment.
2. There is an obvious disequilibrium in the geographical distribution of the Chinese population; over 91% of the population are concentrated in the southeastern region, which occupies 43% of the land area. This leads to a heavy environmental load on regions that are also highly sensitive to external conditions.

3. China has a 18,400 km long coastline. With a highly developed economy, the coastal area would bear the brunt of rising sea level if this were to occur.
4. The volume of freshwater resources per capita in China is only 25% of that of the global average, so China is concerned about the potential impacts of climate change on water resources.

# 2. Impacts of Climate Change in China

China's scientists have made a great number of studies of the impacts of climate change on the economy. Taking into account the calculation results of global circulation models and comments at international conferences relating to China, and assuming that by 2030 the atmospheric $CO_2$ concentration will double, there would be an average global temperature rise of 1–2°C. Even if greenhouse gas (GHG) emissions were to be halted later, there is likely to be a temperature rise of 1–2°C and a sea level rise of approximately 20 cm. The impacts of climate change on major sectors of China are assessed under these conditions.

## 2.1. Agriculture

*Major Positive Effects*

It has been predicted that the temperature will rise by 3°C or more in southwestern and northwestern parts of China, and 2–3° in other regions. This would increase the effective cumulative temperature in some regions by at least 10°C, and extend the effective growing season by one month on average. The increase in agricultural output is estimated to be 2%, or about 8 million tons. The productivity of biomass and economic crops would also increase. In the southeast, the 500 mm rainfall isohyet would benefit the C3 crops and, as a result agricultural output would increase by about 4 million tons. In the northeast, output would increase by 1 million tons or so due to climate warming. In the south, the low temperatures and wet weather conditions in spring would improve, benefiting the growth of wheat, peas, rape, rice, and tropical and subtropical fruits, and the output of grain would increase by 1 million tons or more.

*Major Negative Effects*

Climate warming would increase evaporation from the Earth's surface. It is estimated that with a temperature rise of 2°C in the middle latitude regions, evaporation would increase by about 20%, or by 300–400 mm, accelerating the aridity process in the northern and northwestern regions of China. According to the predictions, at that time, the south, southwest, and northeast might become drier in winter, and the regions from south to northeast will probably become arid in summer.

Under these conditions, the boundary appropriate for agricultural activities would move from the 400 mm to the 450 mm isohyet, and about 13 million ha of cultivated land would be lost. The climate warming in the western regions would be significant. Taking into account the comprehensive effects of rainfall and evaporation, the drying trend would accelerate and salinization would increase, leading to the loss of at least 9 million ha of cultivated land. The degradation of grassland and wind erosion of soil would also be aggravated.

The seasonal droughts caused by warming would have very negative effects on China's agricultural output because the major natural calamity for agriculture is drought. There are already frequent spring droughts in the north, the mid-north of the loess plateau, and the western part of the Northeast Plain. According to the predictions, drought damage to crops in these regions would increase by 5%. Wheat and spring-sown crops would be most affected, with an estimated loss of output of at least 4 million tons. The hot summer drought in July and August would be aggravated in southern regions, the rainfall isohyet would shift northward and return later, affecting the early-maturing and late-shooting rice. Output could be reduced by 20%, corresponding to a loss of 6 million tons of grain. The autumn season in the western regions would often be dry, affecting the growth of late crops. The return of the rainfall line to the south would be postponed, aggravating the damage and prolonging the period of drought. It is estimated that at least 20% of the grain output, about 4 million tons, would be lost. The projected climate warming would aggravate the harmful effects of the dry hot winds in the north. Grain output would be reduced by 5%. At the same time, the problems would be aggravated by plagues of pests, and the costs of pest control would increase by 10–50%.

In conclusion, the comprehensive effects of climate change on agriculture would reduce the agricultural production potential in China by at least 5%. Chinese scientists generally believe that the conclusions of some foreign researchers, who predict that the greenhouse effect would increase China's agricultural output by 10%, are not correct, because the main factor affecting China's agriculture is water, rather than temperature (Table 1).

**Table 1.** Crop production losses in China due to various climatic disasters, 1950–1970.

| | Droughts | Floods | Drought and flood | Cold and frost | Total |
|---|---|---|---|---|---|
| Losses (million tons) | 153.21 | 84.43 | 54.00 | 14.59 | 306.23 |
| Proportion (%) | 50.00 | 27.60 | 17.60 | 4.80 | 100.00 |

**Table 2.** Distribution of China's water resources, 1988.

| | Percentage of water (%) | Population share (%) | Per capita water resources ($m^3$/capita) |
|---|---|---|---|
| River discharge in the North | 14.4 | 43.2 | 938 |
| River discharge in the South | 80.9 | 54.7 | 4,170 |
| Inland rivers | 4.7 | 2.1 | 6,287 |
| Total | 100.0 | 100.0 | 2,818 |

## 2.2. Water resources

The total volume of freshwater resources in China accounts for 5% of that in the world, ranking sixth, but the per capita volume is only about 25% of the world average, so that China has one of the lowest per capita volumes of water resources. In terms of the distribution of water, 81% of water resources are found in the south, where 55% of the population live (Table 2). In short, China's water resources are characterized by less per capita, an uneven distribution in time and space, and frequent floods and droughts.

There are enormous regional differences in the fluctuations in available water resources resulting from rainfall, runoff, and evaporation. In terms of water resources, the most sensitive regions to climate change are the northern arid and semi-arid areas. Under the same conditions of climate change, the resulting changes in runoff in semi-arid areas would be about 1.5 to 2 times of those in semi-humid and humid areas. Generally speaking, in winter, in the south and the northern coastal areas, and in summer, the north and the middle-south of China are the areas where the water resources shortages are most serious. As a result, the soil moisture in winter would decrease remarkably in the south, whereas in summer, all areas except East China and South China, especially the northwest, southwest, northeast, and central areas would become drier. In conclusion, climate change would seriously affect water resources.

The studies conducted using hydrological, groundwater, and runoff models reveal that the impacts of global climate change on runoff would be greater in the north than in the south, and that the impacts on precipitation and evaporation would be more severe on the plains than in the mountain areas. Furthermore, the regions where water resources are most vulnerable to climate change are in the central and eastern parts of China, i.e., the southern Hai River basin, peninsular Shangdong Province, and the middle reaches of Yellow River. For example, it is estimated that if precipitation decreased by 10% in the Hai River delta, close to Tianjin, China's third largest city, groundwater recharge would be reduced by 37%.

## 2.3. Sea level

The southeastern coastal zone of China is the most developed industrial and agricultural area. The lowland plain coastal areas are mainly distributed along Bohai Bay and the estuaries of the Yellow, Yangtze, and Pearl Rivers, with total areas of wasteland of 1.1 million ha. Since ancient times, China has developed and used the coastal areas, much of which are now farmland and fish farms, the most important non-staple food base for the coastal cities.

According to predictions of sea level rise, most of the existing salterns and seawater breeding farms would be flooded or destroyed. Their reconstruction would require more than 500,000 ha of land. In the Pearl River delta, almost half of its area (about 3,500 $km^2$) would be inundated. The more developed areas in the Yangtze and Yellow River deltas would also be seriously affected, and at least 10 million tons of grain would be lost. In addition, there would be other adverse impacts on housing, transportation, and water supplies for residential, industrial, and agricultural usage. Salt water would intrude into inland areas, increasing the range of salinized land, destroying coastal ecosystems and environmental protection facilities.

The deltas of the Yangtze (involving Shanghai), Pearl (involving Guangzhou, Shengzhen), and Hai Rivers (involving Tianjin, Tanggu) along the eastern and southern coasts of China are the most developed regions. However, they are located not only in surface subsidence zones, but are also the zones that are likely to experience comparatively higher sea level rise. In particular in Shanghai, China's largest city, the terrain is flat and low, with an average height above sea level of only 1.8 m. The eastern coastal plain of Shanghai is even lower, and is thus more vulnerable to flooding. It can be concluded that sea level rise would directly threaten economic development in these areas as well as the whole nation.

**Table 3.** Primary energy consumption in China, 1980 and 1990.

| | 1980 | 1990 |
|---|---|---|
| Commercial energy | | |
| Coal (Mt) | 609 | 1,037 |
| Oil (Mt) | 88 | 117 |
| Natural gas (billion $m^3$) | 14.1 | 15.5 |
| Hydropower (TWh) | 58.2 | 126 |
| Subtotal (Mtoe) | 422 | 690 |
| Biomass energy | | |
| Stalks and straw (Mt) | 240 | 266 |
| Firewood (Mt) | 198 | 260 |
| Subtotal (Mtoe) | 160 | 195 |
| Total energy consumption (Mtoe) | 582 | 885 |
| Fossil energy-related $CO_2$ emissions (Mt C) | 387 | 628 |

# 3. Energy-related $CO_2$ Emissions and Mitigation Measures

## 3.1. Energy consumption and $CO_2$ emission scenarios

Commercial energy consumption and composition in China in 1980–1990 are shown in Table 3. From 1980 to 1990, the GNP grew at 8.9% annually and the growth rate of energy consumption was 5.0%, so that the energy elasticity was 0.56. Table 3 also presents rough estimates of biomass energy consumption.

On the basis of various assumptions with regard to developments in population, the economy, and technology, energy demand projections for the year 2000 and beyond have been produced using a sectoral techno-economic analysis model and an energy system optimization model. Two scenarios are made for future energy demand: one is a reference scenario, and the other is the scenario in which some policy actions are assumed to be implemented to reduce greenhouse gas emissions. Scenarios of energy demand and $CO_2$ emissions are listed in Tables 4, 5, and 6.

Since the energy intensity of GNP will improve in future, the annual growth rate will be lower than that of GNP. The growth rate of $CO_2$ emissions will be lower than that of energy consumption because of a shift in energy composition away from the use of coal.

**Table 4.** Commercial energy demand in 2000 and beyond.

| | 2000 | | 2010 | | 2020 | |
|---|---|---|---|---|---|---|
| | Ref. | Policy | Ref. | Policy | Ref. | Policy |
| Commercial energy demand (Mtoe), of which: | 1,022 | 994 | 1,400 | 1,350 | 1,760 | 1,670 |
| Coal (Mt) | 1,505 | 1,410 | 1,890 | 1,750 | 2,240 | 2,030 |
| Oil (Mt) | 165 | 170 | 230 | 220 | 290 | 260 |
| Natural gas (billion $m^3$) | 30 | 32 | 77 | 122 | 123 | 198 |
| Hydropower (TWh) | 260 | 300 | 465 | 440 | 630 | 595 |
| Nuclear (TWh) | 35 | 38 | 145 | 120 | 320 | 260 |
| Renewables (Mtoe) | 0.4 | 0.5 | 1.8 | 2 | 4 | 5 |
| Fossil energy-related $CO_2$ emissions (Mt C) | 910 | 870 | 1,185 | 1,130 | 1,435 | 1,345 |

**Table 5.** Commercial energy structure (%).

| | | 2000 | | 2010 | | 2020 | |
|---|---|---|---|---|---|---|---|
| | 1990 | Ref. | Policy | Ref. | Policy | Ref. | Policy |
| Coal | 75.7 | 73.6 | 71.1 | 67.6 | 64.9 | 63.9 | 60.9 |
| Oil | 17.1 | 16.2 | 17.1 | 16.4 | 16.3 | 16.5 | 15.6 |
| Natural gas | 2.1 | 2.7 | 3.0 | 5.1 | 8.4 | 6.5 | 11.1 |
| Hydro | 5.1 | 6.6 | 7.8 | 8.3 | 8.2 | 8.7 | 8.6 |
| Nuclear | 0 | 0.9 | 1.0 | 2.6 | 2.2 | 4.4 | 3.8 |

**Table 6.** Comparison of various annual growth rates (%).

| | 1990–2000 | 2000–2010 | 2010–2020 |
|---|---|---|---|
| GNP | 8.6 | 6.0 | 5.0 |
| Energy consumption | 3.7 | 3.1 | 2.2 |
| $CO_2$ emissions | 3.3 | 2.7 | 1.8 |

### 3.2. Major measures for mitigating $CO_2$ emissions

The ways of mitigating $CO_2$ concentration in the atmosphere might include efforts in two directions: (1) to limit sources that release $CO_2$; and (2) to develop sources that assimilate $CO_2$. Fossil fuel combustion is currently believed to be the major source of $CO_2$. With the social and economic development in China, the inevitable increase in energy demand will result in rising $CO_2$ emissions. Hence, the realization of $CO_2$ reductions will involve cutting energy consumption, which will then hurt economic development. This dilemma could be alleviated in several ways, such as by improving energy efficiency, or by replacing carbon fuels with non-carbon fuels (hydropower, nuclear, solar, wind, geothermal, etc.). $CO_2$ assimilation could be increased by afforestation and other technologies, although the former is commonly considered the most realistic measure at the present time.

*Improving Energy Utilization Efficiency*

Power generation, industrial boilers and kilns, urban and rural households are now the largest energy consumers in China, and at the same time there exists a fairly large potential for energy conservation. In 1990, for example, the fuel intensity per kWh was 0.275 kgoe, equivalent to a thermal efficiency of power generation of 31.2%. It is estimated that total power generation in 2020 would be 3,450 TWh in the reference scenario, of which 2,500 TWh would be converted from fossil fuels. If the fuel intensity per kWh could be reduced to 0.24 kgoe (efficiency 35.8%) by adopting advanced technologies, about 88 Mtoe would be saved and emissions of 83 Mt C avoided (assuming that the fossil fuel structure would be coal 75%, oil 10%, and natural gas 15%).

In the rural areas, emphasis will be given to encouraging the widest use of fuel-efficient stoves. It is intended that share of these stoves will be greatly increased from 35% in 1990 to 90% in 2000. Since the energy efficiency could be improved from 10% for traditional stoves to 20% for fuel-efficient ones, it is estimated that about 65 Mtoe of energy could be saved in the year 2000 and emissions of 26 Mt C avoided (assuming that biomass would account for 62% of the energy used by rural households in the year 2000).

*Replacing Carbon Fuels by Non-carbon Fuels*

There are abundant hydropower resources in China. It is estimated that the potential exploitable hydropower is as high as 380 GW. By the year 2020, the planned hydro capacity would be 160–170 GW. For nuclear energy, it is expected that nuclear power will be developed rapidly in the next century; 40–50 GW capacity would be established by the year 2020. Based on the same assumption of fuel intensity per kWh, about 175 Mtoe would be replaced and emissions of 163 Mt C avoided.

*Increasing Afforestation*

It is currently argued that $CO_2$ emissions caused by deforestation is about 1.8 billion tons of carbon, representing 25% of global $CO_2$ emissions. Thus one major way of absorbing $CO_2$ is to prevent forest overcutting and to realize net afforestation. At present, forests cover 13% of China's land area, and biomass growth totals about 212 million tons annually. There are still 86 million ha of wasteland and mountains in China, and an afforestation plan has been proposed to have afforested 16–17% of China's land area by the end of this century. Based on this afforestation target, 29–38 million ha of land will be planted in the decade 1990–2000. Meanwhile, great efforts will also be made to expand the areas of firewood plantations, to enhance the fuelwood production and management, to improve existing fuelwood supply shortages, and finally to allow biomass growth to surpass the rate of cutting.

The results of cost–benefit analyses for different technologies to improve energy efficiency, to substitute energy by non-fossil fuels, and to sequester $CO_2$ emissions are summarized in Table 7. It is known from rough analyses that the special costs of $CO_2$ reductions (SCCR) of technological options are generally lower for measures to improve energy efficiency than those for energy substitution. In the particular case of introducing coal-saving stoves, however, the SCCR is very small and would become negative if the price of coal, for example, were to increase to over \$12/ton. It can therefore be concluded that the best means to reduce $CO_2$ emissions is to improve energy efficiency in a number of different ways.

# 4. Institutional Adaptation

## 4.1. International affairs

For hundreds of years humans have released GHGs into the atmosphere through their productive and living activities, but only in recent decades has the international community expressed serious concerns that these emissions could cause climate change. It is generally thought that this is due to limited scientific knowledge. Climate change is caused by human activities, so it should also be overcome through the readjustment of human activities themselves. Furthermore, climate change is a global issue; the influences on production, water resources, sea level rise, etc., are imposed not only upon China as analyzed above, but also on every country around the world. To tackle this global problem, effective international cooperation is required in many fields, because the efforts and function of one country or region are finite.

Based on this principle, the Chinese government wishes to strengthen international cooperation for discussing and finding ways of dealing with global issues such as climate change, as well as other environmental problems. China is actively participating in international actions, such as the Earth

**Table 7.** Strategies for mitigating $CO_2$ emissions (up to the year 2000).

| | Potential (new added) | Total cost ($)[a] | Life-time (years) | Total investment ($ million)[b] | Cumulative $CO_2$ reduction (Mt C) | Specific cost of $CO_2$ reduction ($/t C) |
|---|---|---|---|---|---|---|
| Coal-saving stoves | 64 MH[c] | 1.5/H | 10 | 96 | 305 | 0.3 |
| Retrofitting existing boilers | 0.2 million | 1,400/each | 10 | 280 | 60 | 4.7 |
| Fluidized bed combustion | 0.5 GW | 105/kW | 30 | 53 | 4.5 | 12 |
| Retrofitting existing kilns | 46,000 | 33,900/each | 8 | 1,560 | 80 | 19 |
| Hydropower | 40 GW | 1,010/kW | 50 | 40,400 | 1,900 | 20 |
| Solar heaters | 1.9 million $m^2$ | 110/$m^2$ | 15 | 209 | 8.8 | 24 |
| Nuclear power | 6 GW | 1,185/kW | 30 | 7,110 | 284 | 25 |
| Afforestation | 34 million ha | 620/ha | | 21,080 | 690 | 30 |
| Combined cycle | 0.8 GW | 234/kW | 30 | 188 | 6.3 | 30 |
| Wind generation | 48 MW | 1,270/kW | 20 | 60 | 1.5 | 42 |
| Solar PV | 9.3 MW | 815/kW | 20 | 8 | 0.15 | 49 |
| Urban gasification | 49 MH | 475/H | 30 | 23,275 | 460 | 50 |
| Solar cookers | 60,000 | 50/each | 10 | 3 | 0.05 | 68 |

[a]US$ (1990).
[b]Total cost includes investment cost, operation and maintenance, and fuel costs, which have been discounted to the initial year at the 10% discount rate.
[c]MH = million households.

Summit (UNCED) in June 1992 in Rio, Brazil, and has made the political pledge to conscientiously adhere to the agreements reached at the conference, such as the Framework Convention on Climate Change, *Agenda 21*, etc.

Concerning international affairs, existing international institutional structures or the international economic order have many consequences that are unfavorable for the mitigation of climate change. First, the differences in wealth between developed and developing countries are large, and are continually expanding. Second, developing countries, whose populations account for a majority of the world total, are in highly disadvantageous positions in the terms of international trade and other economic relations. Under the pressure of unfavorable international trade structures or foreign debt, many of them have to export their primary resources in large volumes. Obviously, actions to mitigate climate change can not be separated from the international institutional order. The idea that the problem of climate change can be solved as long as endeavors in terms of technological and financial resources are made, without changing the existing international economic order, is a one-sided view. Two principles for setting up an international institutional structure that is adapted to tackle the issue of climate change may be considered.

First, substantial endeavors should be made to readjust and improve the international economic order. At present, economic and trade relationships are basically controlled by the developed countries, who gain a great number of benefits from them. This state of affairs should be remedied. It is essential that developed countries take certain actions, including abandoning trade barriers, improving trade structures, alleviating foreign debt pressure for developing countries, and so on.

Second, relevant technologies and funds should be provided to developing countries to enable them to take action to avoid climate change. Two kinds of funding agencies are worth considering: one is a "Foundation for Technological Progress on Energy Utilization", which could be used to help developing countries to improve their energy efficiency and also to develop new and renewable forms of energy; the other is a "Green Fund", which could be used to support developing countries to conserve their natural environments, to expand biomass cover, to protect primeval forest, etc. Part of the funding for these agencies could come from new sources; the rest from some transformed foreign debts.

The process has had a good beginning. The GEF (the Global Environment Facility), established in 1990, is providing grants and low-interest loans to developing countries to help them carry out activities to relieve the pressure on threatened ecosystems. A grant of $2 million will go to China for two projects: one focusing on issues and options in GHG emissions control; the other on the protection of China's abundant diversity of biological species. China is now the third largest contributor to greenhouse gas emissions, and these projects will help China to evaluate the macroeconomic feasibility and economic growth implications of limiting GHG emissions, and to formulate policies to mitigate climate change. The work to assess and limit greenhouse gas emissions is also essential to the worldwide effort to reduce global warming.

## 4.2. Internal affairs

Apart from the international regime, it is also important for China to pay more attention in internal affairs to environmental protection, which will make an essential contribution to the mitigation of climate change.

Environmental protection and improvement are closely related to social, economic, technological, and resource issues. Policies, measures, and regulations that have proved to be successful and effective in the past and current practice of China's social and economic development and environmental protection, should be continued. On the other hand, some existing policies need to be adjusted, and institutional mechanisms or new policies and regulations should be adapted in order to meet the needs of the present generation without compromising the ability of future generations to meet their own needs, i.e., sustainable development.

*Economic Development and Environmental Protection*

China is now entering a new period of rapid economic development. The burden on resources, ecosystems, and the environment are becoming heavier, because the economic base is rather weak: a high population growth rate, few natural resources per capita, and backward science and technology. The strategic target for economic development is to strengthen the aggregate quality of the national economy and to improve living standards to reach the same middle-income level of per capita GDP as in developed countries. To realize this target, China must establish its previously close relationship between the environment and development. Developing countries such as China in the initial stages of economic development are confronted with the difficult task of meeting their people's needs and of improving the environment. It is clear that poverty and underdevelopment are the most important causes of environmental degradation, so the priority task is to develop the economy, since a strong economy is a prerequisite for environmental protection. At the same time China is also increasing environmental protection, drawing lessons from the process of industrialization in the past, in order to keep the path toward sustainable development. In the early 1980s the Chinese government started to treat environmental protection as a basic national principle and to incorporate it in plans and programs of social and economic development.

*Population Control*

Rapid population growth increases the difficulties of improving living standards and protecting the environment. Since liberation in 1949, China's population has grown dramatically from 542 million in 1949 to 987 million in 1980, at an average annual rate of 1.96% and by a factor of 1.82. Facing serious population pressure, the government implemented a family planning policy in the late 1970s. Since then, the population has been controlled to a large extent, especially in urban areas, where the growth rate fell to 1.46% in the period 1980–1992. The family planning policy is a necessary measure for China's particular situation, while accelerating the reforms to open up and modernize the economy.

However, the current situation is not entirely optimistic. The population growth rate remains high (increasing by 13–15 million annually); in 1992 the population had reached 1175 million. Such a high growth rate is a heavy burden for China, therefore the family planning policy will continue for some time to come.

Too many unplanned births still occur in some areas, especially among the rural populations who account for about 75–80% of the total. Family planning efforts will focus on those areas in future. In order to implement the policy more effectively, it is expected that the government will encourage natural family planning, based on caring for and protecting the farmers' interests and then helping them to overcome their poverty.

### *Economic and Price Reforms*

The reforms to open up the economy started in the late 1970s after China decided to redirect its principal national strategy toward economic reconstruction. Later, the reforms spread to cover other fields of social, science, government institutions, legislation, etc. The reforms will affect everything that hampers the growth of production in order to put natural resources to reasonable use and to improve productivity. The strategic target of the economic reforms is to shift from the centrally planned to a socialist market economy. China also intends to expand its links with the international community and to gain experiences and lessons by opening up and cultivating the market economy and meshing it with international practice. During the economic reforms all policies and institutions that are inefficient, obsolete or present obstacles to further economic development will be adjusted or removed, and new, efficient as well as effective ones will gradually be created. The reforms also present an opportunity for introducing actions to protect and improve the environment.

More than 90% of $CO_2$ emissions in China are energy-related, and the energy intensity of GNP still remains at a rather high level. Besides exploring new energy resources to meet the increasing demand, energy conservation is being given equal emphasis in the current energy development strategy. Programs will be introduced to encourage energy conservation and to reduce the high energy intensity that is the cause of the excessive GHG emissions.

One of the most important reasons is the unreasonable price of energy. The prices of energy products, especially coal and oil products, are lower in relative terms than those of other products and energy production costs. For example, based on the author's analyses of China's input–output table of 1990, among non-energy-intensive industrial sectors, the cost of energy inputs accounted for only 1% of total inputs in the textiles, food and electronics sectors, and 4% in the machinery sector. The cost was also relatively low even for energy-intensive sectors: 8% in the chemical industry and 10% in the building materials industry. The average for all sectors was 5%. Energy prices have been low for some time, and because of the low cost, energy conservation is not often an urgent issue for factory managers and other producers. As a result, a great deal of energy is wasted in various sectors.

The government has recognized the seriousness of the situation and has tried to solve it in recent years. Although energy prices have been adjusted upward several times in the last 10 years, these were only temporary adjustments rather than substantial reforms. Because the government considers that energy is an important material in national economic development and daily lives, under the centrally planned economy, it should be strictly controlled in the fields of production, allocation, pricing, etc. However, it is rather difficult to conduct a full price reform, since the government has to balance the interests of various departments and groups, and between central and local governments.

The current economic reforms offer a favorable opportunity for price reform, particularly energy. The goal should be a new pricing mechanism in a socialist market economy by making the transition from the current two-tier price system (covering planning and market prices simultaneously) to a unique market price system as soon as possible. It is expected that energy producers will be able to avoid financial losses due to the low prices, and have enough capital to introduce new technologies and to renovate existing equipment to improve productivity or conversion efficiency. Meanwhile, without subsidies from the planning system, it is hoped that energy consumers will introduce more efficient production management and energy conservation under the new market economy, in order to reduce production costs and to strengthen their competitiveness in the market. A direct result will be a decline in the energy intensity of GDP, and thus the GHG emission intensity of GDP.

*Energy-related Legislation*

The lack of a comprehensive energy legislation might also be an important reason for the low efficiency. In fact, no energy-related regulations or laws have so far been debated by the highest legislative body, the National People's Congress. International experience has shown that energy legislation in some countries that are either rich or poor in energy resources has played an important role in protecting energy resources, promoting energy production and substitution, and restraining irrational energy use. Along with environmental regulations and laws, an energy law system should be established to enable the state to formulate a set of energy techno-economic measures for implementing energy policies, to strengthen energy management and promote the rational use of energy, and ultimately to reach the goal of a protected environment. In order to increase the effectiveness of legislation, the energy law system should cover the fields of exploitation, construction, production, distribution and transmission, security, consumption, rewards and penalties.

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# The Impacts of Climate Change on Electric Utilities in Japan

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## Abstract

The potential impacts of climate change are of great concern for electric utilities among other sectors. The effects of climate change fall into two types: direct impacts on electricity demand and the physical effects on electric power facilities; and indirect effects arising from the measures taken to control greenhouse gas emissions.

As a basis for assessing these impacts, this paper summarizes expected local scale climate change and related natural phenomena such as temperature rise, changes in precipitation patterns, sea level rise, etc. They are based on the outputs of widely accepted global climate models.

The impacts on electricity demand are analyzed by observing the current relationships between temperature and electricity demand. The electricity consumption increase is estimated assuming that the global temperature will rise by 3°C. The potential physical impacts of climate change on electric utilities are summarized in an "event tree" showing the likely sequence of impacts.

Finally, a case study on impact assessment for the Hokuriku Electric Power Company is presented. The study was conducted to assess the risks of climate change, based on various predictions or assumptions for future conditions such as climate change, economic growth, electricity demand, fuel prices, generating facilities, etc. The simulations were carried out under the conditions when different emission control measures are taken. The main results are:

- The increases in peak demand and total demand due to climate change are expected to be 10% and 5%, respectively, by the year 2050.
- The impacts on long-term generating costs due to sea level rise and other climate change-induced phenomena are not expected to be large.

- In 2050, if additional low-cost coal-fired power plants are installed, to maintain current emission levels would require a 65% reduction in emissions compared with the no control case; a 20% reduction scenario would require a 73% reduction, and a 50% reduction scenario would require an 83% reduction.

# 1. Introduction

Increasing atmospheric concentrations of greenhouse gases such as $CO_2$, methane, CFCs, and nitrous oxide are expected to result in global climate change which may cause surface air temperature rise, sea level rise, precipitation pattern changes, and other phenomena on both global and local scales. These changes in the natural environment, although subject to large uncertainties, may have considerable impacts on the energy sector, especially on the electric utilities.

One of the direct physical impacts on electric utilities will be the effect of temperature rise on electricity demand. In Japan, especially in summer, when roughly one-third of the peak electricity demand is used for air-conditioners, suppliers are already finding it difficult to meet demand, and an increase in summer temperatures caused by climate change is expected to make the situation even worse.

Other possible direct impacts of climate change will be the physical effects on electric power facilities. For example, thermal and nuclear power plants, most of which are located in coastal zones, could be affected by sea level rise; hydroelectric power plants will be affected by changes in precipitation patterns in both space and time; and the increased probability of strong winds will cause damage to transmission lines and other installations.

The effects of measures to reduce greenhouse gas emissions represent another type of impacts. The impacts are indirect, but the effects on the electric utilities are considered to be much greater than other types. Since the most appropriate decisions must be made under uncertain conditions, it is important for electric utilities to carry out quantitative assessments that take into account both the physical impacts of climate change and the effects of emission control measures.

This paper examines the potential impacts of climate change on electric utilities in Japan based on existing analyses. Potential local climate change and associated natural phenomena in Japan are summarized in Section 2. The impacts on electricity demand are discussed, and a sensitivity analysis of demand to temperature fluctuations is shown in Section 3. The sequential structure of the impacts of climate change on electric utilities is discussed in Section 4, and is summarized in an "event tree" showing the likely sequence of impacts. Section 5 presents a case study of an impact assessment for the Hokuriku Electric Power Company. The study, which was conducted to assess the risks of climate change, is based on a number of predictions and assumptions regarding future conditions such as economic growth, demand growth, fuel prices, future generating facilities, etc. The simulations were carried out under the conditions when different emission control measures are taken.

## 2. Climate Change and Associated Phenomena in Japan

Unfortunately, predictions of climate change are subject to large uncertainties, especially on the regional scale. According to the Meteorological Agency (1991), the following changes in climate in the Asian-Pacific region can be expected:

(a) The middle latitude pluvial rainfall zone will shift to higher latitudes, and precipitation will increase in general.
(b) The areas of snowcover and sea-ice will diminish.
(c) In the northern hemisphere, soil moisture in the middle latitudes will decrease in the summer, while soil moisture in high latitudes will increase in the winter.
(d) In the northern hemisphere middle latitudes, daily fluctuations in surface air temperature caused by large-scale atmospheric disturbances will diminish. There is no particular trend in diurnal variation of land surface temperature, so that further analyses are required.
(e) There are large uncertainties about the behavior of extratropical and tropical cyclones, Bai-u fronts (the front system prevailing in Eastern Asia during the rainy season), and typhoons. Further analyses are also required.

For Japan, the following changes in climate can be expected: the outflows of cold air from the Asian mainland in winter will tend to weaken, and Asian summer monsoons will tend to strengthen, while their starting times will remain uncertain.

In spite of the large uncertainties about regional climate change, an impact assessment for the region has been carried out assuming generally accepted global average conditions for the region. The following is an overview

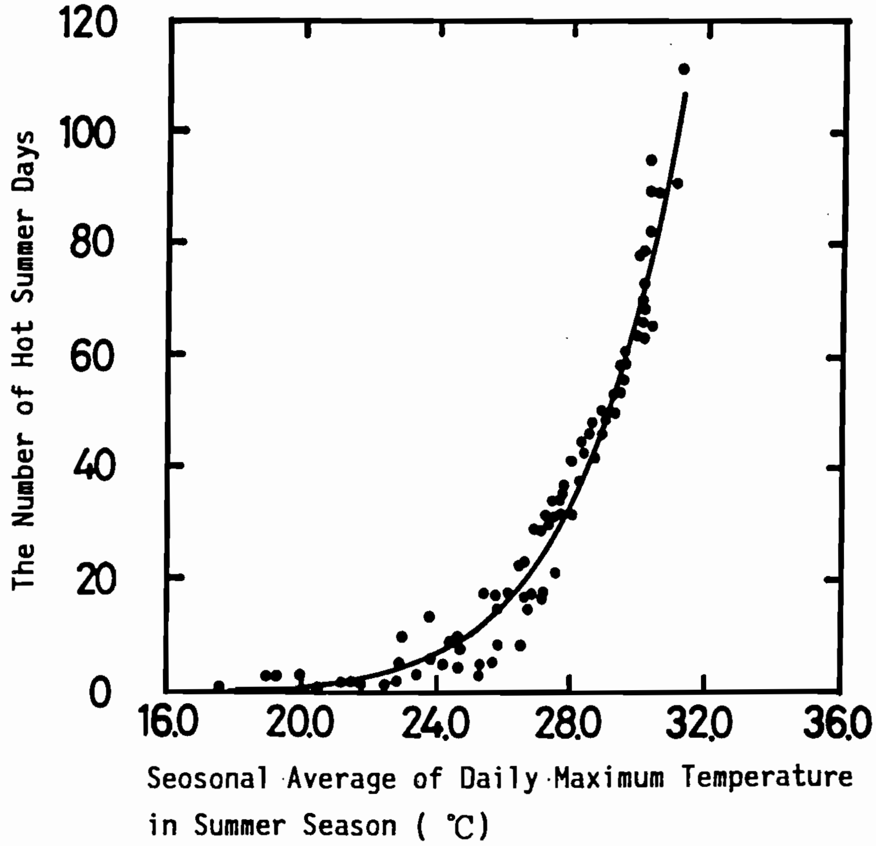


**Figure 1.** Relationship between the number of hot summer days and seasonal average of daily maximum temperature (June–August). Circles represent observation sites. Source: Nishinomiya/CRIEPI, 1990.

of possible climate changes and related phenomena for the region, and for Japan when information is available, with emphasis on the possible impacts on electric utilities.

*Temperature*

The number of hot summer days (defined as the days when the maximum temperature exceeds 30°C) will increase, while the number of winter days (when the minimum temperature falls below 0°C) will decrease. The numbers of these defined days are used as indices in Japan to give a rough idea of the temperature characteristics of the season and the year.

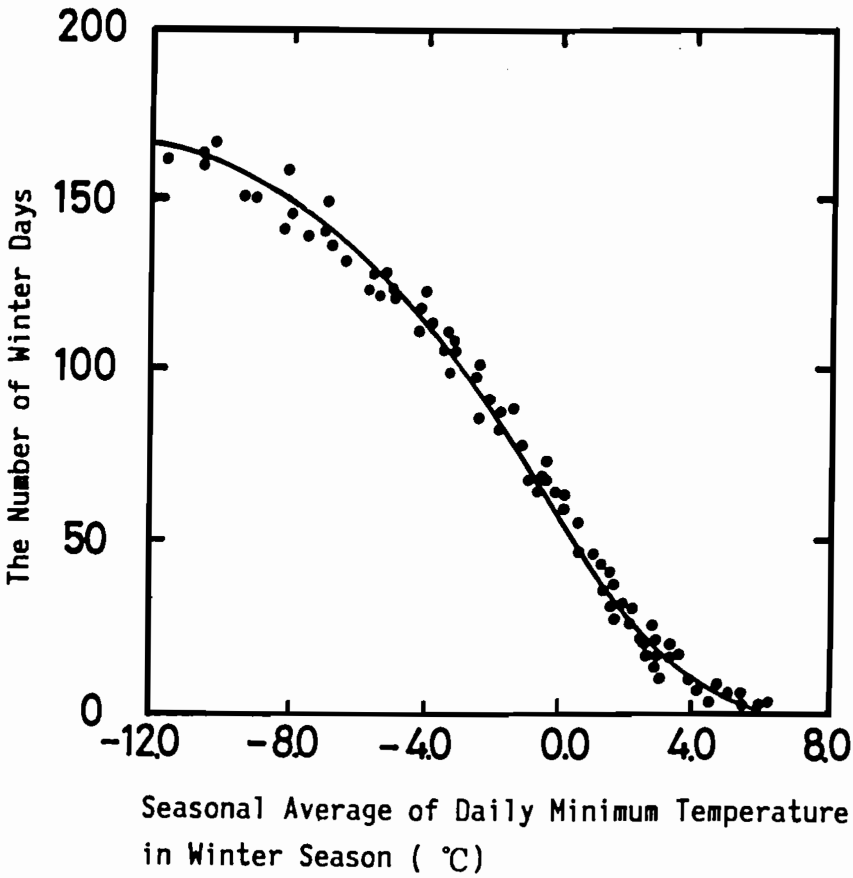


**Figure 2.** Relationship between the number of winter days and seasonal average of daily minimum temperature (December–January). Circles represent observation sites. Source: Nishinomiya/CRIEPI, 1990.

Figure 1 shows the current relationship between the number of hot summer days and the mean daily maximum temperature in the summer (June–August). Assuming a 3°C rise in maximum temperature, the number of hot summer days in Tokyo, for example, will increase from 43 to 114 days per year, if the current relationship between the maximum temperature and the number of hot summer days remains unchanged (Kato, 1990).

Figure 2 shows the relationship between the number of winter days and the mean daily minimum temperature during the winter (December–January). For example, the number of winter days in Tokyo will fall from

28 days to 1 day assuming a 3°C increase in minimum temperature (Kato, 1990).

*Precipitation*

Assuming that the atmospheric $CO_2$ concentration will double, a 7–15% increase in global average precipitation is estimated (Meteorological Agency, 1989). While regional-scale precipitation changes are still uncertain, it is probable that intense rainfall will occur much more frequently because of increased convective rain. At the same time, enhanced convective clouds will bring more thunderstorms. Although, in general, snowfall and snowpack are expected to decrease because of rising temperatures, they will depend on local characteristics of climate and topography.

*Hydrology*

Although early spring snowmelt and increased evaporation are expected to increase summer dryness in the mid to low latitudes, there are large uncertainties about the local characteristics of these phenomena. Since increased precipitation and much more frequent, intense rainfall are expected, the frequencies of high river flow and floods are likely to increase.

*Tropical Cyclones*

The increased sea surface temperature could result in more intense typhoons. It is expected that the maximum wind speeds brought by these typhoons will increase because of the higher sea surface temperature, thus increasing their destructive power. The potential areas affected by typhoons are expected to be enhanced, but there are still many uncertainties about the formation of typhoons, and especially about their frequency.

*Coastlines*

Retreating coastlines and changes in the morphology of coasts associated with sea level rise are expected. Mimura (1993) estimated that the total area below sea level under average high water conditions would become 2,339 $km^2$ compared to the present area of 861 $km^2$. (An area of 861 $km^2$ is already below sea level but is protected by dikes.) Sea water will infiltrate into rivers and into groundwater. In estuaries, sea level rise will also induce backwater effects on river flow.

# 3. Impacts on Electricity Demand

The impacts of climate change on the electric utilities fall roughly into two types: direct impacts on electricity demand and physical effects on electric power supplies, especially on electric power facilities; and indirect effects arising from the measures taken to control greenhouse gas emissions. In this section, the physical impacts on electricity demand are discussed.

## 3.1. Sensitivity of electricity demand to climate change

As electricity cannot be stored and has to be consumed when it is produced, sufficient electric power plants have to be installed and properly managed to meet demand. Supplying electricity for peak demand, which in most regions of Japan occurs on the hottest summer days, is a great concern for electric utilities. In some cases, suppliers have already had difficulties in meeting peak demand because of high temperatures and also because of the widespread use of air-conditioners and large-capacity refrigerators (Ono, 1989). Electricity demand is highly sensitive to fluctuations in temperature, and could be largely affected by climate change.

A considerable number of analyses of the sensitivity of electric demand to temperature fluctuations have been made, mainly for the proper management of power plants by predicting energy demand for the following day. The results of these sensitivity analyses can be used to give a rough idea of the impacts of climate change on electricity demand.

The results of a correlation analysis of daily electricity consumption with various meteorological parameters showed that daily mean temperature had the highest correlation (correlation coefficient: 0.819–0.953), followed by daily maximum temperature (0.766–0.911) and daily minimum temperature (0.767–0.908). It was also reported that a temperature index, defined as a linear combination of properly weighted maximum and minimum temperatures ($T_i = aT_{\max} + bT_{\min}$, where $a + b = 1.0$), also shows a high correlation (0.808–0.945) (Ono, 1989; Ono and Morikiyo, 1985).

In another analysis, the relationship between daily mean temperature and daily electricity demand, shown in Figure 3, is expressed as a piecewise regression model with 24°C as the inflection point. Daily electricity demand increases linearly with temperature: increase ratios are 1% for each 1°C rise for the range 17–24°C, and 2% for each 1°C for the range above 24°C. Significant increases in electricity demand are not observed over 30°C (Ono and Morikiyo, 1985).

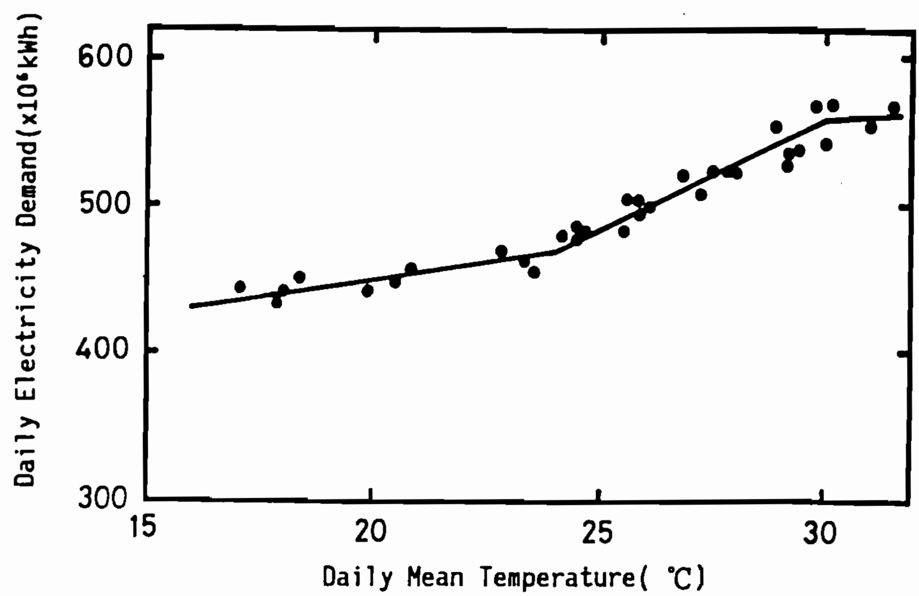


**Figure 3.** Relationship between daily mean temperature and daily electricity demand expressed as a piecewise regression with inflection points at 24 and 30°C (excl. weekends and holidays). Source: Ono and Morikiyo, 1985.

These sensitivities vary from year to year and are also strongly affected by economic conditions. Yuasa (1992) has shown that the highest three-day electricity demand can be expressed as a function of GNP and maximum temperature in August. The result shows that the maximum three-day electricity demand increases by about 3,000 MWh for each 1°C increase in maximum temperature in August.

Kurosaka (1991) examined the relationship between average summer temperature and annual electricity consumption, and showed that a 1°C temperature rise will cause extra 40 kWh of demand by household sector, equivalent to 1.5% of annual electricity demand in 1987.

During winter, electricity is mainly consumed for heat pumps, air-conditioners, and other heating appliances. In contrast with summer, of course, the demand for electric power decreases as the temperature increases. Figure 4 shows an example of an analysis of the relationship between the temperature at 3 p.m. in Tokyo and peak electricity demand. During fall and winter, the lower the temperature, the higher is the peak electric demand (Sato, 1984).

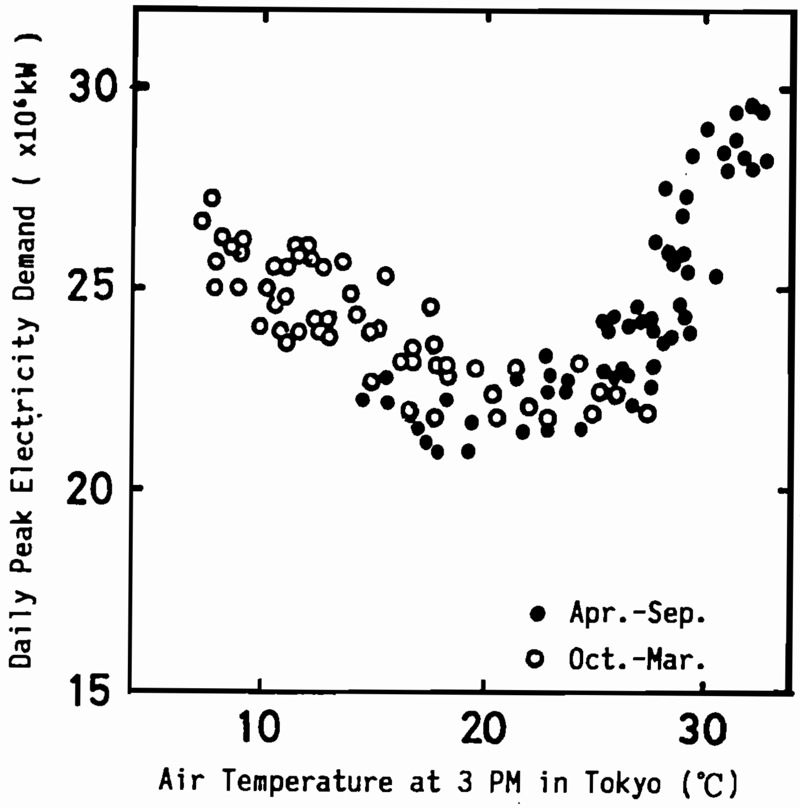


**Figure 4.** Relationship between daily peak electricity demand and temperature at 3 p.m. in Tokyo in 1982, excluding weekends and holidays. Source: Sato, 1984.

### 3.2. Impacts on electricity demand

An estimate of the possible impacts of climate change on electricity demand is shown in Figure 5. The figure compares monthly mean daily electricity demand with and without the effects of climate change. The estimate is based on the relationships between the temperature indices and daily electricity demand shown in Section 3.1. A uniform temperature rise of 3°C throughout the year was assumed for the estimate (Nishinomiya/CRIEPI, 1990).

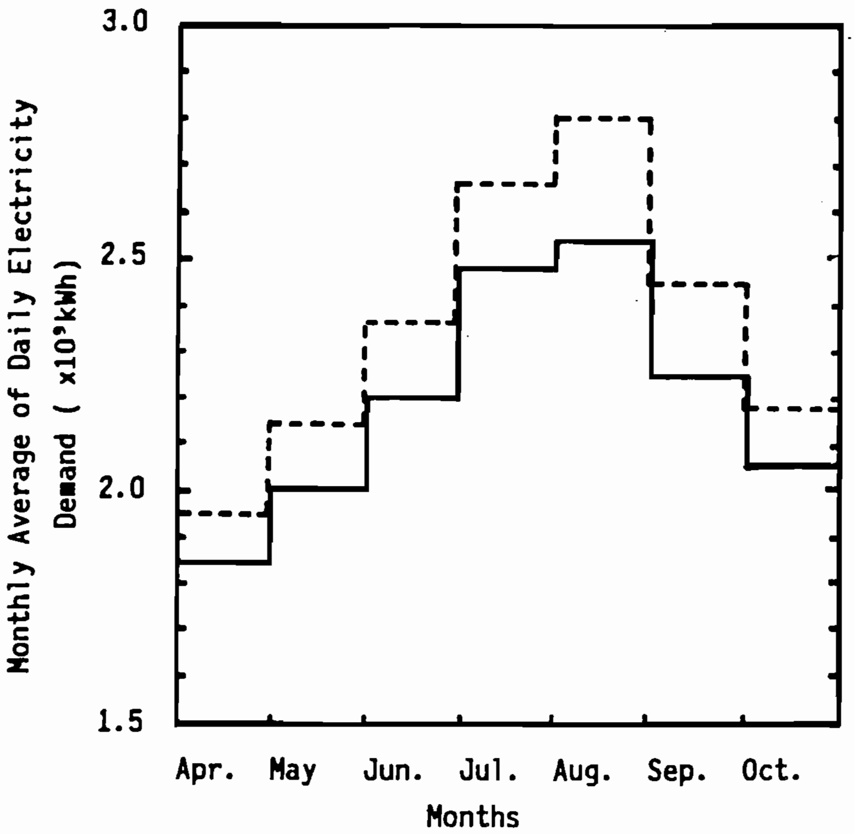


**Figure 5.** Estimated monthly average electricity demand (daily) for the nine electric utilities in year 2000 with (dotted line) and without (solid line) the assumed 3°C increase in air temperature due to climate change. Source: Nishinomiya/CRIEPI, 1990.

## 4. Impacts on Electric Power Facilities

Various natural phenomena induced by climate change would affect the electric power facilities. These phenomena are closely related, and form a complex structure of sequential networks. An "event tree" showing the sequence of events, is very helpful to understand the impact flows. The "event tree" shown in Figure 6 was developed for an analysis of climate change impacts on electric utilities (Nishinomiya/CRIEPI, 1990).

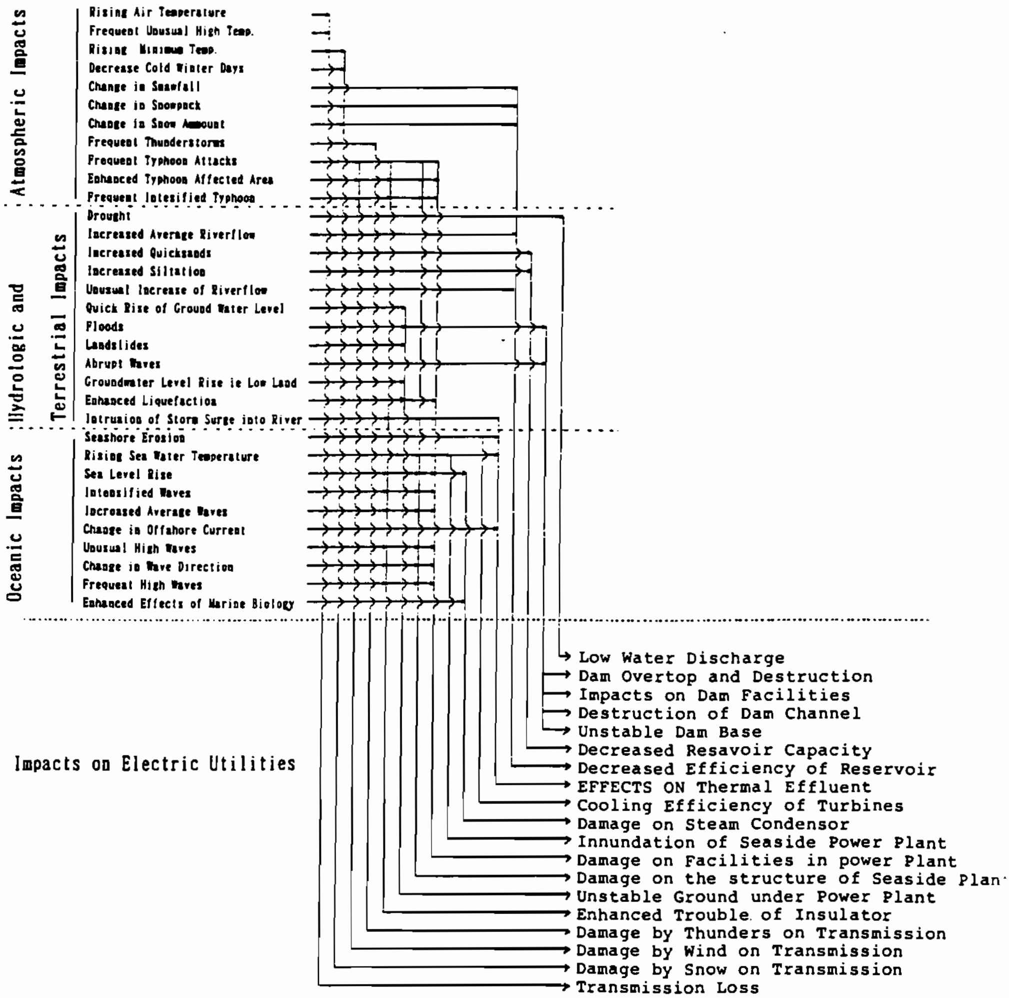


**Figure 6.** "Event tree" showing the likely sequence of impacts of climate change on electric utilities. Source: Nishinomiya/CRIEPI, 1990.

A number of possible impacts of climate change on electric utilities should be considered in the choice of appropriate countermeasures to combat secondary effects of global warming such as sea-level rise, more intense typhoons, etc. (Shirasuna, 1990). Most of these impacts will need further analysis based on updated information on local climate change obtained using a regional climate model. For hydroelectric power facilities, the following types of impacts should be considered:

(a) Changes in precipitation patterns, in both space and time, will affect the potential of hydroelectric power generation and its management.
(b) Erosion and siltation of reservoirs may increase if the frequency of intense rainfall increases.
(c) Long-term changes in both temperature and precipitation may affect watershed vegetation and consequently runoff characteristics.
(d) Reduced snow accumulation and early and rapid snowmelt caused by increased temperature will affect runoff characteristics and thus dam control and management measures.

For thermal and nuclear power facilities, the following types of impacts should be considered:

(a) A reduction in thermal efficiency due to the increased temperature of cooling water sources (oceans, rivers, lakes).
(b) The need to strengthen and raise breakwaters and other coastal constructions to reduce the impacts of sea level rise.
(c) The increased potential for liquefaction during earthquakes, related to rise in the water table linked to sea level rise.

For power transmission and distribution facilities, the following types of impacts should be considered:

(a) The increased incidence of lightning strikes due to the expected increase in thunderstorms.
(b) The increased probability of damage by strong winds due to the expected increase in typhoons.
(c) The increased likelihood of snow accretion damage in some areas due to changes in snowfall characteristics.
(d) The increased incidence of salt deposition on insulator strings of power lines due to the increase in strong winds.

# 5. Impact Assessment for the Hokuriku Electric Power Company

## 5.1. Background

More detailed and comprehensive studies are required to assess the potential impacts of climate change on electric utilities, because suppliers have to reduce the risks of climate change by developing the best mix of generating systems for efficient and cost-effective electricity supply. The following summarizes a case study of the Hokuriku Electric Power Company carried out as

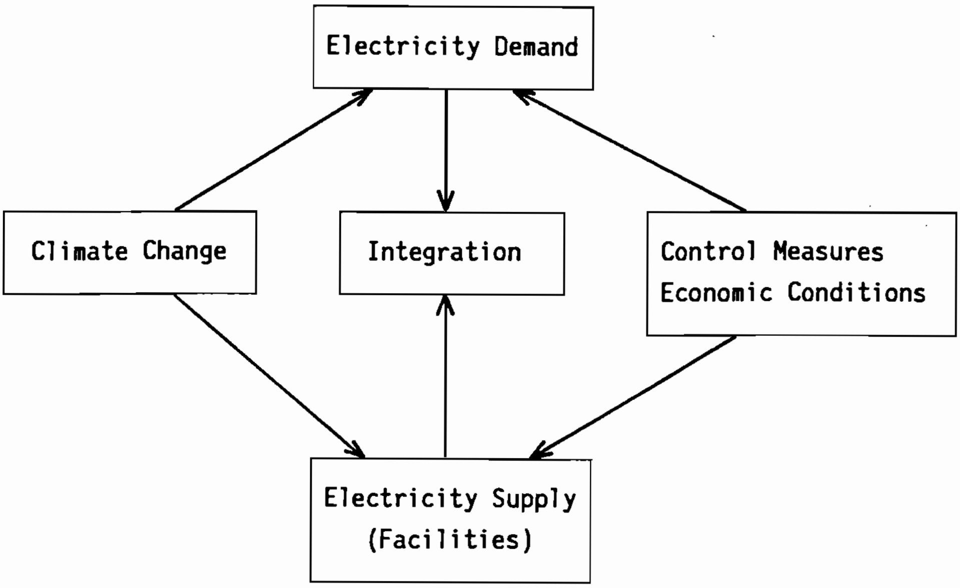


**Figure 7.** Flow of the impact assessment for the Hokuriku Electric Power Company.

a part of a joint Japan–USA research project (Matsui *et al.*, 1993). The study assumes not only the potential physical impacts of climate change but also future economic growth, demand for electricity, fuel prices, future types of electric power generation, and possible measures for controlling greenhouse gas emissions.

## 5.2. Outline of the study

The direct physical impacts of climate change such as temperature rise, precipitation pattern changes, and sea level rise were considered. The impacts of emission control measures were also considered by assuming three scenarios: a stabilization of greenhouse gas emissions at current levels; a 20% reduction in emissions; and a 50% reduction in emissions. These impacts were analized inclusively, together with the expected conditions of electricity demand and supply. The simulation model, called the Integrated Planning Model, was designed to obtain the best combination of generating systems in such a way that generating costs were minimized. Figure 7 shows a flow of the analysis.

This study examined three cases: a base case assuming no climate change; a case assuming climate change and no emission control measures, and a case assuming climate change and emission control measures. Electricity supply and demand were estimated for these three cases, and a comparison of the cases allowed quantitative assessments of the impacts.

## 5.3. Base case scenario

The rate of growth in electric power sales is expected to fall from the past 2.7% to a 0.8–1.7% growth rate. Electric power sales in the year 2050 are anticipated to increase by 60%–180% on the current level.

Due to the planned increase in capacity over the next several years, no additional supply capability is necessary up to 2010. In view of its cost effectiveness (construction, operating costs, etc.), coal has been regarded as the best fuel for new generation capacity. However, since it is estimated that the cost differences between other types of available generating capacity (LNG combustion, combined cycle, nuclear) and coal-fired generation are not large, a rational strategy, taking energy security into account, will include all three types of generating capacity.

## 5.4. Impacts of climate change

The direct impacts of climate change on electric power demand would be relatively small in the Hokuriku area. The expected increase in peak electricity demand will be about 10%, and total electricity demand is expected to increase by about 5%.

To meet the expected increase in peak demand, an increase in generation capacity will be needed. The least-cost plan for responding to the future peak demand increase will be a 36% increase in gas turbine generating capacity, regardless of the effects of climate change. The reason is that gas turbine generators can be constructed with relatively short lead times and can therefore meet peak electric power demand more effectively than other types of generators. As these turbines are relatively inexpensive (the capital costs are about 25% of other generation options), the increase in generating costs will be less than 5% by the year 2050.

The amount of hydroelectric power generated varies by 15% from year to year. If this range is maintained, climate change can have both positive and negative impacts on hydroelectric power generation, with a ±3–4% impact on generating costs. Impacts on hydroelectric power generation will have little effect on electric utility rates in this area, because no major additional hydroelectric capacity is anticipated, and its share in the generating base will decline over the study period.

The impacts of sea level rise, lightning, mountain winds, and snow accretion on power lines on generating costs are uncertain; if any, the effects on long-term costs are not expected to be large.

### 5.5. Impacts of emission controls

It would not be very difficult to maintain the current $CO_2$ emission level up to 2010. However, after 2010 no matter which control scenario is anticipated, if low-cost coal-fired plants are installed, large $CO_2$ emission reductions will be required. In 2050, to maintain current emission levels would require a 65% reduction in emissions compared with the no control scenario. If emissions are to be 20% less than the current level, the emissions reduction from the no control scenario will be 73%, and the 50% reduction scenario would require an 83% reduction.

In response to these requirements for $CO_2$ emission reductions, nuclear power will be used as an alternative to meet part of the future demand. Planned coal-fired plants will make up much of the remainder. LNG combustion combined cycle will be utilized instead of coal-fired plants for shoulder or load-following operations. Generating costs are expected to increase by 10% to meet the assumed $CO_2$ emissions scenarios. If the use of nuclear power plants is limited because of technical, political, or financial reasons, the generating costs may go up by 30% in 2050 compared with the base case.

## 6. Conclusions

The impacts of climate change on electric utilities in Japan have been outlined in some case studies. In general, impact assessment studies have mainly focused on the effects of emission control measures because these are likely to be much greater than the direct physical impacts. The case study of the Hokuriku Electric Power Company provides a good example of the situation: The marginal difference in the total electricity demand due to climate change would be only 5% in the year 2050, while the increase due to other factors such as economic growth will be 60–180%. The study also shows that the physical impacts of climate change on electric facilities are unlikely to be large in terms of long-term generating costs.

Another reason why most assessment studies focus on the effects of emission control measures is the scientific uncertainties surrounding future climate change. Quantitative assessment studies of climate change at the regional scale are limited, and give only rough sketches. Current global climate models are unable to simulate regional-scale climate with adequate accuracy, so that improved models need to be developed, even if this takes time.

Although there are large uncertainties about global climate change, it is extremely important for the electric utilities to assess the potential impacts because they will have to maintain stable electricity supplies in the most effective and appropriate manner under uncertain circumstances. Another reason is that the electric utilities tend to be viewed as major contributors to greenhouse gas emissions. This year (1993) the electric power companies in Japan published a voluntary plan for global environmental protection. Improved impact assessments, based on better scientific knowledge of climate change, will contribute to the long-term plans of the electric utilities.

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# Part 4
# Selected Issues in Integrative Assessments

# Discounting

# Intergenerational Equity, Discounting, and the Role of Cost–Benefit Analysis in Evaluating Global Climate Policy*

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## Abstract

When public policies with impacts far into the future are being debated, the question inevitably is raised whether cost–benefit analysis which discounts future costs and benefits is not biased against future generations and whether, if such discounting is appropriate at all, a lower rate should be used to avoid such bias. The debate on global climate change is no exception. This paper sketches and analyzes the welfare foundations of cost–benefit analysis and from this perspective analyzes the role of cost–benefit analysis in the climate policy debate, particularly with reference to intergenerational effects. The paper concludes that: (1) the cost–benefit criterion cannot provide a definitive basis for deciding whether we should commit to a longer-term program to moderate climate change; (2) the issues of intergenerational equity are not that global climate change will significantly lower the GNP of future generations, but relate to the possibility of science fiction-like changes in the planet that will produce catastrophic effects in the future; and (3) the typical way in which the cost–benefit problem is posed obscures the basic choices that we should be evaluating.

## 1. Introduction

Whenever cost–benefit analysis is used to evaluate projects or policies where benefits and costs extend over long time horizons, questions inevitably are raised with regard to the validity of the cost–benefit methodology in general and more particularly to whether the procedure of discounting future benefits and costs does not bias the analysis against the interest of future

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generations. Some contend that a procedure which discounts future costs and benefits using a positive rate necessarily gives less weight to the well-being of future generations; others contend that because the role of the discount rate becomes so dominant in the decision process when evaluating programs or policies with long time horizons, perhaps a lower discount rate should be used; others question whether cost–benefit analysis is sufficiently robust to form the basis for the decisions regarding global warming which may dramatically affect the future of life on the planet.

This is vividly illustrated in an editorial "Discounting Our Descendants?" by Laura Wallace in the March 1993, V. 30, No. 1, issue of *Finance and Development* (Wallace, 1993). This editorial is followed by two concise comments by William R. Cline, the author of *The Economics of Global Warming* (Cline, 1992),[1] and Nancy Birdsall and Andrew Steer of the World Bank (Birdsall and Steer, 1993). These three pieces highlight almost all of these issues and demonstrate how tricky they can be even in the hands of the most competent economists. In addition, the piece by Cline provides actual estimates of benefits and costs over time which we use as a basis for discussing some of the intergenerational issues.

To set the stage for the analysis to follow, it is useful to quote liberally from "Discounting Our Descendants?" (Wallace, 1993, p. 2):

> ... at the June 1992 Earth Summit in Rio de Janeiro, more than 150 countries signed a convention aimed at stabilizing concentrations of these gases. ... a mechanism for deciding on stronger measures, if warranted, was set up. But few specific measures or targets were included, reflecting a widespread disagreement on just how activist nations should be. The stumbling block ... was the paucity of studies that vigorously set out both the costs and benefits.
>
> For that reason, *The Economics of Global Warming* ... has drawn much attention. Using the technique of cost–benefit analysis, it concludes primarily on economic grounds – with many ecological effects omitted – an "aggressive" action program is warranted. ... Cline advocates the use of a low (about 2%) discount rate. ... a controversial proposition to put it mildly.

The editorial goes on to observe that:

> ... even a small change in the discount rate used in a cost–benefit analysis has a tremendous impact on the bottom line ... some people – especially environmentalists - insist that when it comes to setting the level of the discount rate, long-term investment to protect the environment must be treated differently. They advocate a special low discount rate.

[1] I am grateful to Dr. Cline for supplying me with both a copy of his book and the editorial section from Finance and Development, March 1993.

> Cline, too, advocates a low rate, but ... He argues environmental projects should be treated no differently from other projects ...
>
> Others, such as the World Bank, worry that an especially low discount rate would actually reduce the wealth passed on to the next generation by financing projects whose rates of return are lower than those for other available investments.

These comments and concerns as expressed in the context of global warming have been expressed in previous policy debates, notably the debate over energy policy. Some of these concerns are based on misunderstandings, such as the concern that using a positive discount rate applied to benefits and costs necessarily places a lower value on the welfare of future generations. Other concerns about what we can or cannot conclude on the basis of cost–benefit analysis require a deeper look at the cost–benefit criterion itself and how the application of that criterion is limited in cases where payment of compensation would require intergenerational transfers of resources.

To address these issues we first set forth the basic paradigm of cost–benefit analysis and its analytical foundation in welfare economics, including the well understood, but often neglected, fact that the basic cost–benefit criterion rests on the presumption that net gainers can at least in principle compensate net losers from a given policy action. We will demonstrate that it is not possible, as a practical matter, for governments to design and commit to the intergenerational transfer programs across many generations. This means that even if the cost–benefit criterion is satisfied in the case of global warming, there are potentially important issues of intergenerational welfare that have to be considered in addition to the cost–benefit estimate. One cannot, for example, reject programs to reduce global warming, simply because the present value of the costs exceeds the present value of the benefits. In addition, where there are significant issues of intergenerational equity, one cannot appropriately address these issues by simply adjusting the discount rate used in cost–benefit analysis. Further analysis is required on a case by case basis.

The next section analyzes whether there is, in fact, a significant issue of intergenerational fairness relating to global warming using cost–benefit estimates provided by Cline (1993). The conclusion that emerges is that if the costs and benefits in Cline's analysis are captured within even a very wide margin of error and if his assumptions about world economic growth are at all reasonable, the issue of intergenerational equity is not one of the current generation shortchanging future generations by not investing in greenhouse abatement, but rather one of whether the current generation should be making very large investments in abatement to reduce the costs of global warming for generations, who even after paying the costs of Cline's high damage scenario will be many times richer than we are today. If there is a significant issue of fairness to future generations, it is associated with the potentially catastrophic outcomes of global warming. The fundamental question of intergenerational equity hinges on the rate of per capita income growth and on the magnitude of the effect of global warming.

The next section discusses several different conceptual bases for the discount rate. It then demonstrates that using a positive rate of discount does not necessarily mean putting less value on the well-being of future generations and discusses the rationales for using a rate of discount in public policy analysis that is below the marginal rate of return on capital which in a competitive economy will equal the cost of capital.

The final section of the paper argues that in investment or policy environments where there is a high degree of uncertainty and where relevant information becomes available or can be produced over time, the typical formulation of the cost–benefit problem is not very helpful to decision making. Today's decision or policy problem related to global warming is not whether we should commit to and begin an aggressive program of abatement or whether we should do nothing and wait and see. The important question is, given what we know today, what should we do to position ourselves so to respond effectively to future events? Such a program may call for immediate aggressive abatement or it may call for waiting or taking some other action. The important point is that the decision framework should be sequential, capable of responding to new information, and should take into account the option value of alternative courses of action.

## 2. The Foundations of Cost–Benefit Analysis and Intergenerational Analysis

Cost–benefit analysis can be separated into two parts. The first is the measurement and display of costs and benefits over time. Costs and benefits are typically measured in terms of willingness to pay. For a benefit, it would mean estimating the maximum amount the beneficiary would be willing to pay for that benefit. For a cost, it would mean estimating the minimum amount that the person incurring the cost would be willing to accept as full compensation. To the extent that benefits and costs are represented by goods and services that are traded in competitive markets they can be measured by their market prices. The difficulty comes when benefits and costs, such as those pertaining to environmental changes, are not traded and valued in the market. Despite the fact that these benefits and costs are a more difficult measure, the willingness-to-pay criteria is the guiding principle of measurement.

Once benefits and costs over time are measured, they are then discounted to their present value using some rate of interest or discount. If we assume a perfectly competitive market, free of distortionary taxes and capital market imperfections, then there will be a single market rate of interest, $r$, at which businesses and individuals can borrow and lend. In this case, $r$, should be used to discount benefits and costs over time to their present value, and the net present value of the project or policy is simply the present value of benefits minus the present value of costs. Note, in this ideal case, $r$ would equal both the marginal rate of return on investment and the consumer's rate of interest or marginal rate of time preference.[2]

The second component of cost–benefit analysis is the cost–benefit criterion which states that if the net present value of benefits is positive then the project should be adopted; if not, it should be rejected. In cases where there are several mutually exclusive alternatives, the cost–benefit criterion states that the project with the highest net present value should be chosen. This implies that in cases where there is a budget constraint, the cost–benefit criterion states that if there are more projects with positive net benefits than will fit into the budget, then one should choose that portfolio of projects which maximizes the net present value of the total feasible portfolio. Therefore, having positive net benefits is necessary but not sufficient to justify a project's adoption. This turns out to be a critical point in many cases where a below market rate of discount is used in a cost–benefit evaluation.

The welfare basis for the cost–benefit criterion is the Kaldor-Hicks compensation principle. If the net present value of benefits is positive, then it follows that if one adopts the project, the people receiving the benefits could compensate the people incurring the costs and still have something left over. Therefore, if the cost–benefit criterion is satisfied everyone can be made better off with the appropriate compensation of those incurring costs by those receiving the benefits. Because everyone can be made better off if the cost–benefit criterion is satisfied and appropriate compensation is paid, we can conclude that there is an unambiguous increase in welfare. The problem is that in most cases the appropriate compensation is not paid. Then even where a program or policy meets the cost–benefit criterion, there will in practice be some people who enjoy positive net benefits and others who

[2]For a complete development of this line of argument see Lind (1982).

incur net costs. Unless one gives equal weight to the net benefits or costs of each individual, one cannot conclude that there has been an unambiguous welfare gain.

Nevertheless, the cost–benefit criterion is quite powerful. Suppose, for example, that one wanted to subsidize a given group and the choice was between spending \$1,000,000 on a project that would benefit that group or giving the group the \$1,000,000 in cash. If the present value of the net benefits of the project is positive, (i.e., the present value of future benefits exceeds the initial cost of \$1,000,000), then it is better to adopt the project than to give them the cash. If the benefits are less than \$1,000,000, it would be better to give them the cash. Therefore, whether or not one chooses to require the full compensation of costs or to subsidize the beneficiaries of a project by not requiring them to pay the costs, the project should be adopted only if it meets the cost–benefit criterion. For this reason, one can say that whatever your policy is with regard to redistributing income between the beneficiaries of a project and those incurring the costs, the project should only be adopted if it meets the cost–benefit test.

In the case of global warming policy where the benefits and costs will be distributed over many generations, any compensation scheme will potentially involve intergenerational transfers. Therefore, the question of whether we can make intergenerational transfers in either direction is at the heart of the matter with regard to the applicability of the cost–benefit criterion to the analysis of global warming policy. To see this, suppose that we were in a perfectly competitive world and that all present and future generations could invest or borrow at the competitive market rate of interest, $r$. Then it can be correctly argued that a discount rate of $r$ percent should be applied in the cost–benefit analysis of global warming abatement. This argument, however, hinges on our ability to make intergenerational transfers over many generations.

Suppose we were considering a \$1 billion investment to reduce global warming that would provide a benefit in 100 years of \$7.24 billion which is equivalent to 2% rate of return for 100 years. Suppose that $r = 8\%$. The cost–benefit logic for rejecting that investment is that we could invest and reinvest the \$1 billion at 8% so that in 100 years we could give that generation \$2,199.76 billion or almost 304 times as much value as they would have received from the investment in abatement. This line of argument supports the requirement that global warming investments be evaluated using an 8% rate in the cost–benefit calculations. As Cline correctly points out, this is the essence of the argument made by Summers, Birdsall, and Steer in arguing against his use of 2%.

"Instead, Summers, Birdsall, and Steer seem to argue much more broadly that society should do little to limit greenhouse gas emissions. They implicitly counsel that the public would be better off to set aside money in a "Fund for Future Greenhouse Victims." The money would be invested at 8% ... and the income would compensate future generations for global warming damage at a far smaller cost than through limiting emissions" (Cline, 1993, p. 5).

This is the "give them cash not the project" line of argument that follows straight form the cost–benefit criterion. It is a powerful argument if there is a means of implementing the "give them cash" alternative. Therefore, before adopting the cost–benefit criterion for evaluating global warming policy, one has to investigate the feasibility of implementing such an intergenerational compensation scheme as a practical matter. In many ways, the most interesting intergenerational issue is whether one can structure intergenerational transfers or trades so that we can then pursue efficient investment strategies to maximize the consumption stream across all generations and then take care of any inequities through intergenerational transfers.

There are a number of problems that make the concept of a "Fund for Future Greenhouse Victims" difficult to implement.[3] First, there is the problem that Cline alludes to of how one would set up and manage such a fund so that say 100 years in the future a vast stock of capital goods would be bestowed upon that generation for the production of consumption goods. What we are really talking about is increasing the total savings rate, private savings plus government savings, by increasing taxes and running a government surplus (or a reduced deficit) which will increase the rate of economic growth. However, in addition to the increased rate of investment, one would have to find a way, say through a trust fund, to guarantee that the returns on this additional investment were fully reinvested and not returned to the income stream where they would mostly go to consumption with only a relatively small part being reinvested. Without this continual reinvestment, the arithmetic of compounding which is fundamental to the "give them the cash" alternative does not work. Furthermore, this policy would have to be sustained by successive governments for a hundred years. Even if this generation were to set up such a fund, it could not commit the governments of future intervening generations to do so. There would be every incentive for some future generation to break the chain of intergenerational transfers and consume all or part of the resources in the trust fund. Therefore, in the absence of a potentially viable plan for transferring resources to future

[3] For a discussion of this and some other aspects of the intergenerational transfer problem in the context of global warming see Lind (1990).

generations, the powerful logic behind the cost–benefit criterion breaks down if there are potentially serious issues of generational fairness.

Therefore, a case can be made that we should not automatically apply the standard cost–benefit criterion if it can be demonstrated that future generations would be significantly worse off than the present one as a result of global warming. Whether future generations will be better or worse off will depend primarily on the rate of economic growth. Empirical evidence suggests economic growth has produced an increase in per capita income in the past and this process is continuing today. In fact, economic growth is such a fact of life that every one of the integrated economic models presented in this volume have the assumption of positive economic growth built into their simulations. Therefore, in all likelihood future generations will be much richer than the present one and if they (future generations) want lower levels of greenhouse gases and lower temperature levels they should pay for them. The problem is that possibly the most cost-effective, or perhaps the only way of achieving this is to begin abatement programs today because of the irreversible nature of the process.[4] Therefore, to implement such a program of control where future generations would pay the cost, we would need to implement a scheme whereby the future generations would compensate the present and near-term generations for their investments in emission abatement programs. We know that in private markets such trades can be made through overlapping generations.[5]

To see how this would work through market transactions, suppose that epidemiologists were to predict that in 100 years a virus would return which would wipe out 50% of the world's population. Further, assume that to produce a known vaccine for this virus would take 100 years. In a competitive market, drug companies would at least in theory begin to produce the drug if they could profitably sell it in 100 years and earn a market rate of return even though the officers of these companies and the present shareholders would all be dead when the investment paid off. This can take place because present shareholders can sell their shares to the next generation and this process will repeat itself until the vaccine is sold and paid for by the generation that secures the benefits.

[4]We typically treat global warming as an irreversible process, however, greenhouse gas concentrations will decay over time if not replenished, and it is possible that technologies can be developed which will reduce greenhouse gas concentrations or modify their effects. These possibilities should be explored carefully as they would be a significant factor in any decision to commit immediately to an aggressive abatement program.

[5]The seminal paper of this literature is Samuelson (1958).

The value of each generation's share will go up by the increase in the present value of the investment as time passes. Since each generation has other alternative investments, the vaccine investment will have to earn a market rate of return, say 8%. Furthermore, if the generation facing the epidemic is assumed to be at least as wealthy as the ones before it, even after paying for the vaccine, there is no reason for prior generations to subsidize it. Therefore, the appropriate rate of return on the investment in the vaccine is 8%, the market rate, because the only reason for requiring investors in previous generations to accept a lower return, say through some government program supported by taxes, would be if it were appropriate to subsidize the generation living 100 years from now.

The problem with this line of argument for global warming is that the output of investments in abatement are cooler temperatures in the future which are public goods and therefore cannot be provided profitably in the market. They will have to be provided by governments acting over time. Theoretically, governments could replicate the private market by appropriately transferring resources from younger to older generations. Each generation would make transfers to the previous one equal to the accumulated value of the investment in abatement and then receive later in life a similar transfer from the next generation. Clearly, this does not appear to be feasible in practice.

It follows from the previous example, that if there is no reason to subsidize the generation 100 years from now, and if that generation would not be willing to pay for the cost of a century of investment fully compensating previous generations, which means returning their capital and paying a market rate of interest, i.e., the present value of benefits discounted at the market rate of 8%, does not exceed the present value of costs, then the program should be rejected both on the grounds of intertemporal efficiency and equity. Therefore, even if intergovernmental transfers could be carried out and guaranteed across generations so that compensation could be paid, it follows from the cost–benefit criterion and consideration of intergenerational equity that the discount rate should equal the market rate of return.

However, suppose that in the previous example, the facts were altered to make the cost of the vaccine totally unaffordable to the generation living 100 years from now. More precisely, assume that the amount that this future generation would be willing to pay for the vaccine was less than the accumulated cost of producing it, not including any accumulated interest. Then the investment in the vaccine would have a negative rate of return and would be rejected on the cost–benefit criterion even if a zero rate of discount were used in the cost–benefit calculation. At the same time, current and future generations might well decide to fund the vaccine development on the grounds that it would be morally unacceptable not to develop the vaccine and subject a future generation to the ravages of such an epidemic.

Note that the solution to this particular case is not to lower the discount rate for public projects. One has to evaluate the issue of intergenerational equity separately and make a political decision about how we should deal with this ethical issue. The cost–benefit criterion does not help us with the decision as to whether current generations should subsidize future generations. What the cost–benefit format can do is help us determine the most cost-effective way of implementing that subsidy. This is no different for the case of intergenerational income transfers than for the case of intragenerational transfers. Cost–benefit analysis which uses the willingness-to-pay concept as the basis for measuring benefits and costs which in turn depends on the intergenerational and intragenerational distributions of income as a starting point does not provide a basis for determining whether that distribution of income is equitable or whether redistribution should occur. Furthermore, this situation cannot be solved by tinkering with the discount rate.

Whether we are dealing with public projects which span many generations or ones which occur within one generation, politically, it is often very difficult to design and implement mechanisms through which the beneficiaries of a project will compensate those that incur the costs. There is an extra set of problems when intergenerational transfers are involved because of our inability to commit intervening generations to the plan. This is not only true for the scenario that would give future generations the cash, but also for any continued program of $CO_2$ emissions abatement. The present generation may start a program based on the assumption that it will be continued by future generations, but there can be no guarantees that this will occur. There is one kind of investment or program that avoids this commitment problem. Investments in technology development that will provide future generations with the means of coping cost-effectively with greenhouse gas emissions or of reversing global warming have the property that they will be available to and benefit future generations regardless of what intervening generations choose to do. This characteristic means that such investments and programs merit special attention.

## 3. Global Warming and Fairness To Future

From the previous analysis it is clear that, because it is not possible to commit to and carry out the appropriate intergenerational transfers in either direction that would be required for the beneficiaries of a policy to compensate those incurring the costs or to remedy intergenerational inequities, the cost–benefit criterion is not a complete criterion for evaluating global warming policy. We must also ask whether there are issues of intergenerational equity that might require us to modify conclusions with regard to global warming policy reached on the basis of cost–benefit analysis alone? This question can be subjected to analysis.

To begin this analysis, it is useful to start with the cost and benefit estimates provided by Cline. He assumes (what he refers to as a "modest") 1% rate of growth in per capita gross world product (GWP) (Cline, 1993, p. 5). This would result in per capita GWP levels which in 100 years would be 2.7 times what they are today and in 300 years be 19.8 times today's level. He also estimates potential damages for the year 2050 and the year 2300 for several scenarios. The highest damage estimate is 20% of GWP by the year 2300 (Cline, 1993, p. 4). For purposes of this discussion we will use a damage estimate of 20% of GWP. This means that even if by 2093 people were 2.7 times as rich as people today, and if global warming were to reduce their wealth by 20%, they would still be over twice as rich as the present generation. By the year 2293, after deducting 20% for the cost of global warming, people would be over 15 times as rich as current generations. Can we justify current generations sacrificing 2–3% of GWP to increase the wealth of future generations who even after deduction for the high damage scenario are 2–15 times richer than the present generation? The answer is clearly no on the basis of intergenerational equity which must weigh in favor of the current generation.

The crux of the question on intergenerational equity is (1) will per capita world income continue to grow and at what rate, and (2) what will the magnitude of the costs be imposed by global warming. If one takes the most extreme cost and benefit estimates generated by Cline, the answer has to be that if there is an issue of intergenerational equity, it is whether the present generation should be transferring income through global warming programs to future generations who will be much better off. The real disagreement between the environmentalists who advocate an all-out program to reduce greenhouse gas emissions and economists and others who may be more skeptical is a disagreement over whether future generations will be better off even with global warming than the present one. This in turn hinges on what the rate of per capita income growth will be and how severe the consequences of global warming will be. These two factors are interrelated. All things being equal, the greater the rate of economic growth, the greater will be greenhouse gas emissions and the severity of the greenhouse effect. Therefore, if one assumes slower growth one probably should also assume a lower level of damages from global climate change. This is an issue that deserves further investigation using the integrated assessment models.

It appears from Cline's numbers and other numbers generated from integrated model runs, that only if there were catastrophic greenhouse effects, outcomes that are not even close to the mean of what we would predict, is there possibly a crisis and a case for the present generation to subsidize future generations. This position is well stated by William Nordhaus (1993), a noted contributor to the economic analysis of global warming.

> Most economic studies of the impacts and policies concerning climate change are based on scenarios like the smooth and gradual warming. ... the conclusion that emerges from most economic studies is to impose modest restraints, pack up our tools, and concentrate on more pressing problems ... Yet, even for those who downplay the urgency of most likely scenarios for climate change, a deeper anxiety remains about future uncertainties ... Given the potential of catastrophic surprises, perhaps we should conclude that the major concern lies in the uncertainties and imponderable impacts of climate change rather than in the smooth changes foreseen by the global models.

## 4. What Discount Rate Should We Use?

Before discussing what rate should be used, we need to distinguish between several different concepts of the discount rate and how they may or may not fit into the standard cost–benefit model. In discussing the traditional cost–benefit paradigm in a competitive world, the rate of discount $r$ was equal to the market rate of interest and, in turn, was equal to the marginal rate of return on capital and to every individual's marginal rate of time preference which determines the rate at which individuals would be willing to trade their own current consumption for their own future consumption. It is this own-consumption rate of discount which would be relevant to the cost–benefit model with overlapping generations described in this paper. Only if one accepts the logic of the Kaldor-Hicks compensation scheme in the cost–benefit model is this rate relevant to the analysis of benefits and costs across many generations.

There is a second concept of discounting that has recently entered the literature and that relates to how one would value something received by someone else now as opposed to sometime in the future. An example of this kind of analysis is the study by Cropper and Portney (1992) which attempts to determine how people would value saving a life (not their own) now as opposed to saving a life in the future. Clearly, since people in general do not make this kind of trade-off in their normal day-to-day transactions, we cannot look to a market rate of return or interest to determine their time preference in this sense. Such studies of time preference rely on questionnaires or experimental data. One could imagine asking people similar questions about their willingness to sacrifice their own consumption today for a reduction in the cost of global warming in the future and from that impute an implicit discount rate. This concept of the discount rate is noted for completeness and clarity, but will not be discussed further as it is discussed in another paper by Thomas Schelling (this volume).

The third concept of the discount rate is the rate of discount applied to utility in the optimal growth models. In these models the problem is to maximize social welfare over time by optimally allocating production at each point in time between consumption and investment. More specifically the problem is to maximize

$$W = \int_0^\infty e^{-\delta t} U(C(t))dt \quad , \tag{1}$$

where $C(t)$ is consumption at time $t$, $U(C(t))$ is the utility of consumption at time $t$, and $\delta$ is the discount rate applied to utility, subject to the constraints of technology, the labor force, and resource availability. There are several ways to interpret this formulation of the problem. One would be to consider this to be the optimization problem of a single or representative individual who lived forever. A second interpretation, which is more useful for analyzing intergenerational issues, would be to assume that there is a constant population of identical individuals with the same utility function, i.e., $U(C(t))$ is the same for all individuals regardless of when their consumption takes place. Therefore, $U(C(t))$ can be taken to represent the utility of the population at time $t$. In addition, we will assume that generations are overlapping so that a competitive economy could operate through time.

In the optimal program, one of the conditions of optimality is that

$$r_t = \rho_t = \delta + \eta(C_t)\frac{\dot{C}_t}{C_t} \tag{2}$$

where $r_t$ is the marginal rate of return on investment at time $t$, $\rho_t$ is the individual consumers rate of interest or time preference for consumption, $\delta$ is the utility rate of discount, $\eta(C_t) = -\frac{U''(C(t))}{U'(C(t))}C_t$ is the elasticity of the marginal utility of consumption, and $\frac{\dot{C}_t}{C_t}$ is rate of growth of consumption.[6]

[6]For an excellent discussion of these conditions and terminology see Dasgupta (1982).

If we look at the left side of equation (2), we see that, on the optimal path, the marginal rate of return on investment, $r$, equals the consumer's rate of interest or time preference which is identical to the result for the multiperiod perfectly competitive economy. It would follow from this that the correct rate of discount should be the equilibrium value of $r$ which would equal the market rate of interest and the consumer's rate of time preference.

How then can one justify a lower rate of discount than the market-determined cost of capital for use in cost–benefit analysis. This can be justified if the rate of discount that we should apply to consumption over time for some reason should be lower than the marginal rate of return on capital. There are two lines of argument that have been advanced to reach this conclusion.

The first line of argument for a lower discount rate for consumption begins with equation (2). Instead of equating $\rho$, which we cannot observe directly, to the marginal rate of return on capital, $r$, which we can observe, some economists including Cline attempt to determine $r$ from the right side of equation (2). Generally, the process begins by setting $\delta = 0$ which is justified on the grounds that to have a positive $\delta$ would give less weight to the utility of future generations. The second step is to estimate the elasticity of the marginal utility of consumption $\eta_t$ and the long-run growth rate of consumption $\frac{\dot{C}_t}{C_t}$, and the product of these two terms gives one the rate of time preference for use in discounting long-term costs and benefits. For example, Cline makes exactly this line of argument. He states that

> [T]o estimate the SRTP (social rate of time preference) – which I calculate to be 1.5% – I appeal to basic economic theory – which states that this rate equals the sum of two components (Cline, 1993, p. 4).

In the notation used here, the social rate of time preference is $\rho$ and its two components are $\delta$ and $\eta_t \frac{\dot{C}_t}{C_t}$. With regard to $\delta$, Cline states,

> [T]here is a strong tradition among economists to set this preference at zero, especially for comparisons between the present generations and future generations, who cannot participate in today's decisions (Cline, 1993, p. 4).

He goes on to reason as follows about the second component $\eta_t \frac{\dot{C}_t}{C_t}$:

> This component, in turn, equals the product of (1) the growth rate of per capita income and (2) the responsiveness ("elasticity") of marginal utility with respect to consumption ... For my study, I set the utility based rate at 1.5%. This estimate applies an "elasticity of marginal utility" of 1.5 based on independent calculations by William Fellner and Maurice Scott. It also assumes an average per capita growth rate of 1% over the next three centuries (Cline, 1993, p. 4).

It is important to note that even if the utility rate of discount is zero, the social rate of time preference will be positive as long as consumption is growing over time. Therefore, discounting benefits and costs at a positive rate does not necessarily give less weight to the welfare of future generations.

The second line of argument that has been used to justify discounting at a rate below the marginal rate of return on capital is based on the fact that because of personal and corporate income taxes, the after tax rate of return on investment to the individual investors is much lower than the before tax rate on investment so that individuals do not earn the market rate of return on investment on after-tax basis. If we equate this after-tax rate of return that an individual can earn to that individual's rate of time preference for consumption, then it can be argued that we should discount future consumption streams, i.e., future benefits and costs, at this lower rate. In other words, if we could organize the appropriate system of intergenerational transfers, then hypothetically future generations could fully compensate the previous ones by paying them a rate of return equal to their marginal rate of time preference which will be lower than the market rate and the marginal rate of return on capital.

The problem with this position is that it is not clear that individuals have a well defined rate of time preference which is lower than marginal rate of return capital. For example, many individuals borrow on credit cards and pay rates of interest of 15–25%. Should we be using these rates to evaluate global warming investments? Many economists say yes. More troubling still, from a theoretical point of view, is that we observe some people borrowing on credit cards at 15–25% and simultaneously investing at after tax rates of return in the 1–3% range. Which, if either, of these rates reflects these individuals' rates of time preference? Further, we know from experimental evidence, that people exhibit different rates of time preference in different situations and for different goods. The question is how would one know what the appropriate rate is from this conflicting data. Put differently, do individuals have well defined rates of time preference, and if they do, do they equal any particular rate of interest or return?

Further, there are a number of serious problems with using a discount rate below the marginal rate of return on capital which is generally estimated to be in the range of 5–20% in real terms regardless of the logic behind it. The first problem is that if we were to believe that the rate of time preference were below the rate of return on capital then we are not on the optimal growth path as equation (2) is not satisfied. This means that we should be saving more which Cline fully understands and subscribes to (Cline, 1993, p. 5). However, Alan Manne uses a standard formulation of neoclassical growth model to explore the implications for the level of saving and investment given the discount rate that Cline proposes, and assuming a conservative marginal rate of return on capital of 5%.[7] What he finds is that the optimal program, given these assumptions, would require a large discontinuous increase in savings and investment. Savings rates in the transitional period would be much higher than any historical experience and much higher than rates that we would expect generations living in the near term to accept.

Furthermore, if we were going to increase savings and investment, for example, by running a government surplus which would create a larger pool of total savings in the economy or by raising taxes and making direct public investments, there are many private and public investments that we would want to make before making investments with a 2.0% rate of return. Given that we are not likely to be willing to increase the savings rate to the level implied by Cline's assumptions, it follows that there are many alternative investments to global warming that we should be making before we would invest in climate change abatement. The second-best argument frequently used by economists, including Cline, simply does not apply here, because there are potentially many investments in both the private and public sectors that could be made with the appropriate public policies given the savings that private and public sectors are willing to generate.

Using a 2% rate of discount, Cline calculates an aggressive abatement program would produce a cost–benefit ratio of 1.3. These programs are projected to use up to 2 to 3% of GNP (Cline, 1993, pp. 1, 4.) If one were to evaluate all potential private and public projects that could be implemented through public action using a 2% rate of discount, one would almost certainly find projects with substantially higher cost–benefit ratios than 1.3, the cost of which will exceed the budget for global warming. When there are constrained budgets, the cost–benefit criterion requires that we maximize the present value of net benefits of the total portfolio given the budget constraint. While one cannot prove that most or all of the money in the optimal portfolio would not be invested in $CO_2$ emissions abatement, I believe that this would probably be the case. In any case, to prove Cline's assertion that an aggressive program of abatement is justified, even in a second-best world, one would have to demonstrate that there are no better alternative investments that we could make with this capital.

The problem of adjusting the discount rate for evaluating only one particular investment or policy is that you run the risk of adopting an investment that would be outperformed by many other alternative investments if they

[7] See Manne (this volume). Similar results are reported in King and Rebelo (1993).

were evaluated on the same basis. Even in a second-best world where it would not be possible to put into effect the more efficient investments in the private sector, there are many government investments in very worthwhile projects which would almost certainly outperform $CO_2$ abatement, even using Cline's numbers.

In addition, given the fact that economic growth will almost certainly make future generations better off than the present one, concerns that public decision criteria that use a market rate of discount discriminate against future generations are misplaced. Given any level of saving, the interest of future generations are best served by making the highest return on investments in both the public and private sectors. Using a competitive market-based rate in evaluating public policy decisions will support that objective. This is the response to Cline by Birdsall and Steer (1993, p. 6):

> ... we feel that meeting the needs of future generations will only be possible if investable resources are channeled to projects and programs with the highest environmental, social, and economic rates of return. This is much less likely to happen if the discount rate is set significantly lower than the cost of capital.

One might argue that economic growth will not continue and future generations will not be better off, but in that case the greenhouse problem will be vastly diminished as well. However, the scenario of zero per capita income growth or of declining per capita incomes with global warming should be explored using the integrated modeling capability that we have developed.

Cost–benefit analysis in general and Cline's study in particular are of great value even though they may not provide definitive answers to difficult policy questions. For every public policy decision, it is critical that we try to identify and measure benefits and costs as accurately as possible. This exercise sharpens our understanding of the problem and informs the decision making process. This is true even if we cannot measure all the benefits and costs and if, for one reason or another, we reject the cost–benefit criterion. It is also true regardless of the discounting procedure we chose and regardless of whether we draw the same inferences from the cost–benefit data or not. For example, the arguments in this paper using Cline's cost–benefit estimates do not support his conclusion that we should commit to and immediately begin an expensive, long-term program of abatement. Nevertheless, the cost–benefit analysis that he has done is an important contribution to the global policy debate.

## 5. The Need to Structure the Public Process as a Sequential Decision Process that Makes Use of New Information and that Looks at Alternative Policies as Options

The typical cost–benefit analysis sets out an alternative to taking no action and then estimates benefits and costs over time. In general, mean value estimates are used and risk is supposedly accounted for in the discount rate. The entire analysis is structured as if the policy choice is to do nothing or to commit to some long-term course of action. For most large questions of public policy, when there is a high degree of uncertainty and where new information is becoming available and can be produced, the last thing one should do is commit to a long-term course of action. This is an inappropriate, although traditional, way of formulating the problem of investment under uncertainty.[8]

Many policy issues, including global warming policy, evolve incorrectly into polarized debates over whether we commit all-out action now or no action at all. This polarization, which occurs in both the analytical and political communities, results from a mischaracterization of the policy issues which obscure the choices that we need to evaluate. This is reflected in the following statement with regard to the development of synthetic fuels:

> In economics as elsewhere, great confusion can result from posing issues of widely acknowledged significance in the wrong way. The wrong, but unfortunately common question to ask about large development projects like the government subsidization of synthetic fuel is: "Should we launch a crash program to build a large synfuel industry, say one or two million bbls/day by 1990?"
>
> This all-or-nothing "Manhattan project mentality" is the wrong way to pose the issue. It misses the point that substantial uncertainties about the net benefits of large-scale synfuel production ... make a sequential, information-yielding strategy the relevant policy.
>
> The right question to ask is "Do synfuels look good enough now to make taking a further look worthwhile?" It is quite possible we might reject synfuels development when it is posed as a false all-or-nothing dilemma, yet be in favor of financing one more step to find out more information when the issue is correctly posed as a problem in sequential decision making (Weitzman *et al.*, 1981).

[8] For an excellent discussion of the "real options" approach to the analysis of how we should analyze investments under uncertainty see Dixit and Pyndyck (1994).

This statement characterizes the problem with much of the debate over what our response should be to the potential of global warming. The relevant options are not whether we should commit to a long-term program of aggressive abatement or not. The more tractable question is: Given our concern, what should we be doing over the next ten years to position ourselves to act on new information and new technological developments? We should be asking do we need to begin an aggressive program of abatement right now because of irreversibility or can we wait? If we invest successfully in new technologies that will substantially reduce the cost of abatement in ten years, can we wait and more cost-effectively reach the same level of total abatement by starting later but doing it more efficiently?

This type of analysis requires a sequential planning process. It may lead to a significant program focused on research and development, planning, and information generation in the early years, with aggressive abatement being postponed until we better understand what we are facing and have better means of coping with it. In this type of analysis, timing becomes a critical factor to be analyzed. It would be better to focus our attention on the short-run choices that we need to make. This approach would also avoid the paralysis that often develops when a long-run commitment to a policy such as aggressive abatement may be too expensive to get political support so that the do nothing alternative gets adopted, when in fact, there are many things we should be doing to position ourselves to deal with the possibility of future climate change. As part of the analysis of our short-run strategy, we must explicitly consider the option values of the components of such a strategy as the value of most of what we will do today, including the possibility of aggressive $CO_2$ abatement, is related to how it will position us for the long-run decisions we will have to make when we have more information.

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# The Rate of Time Preference: Implications for the Greenhouse Debate*

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## Abstract

If one adopts a real annual discount rate of 5% or more – and there are no significant climate impacts for half a century – these impacts have a present value that is virtually negligible. Within a benefit–cost framework, it then becomes exceedingly difficult to justify any near-term actions other than "no-regrets" policies.

In the greenhouse debate, it is important to draw a clear distinction between prescriptive and descriptive reasoning. A philosopher or an economist may counsel a low or a zero rate of time preference, but this advice does not provide a good description of the collective outcome of individual choices. In particular, it implies an unrealistically rapid increase in the rate of savings and investment.

## 1. Time Preference: Prescription vs. Description

Time preference has perplexed social philosophers from Aristotle to Mohammed, Thomas Aquinas, Karl Marx and Frank Ramsey. Harrod (1948) described pure time preference as "a polite expression for rapacity and the conquest of reason by passion". Cline (1992, pp. 72–74) has injected some of these ideas into the greenhouse debate through the following observations:

> It is evident ... that the costs of greenhouse abatement occur considerably earlier than the benefits of avoiding global warming damage. Eventually, however, these benefits can be far higher than the abatement costs. As

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> might be expected, the benefit–cost comparison thus turns crucially on the rate chosen for the time discount rate .... All consumption effects may be discounted at the "social rate of time preference" (SRTP). This rate, in turn, depends on the rate of growth of per capita income, and on the rate at which marginal utility of income tapers off for higher income levels ("elasticity of marginal utility").

If one adopts a real annual discount rate of 5% or more – and there are no significant climate impacts for half a century or more – these impacts have a present value that is virtually negligible. Within a benefit–cost framework, it would then be exceedingly difficult to justify any near-term actions other than "no-regrets" policies. In the greenhouse debate, it is important to draw a clear distinction between prescriptive and descriptive reasoning. A philosopher or an economist may counsel a low or a zero rate of time preference, but is this advice intended to *describe* the collective outcome of individual choices? Koopmans (1965, p. 226) takes a more pragmatic view. In advocating the usefulness of thought experiments with simple aggregate models of technology and growth, he notes:

> The underlying idea of this exploratory approach is that the problem of optimal growth is too complicated, or at least too unfamiliar, for one to feel comfortable in making an entirely a priori choice of an optimality criterion before one knows the implications of alternative choices. One may wish to choose between principles on the basis of the results of their application. In order to do so, one first needs to know what these results are. This is an economic question logically prior to the ethical or political choice of a criterion.

This paper provides a simple numerical example with an aggregate growth model. Two alternative rates of time preference are compared – over the short and long term. During the near term (say, the next 10–20 years), the time preference parameter can make a dramatic difference with respect to the optimal rate of aggregate investment, but it does not greatly affect the marginal productivity of capital. The rate of investment is crucial to a macroeconomic (i.e., top-down) view of the world. The marginal productivity of capital is crucial to a microeconomic (bottom-up) view of project and sectoral decisions. Both the top-down and bottom-up implications must be considered if we are to compare alternative allocations of today's scarce resources to competing needs in the present and in the future.

This paper does not deal explicitly with the *uncertainties* inherent in the global climate debate. When there is uncertainty, we need not commit once-for-all to a specific course of action. Instead, it is optimal to follow an "act, then learn" strategy, and to hedge against uncertainties. Today's decisions will be much more heavily influenced by the near-term rather than the distant-future rate of return on capital.

## 2. An Aggregate Growth Model

The following calculations are based upon an aggregate growth model that stems from the work of Ramsey (1928). Consider an economy in which there is a single agent acting as producer, consumer, investor, and saver. This is a closed economy in which we need not distinguish between domestic savings and investment. The labor force is constant, but is continually augmented by technological change at the annual rate $g$. This is sometimes described as a Harrod-neutral specification of technical change. Thus, the effective labor force is $L_0(1+g)^t$, where $L_0$ denotes the labor force at time 0.

Let $I_0$ and $K_0$, respectively, denote the rate of investment (net of depreciation) and the capital stock at time 0. These are the initial conditions. Thereafter, the rates of net investment, consumption and capital stock (respectively $I_t$, $C_t$, and $K_t$) are decision variables. Neglecting depreciation, and assuming a one-year lag between investment and capital stock, the capital formation process of this economy may be written:

$$K_{t+1} = K_t + I_t \tag{1}$$

Let the net national product be a constant returns function of the inputs of labor and capital, $f(K_t, L_t)$. Assume that this function is differentiable and strictly concave. Its partial derivative with respect to $K_t$ is termed the marginal productivity of capital. In a competitive economy, this represents the rate of return on capital at time $t$. For short, this is abbreviated $r_t$. The economy's net output is used both for consumption and net capital formation:

$$f(K_t, L_t) = C_t + I_t \tag{2}$$

For each individual period, there is a cardinal "utility" function, $U(C_t)$. Marginal utility is an isoelastic function of consumption. That is, $U' = C^{-v}$, where the elasticity parameter $v > 0$. The time-honored philosophical controversy centers around the appropriate value for $\rho$, the one period rate of time preference for utility. It is important to be able to analyze cases in which $\rho$ is close to zero. Alternative consumption and investment sequences are evaluated in terms of their impact on discounted cardinal "utility" over an infinite horizon. That is, they are chosen so as to maximize:

$$\sum_t (1+\rho)^{-t} U(C_t) \quad . \tag{3}$$

If there is an optimal steady-state growth path, the rate of return on capital converges to a time-independent value, $r$. It may then be shown that the rate of return, the rate of time preference, and the utility elasticity parameter are interrelated as follows:

$$g = (r - \rho)/v \quad . \tag{4}$$

For a calculus-of-variations proof of this proposition, see, e.g., Chakravarty (1969, p. 65).

If we are attempting to describe the *initial* state of the economy, the rate of return on capital and the rate of technological progress are objectively observable statistical parameters. The rate of time preference and the elasticity of marginal utility are inherently subjective, and there is no generally agreed-upon way to determine their values. This is the point at which we move into thought experiments with a numerical model. The following computations were performed with the GAMS/MINOS software described in Brooke *et al.* (1988).

## 3. Numerical Experiments: Logarithmic Utility Function

For our central example, we describe the case in which $v = 1$. That is, $U(C_t) = \log C_t$, and there is a unitary elasticity of substitution between consumption at different dates. In this specific instance, equation (4) implies that the steady-state optimal growth rate $g = r - \rho$.

Let the production function be Cobb–Douglas in form, with the exponent $\alpha$ denoting the optimal value share of capital in net output. If the initial level of the net national product is normalized as 1.00, the production function may be written:

$$f(K_t, L_t) = (K_t/K_0)^{\alpha}(1+g)^{(1-\alpha)t} \tag{5}$$

For concreteness, suppose that $\alpha = 15\%$, and $K_0 = 3.00$. With these assumptions, the initial marginal productivity of capital, $r_0 = \alpha/K_0 = 5\%$. Suppose also that the technological growth rate $g = 2\%$. In order for the economy to grow at this constant exponential rate, $I_0 = g\ K_0 = .06$. Since $K_0$ and $I_0$ are in steady-state proportions at time 0, it will be optimal for this economy to grow at a constant geometric rate if and only if $\rho = r_0 - g = 3\%$. This is the type of reasoning adopted by Manne and Richels (1992) in their Global 2100 model. They state explicitly that: "The utility discount rates are chosen for descriptive rather than normative purposes." In his dynamic integrated climate-economy model, Nordhaus (1992) makes a similar set of assumptions.

As an alternative perspective, consider Cline's arguments. Suppose that there is a discontinuous shift in policy at time 0, and that the decision-making agent adopts a lower rate of time preference, e.g., $\rho = 1\%$. It remains feasible for the economy to grow at a steady rate of 2%, but this is not an optimal policy. With $\rho = 1\%$, it is preferable to raise the rate of investment immediately so as to drive down the rate of return on capital from 5% toward its long-term steady-state value of only 3%.

Figure 1 shows the difference in the investment paths. Investment is shown as an index number, with 100 being its value at time 0. With $\rho = 3\%$, investment grows at a steady rate of 2% throughout a time horizon extending more than 50 years into the future. With $\rho$ dropping to 1%, the optimal policy entails a sharply discontinuous rise in investment for the first decade, a leveling-off for another decade, and finally a resumption of growth at a 2% rate but at a higher absolute level of investment. The lower value of $\rho$ implies a sharp change in the pattern of growth. As a normative policy prescription, the logic is consistent. The lower value of $\rho$ does *not*, however, provide a good description of the actual initial state of the system.

Now consider the implications for the time path of the marginal productivity of capital. This is best seen when we calculate the present value price of aggregate output. Output may be employed either for consumption or investment. It is convenient to normalize the price of output by taking 1.00 as its value at time 1. Along the steady-state path ($\rho = 3\%$), the present value price of aggregate output declines at a compound exponential rate of 5%. Relative prices remain constant, and there is no change in the marginal productivity of capital from its initial level, $r_0$ (see Figure 2).

With $\rho = 1\%$, there is a sharp step-up in investment. This leads to a gradual but not an immediate decline in the 5% initial marginal productivity of capital toward its new steady-state value of 3%. The two present value price series virtually coincide during the first decade, and they diverge only gradually thereafter. In either case, the net result is that a low value is placed upon aggregate output from year 50 onward. Figure 2 suggests that low rates of time preference do not in themselves provide a compelling argument to consider the impact of today's activities upon climate change one or two centuries in the future. It is optimal for today's decisions to be influenced

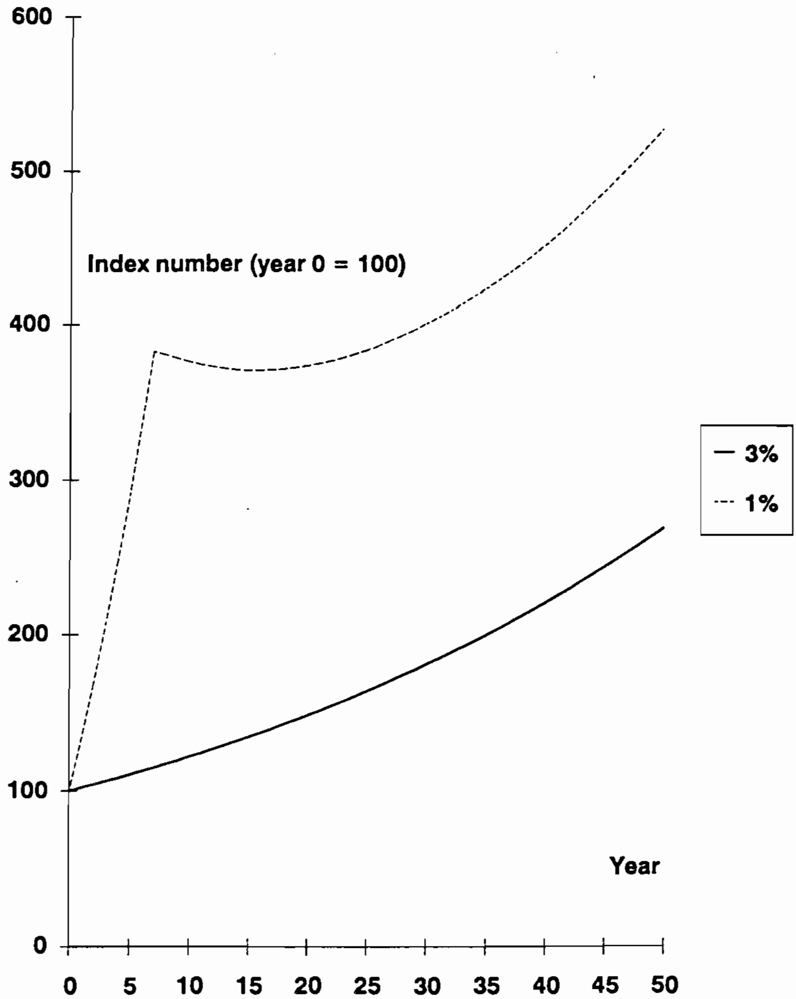


**Figure 1.** Net investment: alternative rates of time preference.

heavily by the opportunity cost of capital during the near term. Low rates of time preference do, however, require that we think clearly about the pros and cons of stepping up investment in both human and physical capital during the near future.

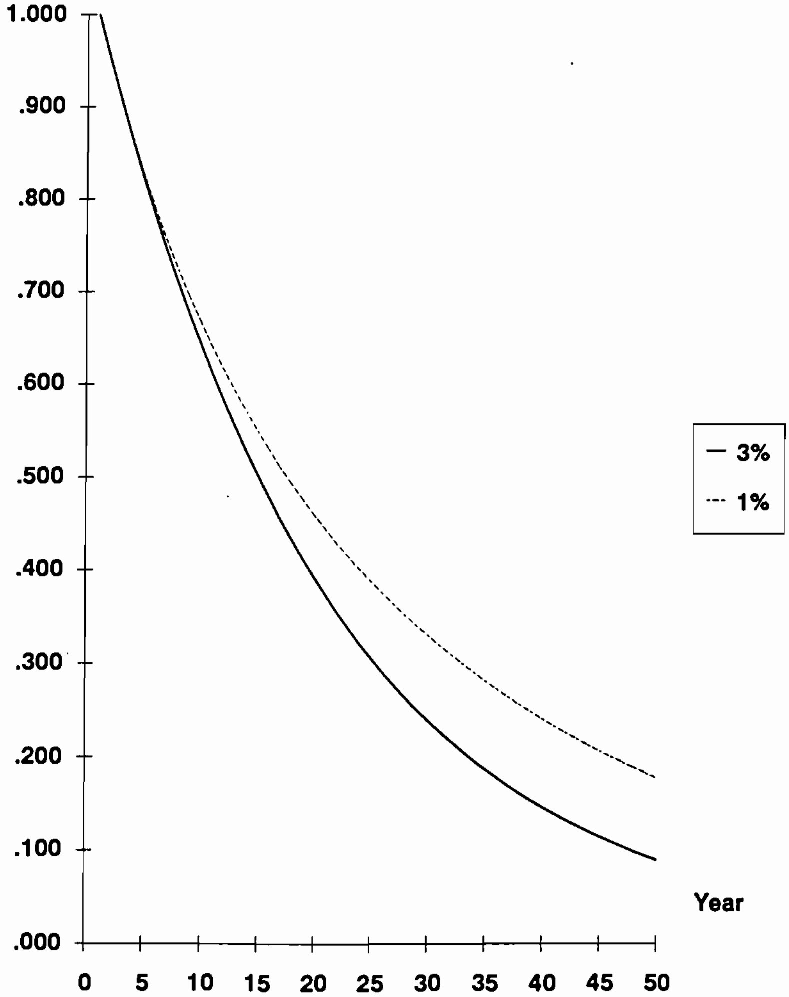


**Figure 2.** Present value price of aggregate output: alternative rates of time preference.

## 4. Implications of a Zero Value for $\rho$ and a Nonunitary Value for $v$

Now suppose that we wish to consider a world in which the pure rate of time preference is zero. There is a logical difficulty when $\rho = 0$, the elasticity parameter $v \leq 1$, and the time horizon is infinite. In this case, the value of the maximand (equation 3) is unbounded, and there is no meaningful optimal solution to the stated problem. To get around this difficulty, we specify that $v > 1$. This means that there is a less than unitary elasticity of substitution between consumption at different points of time, and there is a strong aversion to inequalities of consumption at different dates. The single-period utility function may now be written: $U(C_t) = (1 - v)^{-1}C_t^{1-v}$.

The optimal steady-state growth equation (4) remains unchanged. Suppose that the production function, technology growth rate, and initial conditions are identical to those considered previously, but that $\rho = 0$. In this case, equation (4) implies that: $2\% = (5\%\text{–}0\%)/v$. In order for steady-state growth to be optimal from time 0 onward, this means that $v = 2.5$. There is no way to distinguish between two steady-state growth economies. In one, $\rho = 3\%$ and $v = 1$. In the other, $\rho = 0\%$ and $v = 2.5$. The solution values are identical in these two cases. We cannot divorce the numerical choice of the time preference parameter from that of the elasticity of marginal utility. Because of equation (4), both are essential to defining a model that provides a reasonable description of the macroeconomic context within which any global climate policies must be considered.

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# Intergenerational Discounting

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## Abstract

A "discount rate" for the consumption of future generations from current investments for their benefit is typically composed of two parts: "time preference" and an allowance for the lower marginal utility of consumption due to higher average levels of consumption in the future. Time preference would be involved if one were postponing one's own consumption; it has little or nothing to do with income redistribution, which is what greenhouse abatement is about. A lower marginal utility of consumption is an anomaly in income redistribution: we rarely deliberately transfer consumption from the less to the more well-to-do. Time may serve as a kind of measure of distance; we may prefer beneficiaries who are closer in time, in geographical distance, in culture, surely in kinship. Maybe to keep our thinking straight we should use a term like "depreciation," rather than "discounting."

## 1. Introduction

Economists who deal with very long-term policy issues, like greenhouse gas emissions over the next century or two, are unanimous that future benefits – additions to future consumption – need to be discounted to be commensurable with the consumption earlier foregone to produce those benefits. And there is a near consensus that the appropriate discount rate should be conceptualized as consisting of two components (Cline, 1992; Manne, 1992; Nordhaus, 1992; Fankhauser, 1993).

One is pure time preference and "deals with the impatience of consumers and reflects their inborn preference of immediate over postponed consumption" (Fankhauser, 1993, p. 13). The second reflects the changing marginal utility of consumption with the passage of time, and is decomposed into a rate of growth of consumption per capita and an elasticity of utility with respect to consumption. The two components, pure preference for early over later utility and declining utility with growing per capita consumption, are used to compare not only utility increments in the year, say, 2050 with costs incurred in 1993, but to compare utility increments in the year 2150 with increments in the year 2050.

I first discuss "pure time preference" and then the relevance of the elasticity of utility with respect to income or consumption.

## 2. Pure Time Preference

Alan Manne introduces his discussion of time preference with a quotation from Roy Harrod characterizing time preference as "a polite expression for rapacity and the conquest of reason by passion." I quoted Fankhauser above about "impatience" and an inborn preference of immediate over postponed consumption. I am dubious about the ubiquity of that inborn impatience of consumers, at least for adults with decent levels of income, but my argument is that any kind of time preference pertinent to discounting the long-term costs and benefits of greenhouse gas abatement cannot have anything to do with the "pure rate of time preference" defined in this fashion.

That is because the alleged inborn preference for earlier rather than later consumption is exclusively concerned with the consumer's impatience with respect to his or her own consumption. Alan Manne introduces time preference by asking us to consider an economy in which there is "a single agent acting as producer, consumer, investor and saver." I suppose such an agent could have an inborn impatience about consumption. But greenhouse policy is not about saving for later consumption. It is about foregoing consumption in order that somebody else at a later time be able to enjoy more consumption than would otherwise be available.

Introspectively I can find no impatience about an increment of consumption that may accrue to people whom I shall never know and who do not now exist, in the year 2150, compared with an increment closer in time, accruing to the people whom I shall never know, and who do not now exist, who might enjoy it instead in the year 2100, or closer still to the people in the year 2050.

I can imagine reasons – some of them may even appeal to me – for preferring a boost to consumption in 2025 to the same boost of consumption in 2075, but it is hard to see that it has anything to do with impatience and the inborn preference of immediate over postponed consumption. In 2025 my oldest son will be the age I am today and his brothers a little younger; with a little luck they will be alive and healthy and my grandchildren will be the ages that my children are today and my great grandchildren (whom

I do not yet know) will have most of their lives ahead of them. Seventy five years later they will all be strangers to me. My genes may be as plentiful in the population at the later date but they will be spread thinner. I probably would prefer the benefits to accrue to my own grandchildren rather than to their grandchildren, but I must remind myself that my grandchildren's happiness may depend on their perceived prospects for their own grandchildren, and my "time preference" becomes attenuated.

The point of all this is that we may have grounds for preferring utility increments to occur earlier rather than later to the descendants of people now alive, but it cannot have anything to do with the kind of time preference that Roy Harrod or Samuel Fankhauser were talking about, or Alan Manne or William Nordhaus.

Actually, time may serve as a kind of measure of "distance." The people who are going to be living in 2150 I may consider "farther away" than the people who will be living in 2050. (They are also likely to be at least somewhat different in racial composition and geographic distribution.) I observe that in redistributing income via transfer payments, foreign aid, charity, etc., people are expected to differentiate, and do differentiate, among recipient peoples according to several kinds of distance or proximity. One is geographical: Americans are expected to be more interested in their own cities than in distant cities, their own country than distant countries. Another is political: east coast Americans are more interested in the people of Los Angeles than in the people of Quebec. Another is cultural: some people are closer in language, religion, and other kinds of heritage. Sheer familiarity seems to matter, and of course kinship does.

To be less interested in the welfare of East Africans than former Yugoslavians is less like "discounting" than, perhaps, "depreciating." When we count future welfare less than our own we are depreciating generations that are distant in time, in familiarity, in culture, in kinship, and along other dimensions. (Their is no reason to suppose that the depreciation would be exponential. Beyond certain distances there may be no further depreciation for time, culture, geography, race, or kinship.)

The crucial point is that these are not "saving" decisions we are talking about, i.e., not decisions about postponing our consumption, but decisions about redistributing income – our income. To invest resources now in reduced greenhouse emissions is to transfer consumption from ourselves – whoever "we" are who are making these sacrifices – for the benefit of people distant in the future. It is very much like making sacrifices now for people who are distant geographically or distant culturally. Deciding whether I care more about the people who will be alive in 2150 than the people who will be alive in 2050 is a little like deciding whether I care more about people in one continent than in another, or about English speaking people more than people who speak other languages, or about people who share my history and my culture more than people who don't. People do have preferences about whom to help; the preferences show up in charitable giving, in foreign aid, in immigration policy, in military intervention.

What we are talking about is very much like a foreign aid program, with some of the foreigners being our own descendants who live not on another continent but in another century.

William Cline half agrees with me. He, too, argues that impatience or "myopia" "may be a legitimate basis for a single individual's preferring consumption earlier rather than later in his lifetime" but is "hardly a justifiable basis for making intergenerational comparisons" (Cline, 1992, p. 249).

He disagrees in believing that we should not prefer – except on marginal utility grounds, which I am about to discuss – our own consumption to the consumption of future people. I expect that, whether or not we should, we all do. If we don't there is a most extraordinary anomaly: we greatly prefer our own consumption to that of distant, or even quite close, contemporaries but not to that of people distant in future time. It would be strange to forego a percent or two of GNP for fifty years for the benefit of Indians, Chinese, Indonesians and others who will be living fifty to a hundred years from now – and likely much better off than today's Indians, Chinese, and Indonesians – and not a tenth of that amount to increase the consumption of contemporary Indians, Chinese, and Indonesians. At its peak the Marshall Plan took about 1.5% of US GNP; it went to the foreigners "closest" to the Americans in most respects; and it was recognized as a short-run emergency. Americans do nothing like that now for anybody alive, except other living Americans. Whether that is good or bad, I do not see why we should expect them so much to prefer to help the unborn.

## 3. Elasticity of Utility of Consumption

It is time now to bring in that other component of the discount rate, namely, the rate of change over time of the marginal utility of consumption. The argument for including that component must rest on the assumption that in transferring income, or redistributing income, an important goal is to maximize the integral over time of the aggregate utility of consumption. The expectation is that on average the marginal utility of global consumption will decline over time as a result of rising consumption per capita. Resources invested now out of our own incomes will benefit people in the future who are expected to be better off than we are – an unaccustomed direction for redistributing income.

Both within countries and among countries we expect civilized governments to redistribute toward the poorer countries and toward the poorer elements of their own populations. Doing it that way probably, as Abba Lerner (1944) argued in *The Economics of Control* fifty years ago, increases total utility. But I doubt whether that is the only reason why people prefer to see income redistributed from rich to poor rather than the other way around.

The argument for transferring consumption from the poor to the rich, or from the decently well off to the much better off, would be that the resources transferred grow in the process, and grow so much that though the marginal utility of the recipient is lower than that of the donor, the magnitude that the gift achieves in transit more than compensates.

There is not much room for this idea in contemporary transfers. If a poor farmer has some poor soil and a richer farmer has rich soil somebody could argue that extracting seed from the poor farmer and giving it to the rich farmer will so enhance the resulting crop that the somewhat utility-satiated rich farmer will gain more utility than the poor farmer loses. But that argument is easily and quickly turned into an argument for trade: the poor farmer is better off selling the seed to the rich farmer, and their joint utility is even higher. The ethical interest arises only if trade is not possible, as when we outfit somebody who will emigrate to the new world, become rich, and never be heard from again, or as we contemplate transferring consumption forward in time to people who have no way to reciprocate.

Arthur Okun introduced the "leaky bucket" in his 1974 Godkin Lecture *Equality and Efficiency: The Big Tradeoff* (Okun, 1975). Transferring consumption from those who have plenty to those who do not have enough typically entails inefficiency – some administrative costs or some deadweight losses due to tax avoidance or transfer seeking. His analogy was carrying water from where it was plentiful to where it was scarce in a leaky bucket. The "big tradeoff" was deciding how leaky the bucket can be before we judge the effort not worthwhile. Clearly if the bucket arrives dry the effort was a mistake; if the bucket arrives three quarters full or one quarter full, or even a sixteenth, somebody in charge has to consider what discount ratio is acceptable.

Somebody might – not many people will – use some elasticity to calculate the marginal utility of water where it is scarce and where it is not and decide whether total utility goes up with the leaky-bucket transfer. Marginal utility is clearly pertinent, for those who understand it, but probably rarely decisive even for those who do understand it. Enough attention was paid to John Rawls' *Theory of Justice* (1971) by quite sophisticated people to somewhat dethrone utility maximization, at least to deny it exclusive status. And Rawls was mainly talking about transferring from rich to poor.

Okun never got around to talking about the other bucket, the "incubation bucket" in which the good things multiply in transit so that more arrives at the destination than was removed from the origin. The trade-off question here would be, what sacrifice of food where it is scarce would be worthwhile if, in being transported to where it was abundant, it grew handsomely. An alternative way to phrase the question would be, recognizing the advantage of moving resources from where they are less fruitful to where they are more fruitful, how much do we want to "discount" the greater fruitfulness when it accrues to people who already enjoy bountiful supply. And of course Okun, concerned with contemporary transfers, could not be interested because the market would take care of the efficiency problem, and nobody is interested in helping the rich at the expense of the poor.

The conclusion I reach is that it is legitimate and almost inevitable that most of us will want to discount the extra consumption provided for (or conserved for) our better-off descendants, because they are likely to be better off as well as because they are distant and it is our hard-earned consumption that somebody is proposing we transfer forward in time. I think I can see an argument that the discount should be at least as great as needed to compensate the reduced marginal utility of that future consumption. But if some people were not convinced that they should transfer their own consumption forward in time to future strangers simply because the well-to-do would benefit more than they would lose, I would not argue with them.

To sum up, I would emphasize that in "discounting" or "depreciating" additions to future consumption the analogy with saving or postponing – being impatient and requiring compensation through the interest rate – is inappropriate. We are not saving for the future; we are not postponing; we are making intergenerational transfers forward in time. We are not the ones who will consume the increments that we are attempting to bring about if we expensively reduce carbon emissions. We are trying to transfer consumption from ourselves to some other people. The analogy, or at least a better analogy, is transferring resources from North America and Western Europe to Africa or the Middle East, South or Southeast Asia, China, Russia, or poor peoples anywhere. It is an aid program, not a saving program. There may be some reason for some people to prefer consumption increments that occur in 2075 over consumption increments that occur in 2125, just as there may be people who prefer consumption increments to occur in West Africa rather than East Africa, or in Boston rather than Los Angeles. And I have no quarrel with people who, when they are prepared to contribute large amounts to charity, indulge their own preferences about who should constitute the beneficiaries.

If you tell me that you are utterly indifferent between a consumption increment that accrues to people (at the same level of per capita income) in 2050 or 2150, that you see no reason to "discount" the increment in 2150 back to 2050 for comparison, I can only respond that I don't see any reason why you should. And surely not on account of impatience.

What should matter is your expectation about the course of per capita consumption over the next century or two. If both the developed and the developing worlds continue to grow in per capita consumption as they have done for the past forty years the people in most countries are likely to be much better off in material welfare fifty, seventy-five, or hundred years from now than they are now. What we ought to feel we owe them is not the kind of ethical issue we have much practice with, because we aren't used to thinking about making our own sacrifices, or imposing sacrifices on our contemporaries, for the benefit of people who are substantially better off.

We must avoid a fallacy of composition here. If average per capita income rises in every country for the next hundred years, and if the poorer populations grow more rapidly than the wealthier populations, and if most of the economic sacrifices in the interest of carbon abatement are borne by the countries that can best afford it, the transfers will tend to be from the well-to-do people of Western Europe, North America, and Japan to the residents of what we now call the "developing" countries, who will be far better off a century from now than they are now, but may not yet be as well off, a century from now, as we are now in Western Europe, North America, and Japan.

The significance of that point to me is that in deciding how to value consumption increments over the coming century or two we need scenarios or trajectories of population and per capita consumption around the globe, together with estimates of climate vulnerabilities associated with those populations and those levels of per capita income. It is not a matter of interest rates or discount rates.

## 4. Summary

Where does this leave the subject of discounting? Is there any role for a discount rate or interest rate?

I think the answer is that the market rate of interest tells us something about the opportunity cost of $CO_2$ abatement. If we are prepared to transfer consumption forward to those later generations, we want to do it efficiently. We want what is sometimes called "target efficiency" – bestowing those consumption increments on the particular populations we intend to benefit – and we want to bring about those consumption increments in the most cost-effective way. The market rate of interest tells us something – maybe not a lot, but something – about what future returns we might expect on a large-scale public investment program that we might undertake for the benefit of future populations. If we can add more consumption for the people we are trying to help by directly investing in income growth than by abating carbon dioxide emissions, the former should be preferred.

Carbon dioxide abatement is probably "target efficient." Poorer countries are probably more vulnerable to climate change than wealthier countries. Direct investments in public health, birth control, training and education, research, physical infrastructure, water resources, etc., can also be directed to target populations, so the advantage may go either way. If we knew how to calculate the additional growth attributable to public investment in developing countries, we could compare that to the expected consumption growth due to slowing climate change, and take our choice. If we don't know how to do that, then some market rate of interest may be a good proxy. (The market rate of interest in developed countries may not be the best proxy.)

I doubt whether developing countries would prefer to defer consumption increments to later generations, whether what is deferred comes out of their own resources or out of resources made available by wealthier countries. I would expect, if offered a choice of immediate development assistance or equivalent investments in carbon abatement, potential aid recipients would elect the immediate. So if we, the developed, elect carbon abatement for their benefit, it is our choice of their descendants over themselves.

Whichever we choose, there is probably no reliable way to constrain our own descendants' choice to continue what we began. We can invest in the consumption of future generations via carbon abatement or via public investments; in 2050 they can discontinue the direct investment in rising consumption, or they can discontinue the costs of carbon abatement. There may be institutional reasons for expecting discontinuance to be more likely with one program or the other, but the case has to be made, not taken for granted.

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# Discounting in Integrated Assessments of Climate Change

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## Abstract

One of the key decisions that economists working on integrated studies of climate change face is the selection of the method of accounting for damages resulting from possible climate change across a long temporal scale and the method for the intertemporal comparison of the costs associated with possible greenhouse gas abatement strategies. Sensitivity tests show that the method applied and the resulting discount rate has a major impact on the optimal climate strategy.

The paper is intended to provide a short review of the various techniques that have been proposed and applied in various integrated models of climate change. The underlying problem is the following dilemma. One can attempt to be consistent with the economic theory and empirical observations, but in this case the derived discount rate will be on the order of 5 to 8%. As a result, even possibly significant damages from climate change turn out to be negligible when considered at their present value. The artificially low discount rate based on ethical reasoning, on the other hand, makes our climate-related decisions and resource allocations inconsistent with the majority of other public policy decisions.

## 1. Introduction

*Varietas delectat.* So held the ancient Romans, although a reviewer of the increasing number of integrated climate–economy models analyzing global climate change might be tempted to add that "too much variety is confusing". The reason for the confusion is that integrated assessments vary in many respects, ranging from the ways in which the underlying socioeconomic development scenarios and energy–economy relationships are formulated on the cost side; to the selection, parameterization, and the method of integration of atmospheric models of greenhouse gas (GHG) accumulation and climate change into the overall framework; down to the approaches to assessing the potential impacts and adaptation strategies in order to quantify economic benefits. The room for "product differentiation" in integrated models of climate change is much bigger than, for example, in the long-established field of energy modeling. Modelers make full use of this opportunity and have produced an extremely diverse set of models to describe climate-economy interactions. This variety also characterizes the techniques and rates of discounting that are adopted in integrated assessments, although there seems to be general agreement that the costs and benefits that will accrue at different points in time need to be comparable .

A series of efforts, like the International Energy Workshop (IEW) organized by IIASA and Stanford University (see Manne *et al.*, 1992) or the Energy Modeling Forum (EMF) (see, for example, Energy Modeling Forum, 1993) have demonstrated the merits as well as the pitfalls and difficulties of comparing energy-economy models and their results. A thorough comparative evaluation of climate-economy models will probably be an order of magnitude more difficult. Therefore, a simple comparison of the discount rates and the results of the various models provides an overview of a small part of the problem only. Yet, in view of the important role of discount rates in intertemporal economic analyses, and the associated intense debate on the discounting issue in the climate economics literature (see Lind, this volume), it might be useful to take a first step toward clarifying how the choice of discount rates can influence the policy alternatives that emerge from the integrated models. I hope that some lessons can be learned from this initial attempt, and that they might be useful for those who plan to carry out more systematic model comparisons under the EMF, IEW, or the like.

The paper sets out by presenting a concise summary of recent arguments and techniques for discounting in cost-benefit analyses of public projects with an emphasis on those involving long time horizons (Section 2). Discounting techniques and rates applied in selected integrative assessments of the costs and benefits of global climate change are presented and compared in Section 3. Finally, the issue of the sensitivity of model results with respect to the effective discount rate is discussed and some conclusions are drawn in Section 4.

## 2. Discounting Techniques

When we attempt to identify the underlying techniques and conceptual backgrounds of the specific discount rates used in different climate-economy models, we find two basic approaches and a number of variations. The first approach is rooted in the ideal world of optimal growth models with no distortions, while the other approach attempts to alleviate the conceptual and technical difficulties resulting from the presence of distortionary taxes in the economy.

A convenient starting point to explain how the effective discount rate is derived for the various models is a simple optimal growth model as formulated by Ramsey (1928) and explained in some detail by Manne (this volume) and Nordhaus (1994a). Our discussion here is based on Solow (1970). The optimality criterion for the growth path is to maximize the social value of the future consumption stream by discounting all future utility back to the present using a social rate of time preference and computing the sum of these discounted utilities over an infinite time horizon. For the continuous case (Solow, 1970, p. 82), the problem is to maximize:

$$W = \int_0^\infty e^{-(a-n)t} U(c) dt \tag{1}$$

where $W$ is the social value of the consumption stream, $a$ is the rate of social time preference, $n$ is the rate of population growth, and $c$ is per capita consumption. Solow identifies the necessary condition for optimality as:

$$\frac{d/dt(U')}{U'} = -\{r^*(t) - a\} \tag{2}$$

where $r^*(t)$ is the marginal productivity of capital at time $t$ along the optimal path and, given the assumption of competitive markets, it is equal to the instantaneous real interest rate. Thus, the optimality criterion states that the social marginal utility of per capita consumption is declining at the rate given by the difference between the marginal productivity of capital and the social rate of time preference. By differentiating Equation (2), Solow derives:

$$\frac{U''(c^*)dc^*/dt}{U'(c^*)} = \frac{c^*U''(c^*)}{U'(c^*)} \ \frac{1}{c^*} \ \frac{dc^*}{dt} = -j\frac{\dot{(c^*)}}{c^*} = -(r^* - a) \tag{3}$$

where $j$ is minus the elasticity of the social marginal utility of per capita consumption. Under steady-state conditions, Solow then takes $f$ as the rate of labor-augmenting technical progress, that is, the steady-state rate of growth of output and consumption per capita. Thus along the optimal steady state path, it must hold that:

$$r^* = a + jf \tag{4}$$

To summarize: in the optimal growth framework, the real interest rate is equal to the discount rate on goods and services, and is derived from three factors: time discounting (a) (this is $\rho$ in both Alan Manne's discussion (this volume) and in the DICE documentation (Nordhaus, 1994a), the elasticity of the marginal utility of consumption ($j$ here, $v$ in Alan Manne's paper and $\alpha$ in the Nordhaus analysis), and the growth in consumption ($f$) ($g$ in both the Manne and Nordhaus papers).

In this model of an ideal world, the social rate of time preference (observed from the consumption rate of interest) and the opportunity cost of private capital (observed from the marginal rate of return on private investment) are equal and they are both equal to the market rate of interest. Once the assumptions about ideal conditions are abandoned, however, the social rate of time preference and the marginal rate of return on private investments diverge due to market imperfections, notably corporate profit tax and personal income tax.

Searching for the appropriate discount rate in a world with distortionary taxes, Lind (1982) developed what was the dominant discounting technique for cost-benefit analyses throughout the 1980s. Lind first established an analytical framework to separate the issues of time preference and the opportunity cost of public investments. He argued that the social rate of discount should be equal to the social rate of time preference as determined by the consumption rate of interest. The basis for its numerical estimation are the returns on market instruments that are available to investors. The effects on private capital formation should be accounted for by using a conversion technique and the concept of the "shadow price" of capital. This latter represents "the present value of the future stream of consumption benefits associated with \$1 of private investment discounted at the social rate of time preference" (Lind, 1982, p. 39). This way, effects on capital formation are converted to their consumption equivalents through the use of the shadow price of capital. Finally, a single rate of discount, the consumer's rate of interest, is applied to the benefit and cost streams.

A practical difficulty of the "shadow price of capital" approach is that to compute it one needs to know the marginal rate of return on private capital, the marginal rate of taxation on capital income, rates of depreciation and reinvestment, the consumer's rate of interest, and the marginal propensity to save. Nordhaus (1994b) concluded that while the Lind approach is extremely useful and elegant in consolidating capital-market distortions, it is impossible to apply. The practical obstacle arises from the need to account for all flows in and out of consumption and investment, which requires a much deeper understanding of their governing forces than is currently the case.

It is obvious that the Ramsey-based discounting is a special case of the consumption-equivalent technique. In the absence of distortions, all shadow prices are equal to one, so there is no need to convert expenditures into consumption equivalents before a uniform discount rate can be applied.

In his amendment of the consumption-equivalent technique, Lind (1990) revisited the government's discount rate policy for public projects in light of new observations on international capital mobility, the effects of financing government deficit on crowding out private investments, and in behavioral economics on the individual's rate of time preference. His most important conclusion relevant to the problem of climate change (and long-term policies in general) is that international resource allocations should be based either on a utility function over time or on some other decision rule incorporating intergenerational equity. Lacking these, however, the government's long-term borrowing rate should be used in evaluating the effects of projects involving long-run intergenerational resource allocations.

The global warming problem added a new impetus to the discounting debate. Broome (1992), for example, devoted almost half of his book on the costs of global warming to the problem of discounting. His starting point was that the real problem is discounting future well-being and that discounting of commodities is just a practical short-cut to discounting well-being. If and when it works, appropriate discount rates for commodities can be derived from the markets: the consumer interest rate or the producer interest rate might offer good starting points. However, Broome presents a long list of arguments why the short-cuts are inadequate in the context of global warming. The consumer interest rate is not appropriate because future generations are not present in the market, therefore the consumer rate of interest does not include the effects of their preferences and thus the value of future commodities. The producer rate of interest is not appropriate either because the production of commodities involves GHG emissions and other environmental damages and these negative externalities are not included in the producer interest rate, which therefore does not represent the true opportunity cost of commodities. Given all these difficulties involved in the short-cuts, one needs to address the problem of discounting future well-being directly. Broome's solution to the problem is the use of a zero discount rate.

**Table 1.** Discount rates and implications.

| Model | Eff.disc.rate/ marg.prod.cap. | $a$ | $j$ | $f$ | Shadow val. along opt.path/ marg.soc.cost em. (\$/tC) |
|---|---|---|---|---|---|
| Integrated benefit–cost analyses | | | | | |
| DICE | 6 | 3 | 1 | 3 | 5.3 → 10.0 |
| | 6 | 1 | 2 | 3 | 10.1 |
| | 6 | 0.1 | 2.5 | 3 | 10.3 |
| CETA | 5 | 3 | 1 | 2 | 11 → 20 |
| PAGE | 5 | | | | 20 (5–40) |
| Stochastic | '1.5–6' | 0.5 '0–3' | 1 | 2 | 20 → 27 (mean) |
| Greenhouse Damage | 5 | 3 | 1 | 2 | 5.5 |
| Model | 2 | 0 | 1 | 2 | 48.8 |
| Cline | 1.5 | 0 | 1.5 | 1 | q=0.74–4.18 |
| | 3 | 0 | | | q=0.44–1.71 |
| | 5 | 0 | | | q=0.33–1.12 |
| Cost-effective analysis | | | | | |
| G2100 | 5 | 3 | 1 | 2 | {0–208} |

# 3. Discount Rates

A set of integrated assessments that have been developed to analyze cost-benefit relationships of various climate policies – ranging from inaction to drastic GHG abatement measures – is presented in Table 1. Here we are primarily interested in the relationships between the effective discount rate and the shadow value of carbon emissions along the optimal path.

## 3.1. DICE

The pioneering work in the field of climate economics has been that of Nordhaus (see, for example, Nordhaus and Yohe, 1983). His most recent efforts include DICE, the Dynamic Integrated model of Climate and the Economy (Nordhaus, 1992, 1994a). This is probably the best starting point because it is well known, marvelously documented, transparent, and easily accessible. Moreover, it has often been used as a benchmark or reference point in other studies.

Given the extremely long time lags between GHG emissions and their economic impacts, the concept and models of optimal growth offer a convenient framework for analysis. Nordhaus took the model version formulated by Frank Ramsey in 1928 and extended it to include both the impacts of anthropogenic climate change and the allocation of resources to reduce the emissions that induce it. The optimization criterion in DICE is to maximize the discounted sum of the utility of per capita consumption, that is, the value of a traditional social welfare function. Paths of optimal growth affected by climate change or a mitigation policy are diverted from the unconstrained optimal path as a result of losses in output due to global warming and the diversion of resources to reduce emissions. Output is computed from a standard, constant-return-to-scale Cobb-Douglas production function. Together with the output of goods and services, GHG emissions are also generated according to a slowly declining emissions/output ratio.

A small set of equations traces the fate of GHG emissions in the atmosphere. First, their accumulation and transportation are determined. Total radiative forcing and climate dynamics are calculated using a simple, three-layer reduced-form coupled atmosphere-ocean model. The resulting globally and seasonally averaged temperature change drives a quadratic damage function to feed back climate impacts to the production function.

In the DICE model, utility discounting is included in the objective function. Future utility flows are discounted at the pure rate of social time preference ($a$ in Table 1) of 3%. Combined with the elasticity parameter ($j$ in Table 1) of 1 that follows from the logarithmic utility function and a growth rate ($f$) of 3%, the effective discount rate in DICE is 6%. This, together with all the other "best-guess" values for the various model parameters, provides a carbon tax equivalent on GHGs along the optimal path starting at US$(1990) 5.3 per ton of carbon.

An important point in the DICE analysis and, in fact, in all optimal growth models is that if societies were to decide to be less impatient and to reduce the pure rate of social time preference ($a$) to a low level like 0.1 and the economy was still growing, then the implications for the shadow value of carbon emissions would not necessarily show dramatic increases. For the period 1995–2025, the US$ 5.3–10 per ton C values for the central case solution would change to marginally higher values.

## 3.2. CETA

A cost–benefit model developed by Peck and Teisberg (1992) has been used in various studies to explore the relationship between the value of information about impacts and damages and the optimal time path for emission controls (Peck and Teisberg, 1994). The authors investigate the sensitivity of optimal carbon control strategies to parameters of their Carbon Emission Trajectory Assessment (CETA) model (see Peck and Teisberg, 1992). The model has five modules. Emissions projections and cost calculations are based on the Global 2100 model (see Manne and Richels, 1992). Impact and damage assessments are treated similarly to DICE (see above).

CETA is then used in a simple decision tree framework to estimate the value of information about global warming uncertainties. The results of Peck and Teisberg suggest that if an optimal control policy is used under uncertainty, the eventual resolution of uncertainty has a high value relative to current research budgets, and resolving uncertainty about the costs of warming is nearly as important as resolving uncertainty about the extent of warming. In addition, the CETA calculations show that the benefits associated with the immediate resolution of uncertainty would not be much higher than if it were resolved within the next two decades. This implies that some time is available to plan and execute a carefully designed research program. In contrast, the CETA results suggest that if the real world political process were to result in a suboptimal control policy being chosen under uncertainty, and this poor choice could have been prevented by the early resolution of uncertainty, then the benefit of early resolution would have been significantly higher.

The CETA model uses an effective discount rate of 5%. Calculated shadow values range from US$(1990) 11 to 20 per ton of carbon. These higher shadow value figures, compared to those in DICE, however, are only partially due to the slightly lower initial discount rate (5% compared to 6% in DICE). Rather, they are due to the larger size of damage calculated in CETA. In DICE, damage is directly proportional to income, whereas in CETA damage is proportional to the size of the labor force (expressed in efficiency units). It is also worth noting that the case presented here is only one of many cases investigated by Peck and Teisberg. Their analysis is famous for providing insights into the sensitivity of the shadow value of carbon emissions with respect to different assumptions on the level and exponent of the damage function.

## 3.3. PAGE

Another example of a fully integrated climate-economy model is PAGE, the model for Policy Analysis of the Greenhouse Effect (Hope *et al.*, 1993). It is a probabilistic model that includes a simple representation of all important elements of climate change, from emission policies and control costs to impact mitigation strategies and damages. To demonstrate the effects of individual perceptions of the global warming problem, the model uses multiattribute utility functions. The PAGE model covers the globe and divides it into four major regions: the European Community (EC); the rest of the OECD, Eastern Europe and the former Soviet Union; and the rest of the world. The model's time horizon covers the period 1990–2100. In addition to $CO_2$, other major GHGs are also included, notably $CH_4$, CFCs, and HCFCs.

An individual model run starts with specifying a preventive (GHG abatement) and an adaptive (impact mitigation) strategy by the user. Emission control policies (or the lack of them) affect global temperature change and generate prevention costs. Adaptive policies (if applied) comprise the second part of the total estimated costs. Non-monetizable environmental and social impacts are included in the model as a multiplier of the total economic impacts in a computation to show how high they would need to be in order to justify adoption of the prespecified policies. The PAGE model uses a uniform discount rate of 5%. The shadow values of GHG emissions calculated under various parameter constellations range from US$ 5 to 40 per ton of $CO_2$ equivalent.

### 3.4. Fankhauser

The objective of the Stochastic Greenhouse Damage Model (Fankhauser, 1993a) is to provide an order of magnitude assessment of the social costs (the shadow value) of GHG emissions. This is implemented in the context of a stochastic model where uncertain factors are defined as random variables. This is the opposite of what optimization models do where marginal costs are determined by the intersect with the damage function. In this model, the marginal costs are calculated at the emissions level actually observed. Their best-guess figures are taken together with a distribution of future emissions that is unknown. Therefore, as Fankhauser notes, the numbers presented in the shadow value column of Table 1 for the Stochastic Greenhouse Damage Model give little indication of the socially optimal carbon tax. These results are more relevant for individual abatement projects if the world were to follow the optimal path.

In terms of discounting, Fankhauser follows Lind's consumption-equivalent technique: all investment effects are converted to consumption equivalents using a shadow price of capital and then the social rate of time preference is used for discounting. The relatively low discount rates by Fankhauser's stochastic base case do not lead to overwhelmingly high shadow values where the means range from US$ 20 to 27 per ton C.

It is interesting to observe that when Fankhauser uses an effective discount rate (5%) closer to Nordhaus's value (6%), his calculated shadow values (US$ 5.5 per ton C) get very close to the initial optimum path value from DICE (US$ 5.3 per ton C). Yet, we must bear in mind that the ways these numbers have been derived as well as their interpretations are quite different.

## 3.5. Cline

One of the first attempts to bring together a diverse set of benefit and cost assessments into a consistent cost-benefit framework was made by Cline (1992). The large differences in the amount and quality of data sources to estimate the two terms of the cost-benefit ratio reflect the imbalances in the number of studies and reliability of results of the then available global warming studies: a small number of impact and damage assessments conducted mainly in Europe and North America to estimate benefits, versus a diverse set of global energy-economy models to calculate costs.

Cline identified 16 damage categories. He surveyed several studies conducted in the potential impact areas largely independently of each other to make his own damage estimates for each category. Most studies, however, were conducted in the United States or in other developed market economies where climate sensitivity is lower and capacities for adaptation are higher than in less developed countries. Extrapolation is difficult, but is the only plausible solution to generate global estimates.

Another problem is that of the temporal dynamics. Trying to extract the maximum amount of information from the then available material, Cline made estimates for two comparative static scenarios: the usual $2\times CO_2$ equivalent equilibrium warming (assumed to be 2.5°C) and what he called "very-long-term warming" (taken to be 10°C associated with an $8\times CO_2$ equivalent level of GHG concentrations and to be reached by the year 2275).

Due to the large number of source studies and the large diversity of assumptions behind them, it is a major task to make them compatible and to derive damage estimates that fit together. Despite the slight tendency to overestimate the impacts of climate change in many of the source assessment studies, Cline's aggregate estimates were very close to those turned up by other studies (Nordhaus, 1991; Fankhauser, 1993b).

On the cost side, the availability of consistent and well-documented modeling results provides a more promising starting point. Nevertheless, global energy models differ significantly in their basic socioeconomic and technological assumptions, energy sector detail, time horizons, and regional and temporal resolution. This makes the selection of a single study as a representative of some kind of consensus clearly impossible. Cline conducted an in-depth survey of six state-of-the-art global energy-economy models and developed a synthesis based on their results.

Damage assessments and cost estimates are then synthesized in a cost-benefit model that incorporates other aspects of climate policy, such as the costs of reduced deforestation and increased afforestation. The final results are presented as 36 combinations of the four key parameters: the social rate of time preference, the climate sensitivity factor, the exponent of the damage function, and the base value of the damage function.

Cline also uses Lind's consumption-equivalent technique as a starting point for his discussion of the appropriate rate and technique of discounting. There are, however, two important distinctive features. First, Cline argues on ethical grounds for an $a = 0$ (zero rate of pure time preference) as an appropriate value to use for intergenerational problems. Second, he contends that growth discounting (which is associated with the declining marginal utility as income rises) is the social rate of time preference in his benefit/cost framework and it is already and directly included in the utility function.

Cline's conclusion from his cost-benefit analysis is that the "benefits of an aggressive program of abatement warrant the costs of reducing the GHG emissions if policy-makers are risk averse, or if one is pessimistic and concentrates on high-damage cases" (Cline, 1992, p. 311). In particular, a combination of low discount rate and high damage is necessary to justify undertaking significant abatement action.

### 3.6. Global 2100

The final example, the Global 2100 model, is not an integrated model but is included in Table 1 to provide a comparison between integrated assessments and an earlier cost effectiveness study. (In fact, it has also become part of an integrated model by now; see the paper by Manne *et al.* (this volume) on MERGE.) The Global 2100 model itself has been through many changes and modifications over the past few years. Here, we refer to the version as presented by Manne and Richels (1992). The model disaggregates the world into five geopolitical regions: the United States, the rest of the OECD, the former Soviet Union, China, and the rest of the world. For each region, relationships between the energy sector and the rest of the economy are modeled by combining two models: ETA (an energy technology process model) and MACRO (an aggregated production function quantifying the substitution relationships between capital, labor, and energy inputs). Regional models can be linked in various ways, most typically through the international crude oil market and, for the purposes of analyzing various carbon emission abatement strategies, through an international market of carbon emission permits.

In the Global 2100 model, the macroeconomic assumptions follow the optimal growth tradition as far as discounting is concerned. They provide an effective discount rate of 5%. The carbon tax depends on the policy and the scenario specified. For the 20% carbon emissions reduction scenario, for example, the carbon tax starts at zero and rises to US$ 208 which is basically the equilibrium value for the long-run backstop technology.

## 4. Discussion and Summary

The figures collected in Table 1 indicate that the selection of the technique of discounting makes a difference in the outcome of integrated assessments, and that the discount rate is a sensitive parameter in these models. However, the sensitivity is also determined by the overall model formulation. Moreover, the discount rate is not the only uncertain or disputed parameter in integrated assessments that has an important influence on the model results.

As we have seen in the DICE model, becoming less impatient (reducing a to almost zero) in an optimal growth framework does not necessarily lead to higher shadow values and more ambitious carbon abatement, because respective changes in the exponent of the utility function compensate the effect of a lower a and lead to the same effective discount rate. In contrast, increasing or reducing the discount rate in Fankhauser's Stochastic Greenhouse Damage Model could make a major difference in the appraisal of small-scale abatement projects.

In DICE, the pure rate of social time preference is ranked sixth on the list of overall indices of uncertainties. This implies that the outcome of the DICE model is moderately sensitive to the value of the pure rates of time preference. Looking at the policy parameters, however, Nordhaus finds that the control rate of GHGs are significantly affected by the economic variables, including the social rate of time preference.

Only three of the integrated studies included in this survey published information about the sensitivity of their results with respect to changes in the discount rate. This sample is not truly representative since the majority of integrated assessments do not include sensitivity tests for the discount rate, or do not hold it sufficiently important to report them in the literature. A systematic comparative study of integrated assessments following the organizational principles of the Energy Modeling Forum might be in a better position to solicit explicit sensitivity tests from each participating model based on a generally agreed protocol. These efforts will then provide a much better foundation for understanding the relative importance of discounting in integrated climate-economy models.

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# Technological Change and Trajectories

# Technical Progress and Climatic Change

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## Abstract

The global warming debate has neglected and thus underestimated the importance of technical change in considering reduction in greenhouse gases and adaptation to climate change. Relevant quantitative cases of long-run technical change during the past 100 years are presented in computing, communications, transport, energy, and agriculture. A noteworthy technological trajectory is that of decarbonization, or decreasing carbon intensity of primary energy. If we are not at the end of the history of technology, the cost structure for mitigation and adaptation changes and could be cheap.

## 1. Introduction

One hundred years ago icebergs were a major climatic threat impeding travel between North America and Europe. 1,513 lives ended when the British liner Titanic collided with one on 14 April 1912. 50 years later jets overflew liners. Anticipating the solution to the iceberg danger required understanding not only the rates and paths on which icebergs travel but the ways humans travel, too.

My premise is that nearly everyone in the global warming debate, from atmospheric scientists and agronomists to energy engineers and politicians, largely neglects to consider, and thus underestimates, the importance of technical change in considering reduction in greenhouse gases and adaptation to climate change.

Of course, not all technical change is good with respect to climate or any other facet of our world. Technology can destroy as well as better us. Advances in technology such as the internal combustion engine have generated the outpouring of greenhouse gases in the first place. When Alfred J. Lotka made his landmark projection of anthropogenic climatic change in 1924, he figured 500 years to double atmospheric carbon (Lotka, 1924).

*I am grateful to Perrin Meyer for assistance.

He did not foresee the explosion of energy demand and the gadgets that collectively would make the mushroom possible.

Technical change, the blind spot in Lotka's otherwise remarkably perceptive work, is precisely my focus. To think reliably for the long-term, we must question carefully what stays the same and what can change.

For purposes of this paper, let us assume that most innovation is humane and responsible. A companion exercise which emphasizes demonic aspects of technology and technological failures in the face of climate change would certainly also be worthwhile.

Not all human societies need have asked our question about technical progress in the face of climatic change. For some societies, time stands still or cycles with little development. Of course, the function of innovation has existed in all civilizations. Medieval European guilds, for example, transmitted knowledge about their crafts along dozens of generations, combining it with many inventions. Many inventions originated in China, of which gunpowder and the spinning wheel are among the most famous.

But something new happened in Western civilization about 300 years ago. One might call it organized social learning. Successful societies are learning systems, as Cesare Marchetti observed (1980). In fact, the greatest contribution of the West during the last few centuries has been the zeal with which it has systematized the learning process. The main mechanisms include the invention and fostering of modern science, institutions for the retention and transmission of knowledge (such as universities), and the aggressive diffusion of research and development throughout the economic system.

Attempts have been made to quantify the takeoff of modern science and technology. Early in the 20th century, the German chemist Ludwig Darmstaedter carefully listed important scientific and technological discoveries and inventions back to 1400 AD (Darmstaedter, 1908). The list is certainly not complete, but it may be representative. The message is firm: some kind of take-off, albeit bumpy, did occur about 1700, and by 1900 the level of activity was an order of magnitude higher (Figure 1).

Fear that humanity was running out of inventions partly motivated Darmstaedter's history. Scientists and engineers themselves have often stated that the pool of ideas is near exhaustion. In 1899 Charles H. Duell, US Commissioner of Patents, urged President William McKinley to abolish the Patent Office, stating "Everything that can be invented has been invented" (Cerf and Navasky, 1984, p. 203). After the telephone and electric light what could follow? Darmstaedter's lists peaked about 1880.

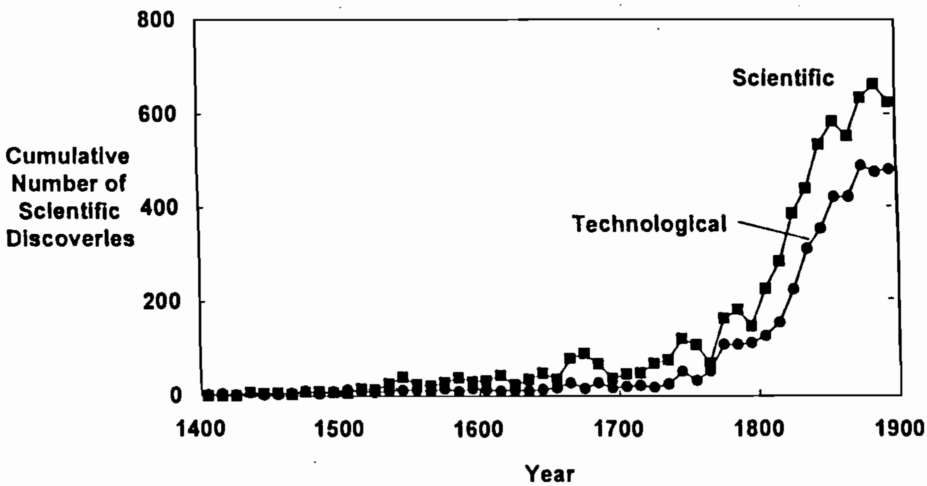


**Figure 1.** Decadal number of scientific and technological discoveries, 1400–1900. Source of data: Darmstaedter, 1908.

In fact, we do know that invention and innovation are not distributed evenly but come in spurts (Mensch, 1979). But they have come with ever increasing intensity. The slow periods for diffusion of innovations flatten the world economy and drain confidence from many of us. Perhaps the 1990s are an economic trough. In any case, understanding the accumulated surges of technical progress during the 20th century can help us glimpse 2050 and 2100, when the heat may be on.

## 2. Evidence of Technical Progress

Let us begin with examples from computing, communications, and transport.

Modern computing began in the late 1940s with the ENIAC machine, operating on vacuum tubes. One of the first customers for the most advanced machines was always the US military, in particular, the national laboratories such as Los Alamos, which designed nuclear weapons. The top computer speed at Los Alamos, shown in Figure 2, increased one billion times in 43 years.

We know that mechanical and electromechanical calculating machines had a history of improvement before John von Neumann and others began to tinker in the 1940s. And we know that the current Cray machines are

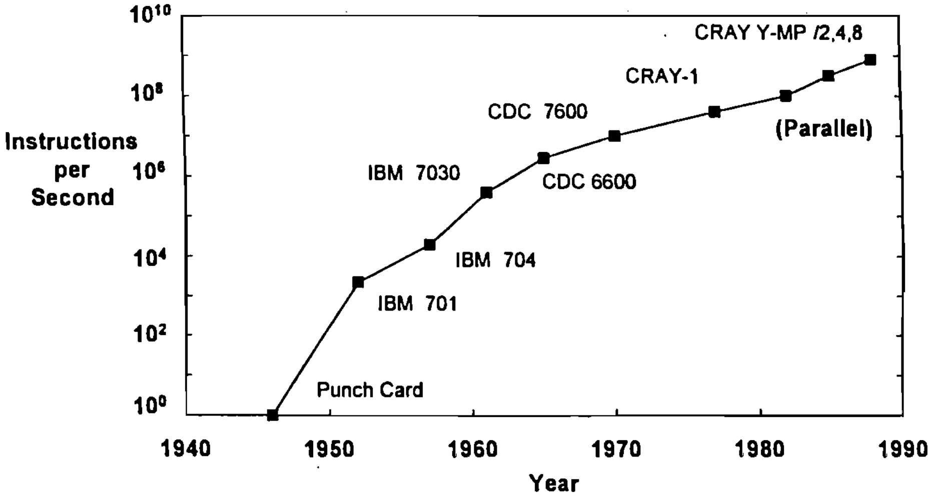


**Figure 2.** Computer speed, Los Alamos National Laboratory. Source of data: Worlton, 1988.

not the *ne plus ultra*. Parallel machines already promise a further pulse of speed. Quantum computing looms beyond (Lloyd, 1993).

When Darmstaedter wanted to telephone, he was no doubt excited by the speed and distance his message could travel but probably frustrated by the capacity of the available lines. Long-distance calls had to be booked in advance. In the days of the telegraph it was one line, one message. In one hundred years, as Figure 3 shows, engineers have upped relative channel capacity by one hundred million times. In fact, fiber optics appear to initiate a new trajectory, above the line that described best performance from 1890 to 1980.

Without computers, modern numerical climate models would not be tractable. Without telecommunications, global conferences would be difficult to organize. Without airplanes, Americans would rarely attend meetings in Europe. In 1893, it probably would have required three weeks to travel from a laboratory in Stanford, California, to a conference hall in Laxenburg, Austria, assuming no detours from icebergs. Airplanes first shrank our continents and then made it possible to hop from one to another.

Propulsion for aircraft, shown in Figure 4, has improved by one hundred thousand times in 90 years. In fact, we can see clearly that the aeronauts have exploited two trajectories, one for pistons, ending about 1940, and one for jets, culminating in the present.

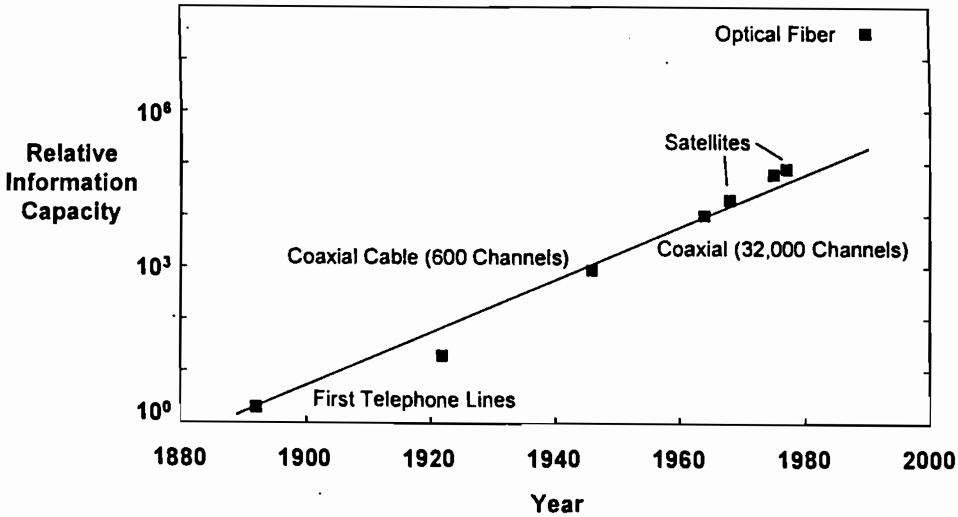


**Figure 3.** Communication channel capacity. Source: Patel, 1987.

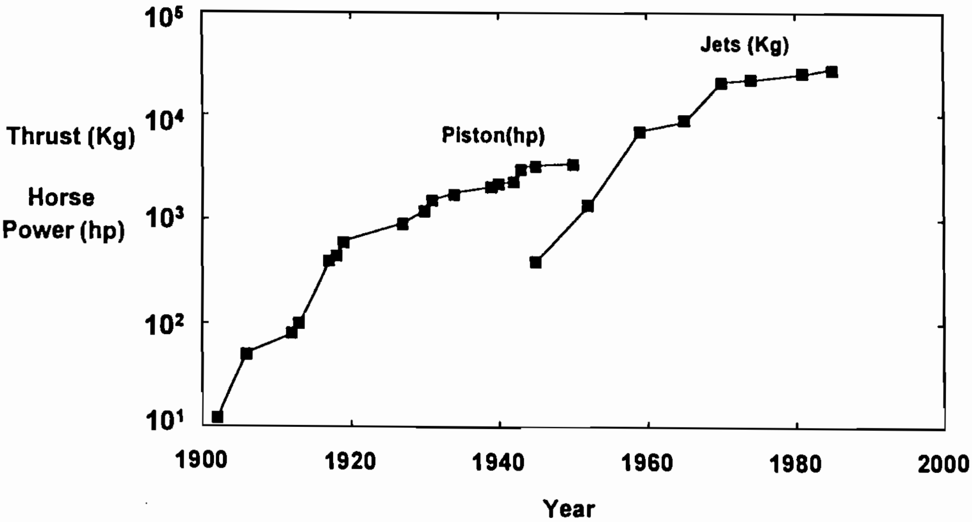


**Figure 4.** Performance of aircraft engines. After Grübler, 1990. Sources of data: Angelucci and Matricardi, 1977; Grey, 1969; Taylor, 1984.

The aircraft engines exemplify that continuing improvement of any technology eventually becomes limited by some physical principle. A new technology then overtakes the old by becoming more cost effective and permitting a broader range of operating characteristics such as speed or bandwidth. The present wave of jet development may have broken. But, linear motors are just starting. These may power the magnetically levitated trains (terra-planes) of the 21st century at 2000–3000 km/hour.

These examples from information, communications, and transport bear importantly on the economy and society as a whole. Yet, one can argue that they matter only indirectly for emissions of greenhouse gases and for adaptation to climatic change. In fact, this view is wrong. Simply recall that weather forecasts, a pre-eminent form of adaptation, are the product of satellites, computers, radio, and video (and earlier, telegraphs and telephones). Assessing prospects for climate change requires broad consideration of technical progress. Nevertheless, let us look at agriculture and energy, where the links between climate and technology are most obvious.

It is common to believe that the revolution in agricultural productivity preceded the revolution in industrial productivity. In the United States, this was not the case. Thomas Jefferson's Virginia fields yielded roughly the same number of bushels of wheat in 1800 as the average American field yielded until about 1940. Americans harvested more by bringing in more land.

Productivity per hectare took off in the United States in the 1940s, just like jet engines and computers, as is evident from Figure 5. US wheat yields have tripled since 1940, and corn yields have quintupled. Other crops show similar trajectories. Yields in agriculture synthesize a cluster of innovations, including tractors, seeds, chemicals, and irrigation, joined through timely information flows and better organized markets.

Fears are chronic that societies have exhausted their agricultural potential. The Latin church father Tertullian wrote circa 200 AD "The most convincing examinations of the phenomenon of overpopulation hold that we humans have by this time become a weight on the Earth, that the fruits of nature are hardly sufficient for our needs, and that a general scarcity of provisions exists which carries with it dissatisfaction and protests, given that the Earth is no more able to guarantee the sustenance of all. We thus ought not to be astonished that plagues and famines, wars and earthquakes come to be considered as remedies, with the task, held necessary, of reordering and limiting the excess population."

Two millennia later the agricultural frontier is still spacious, even without invoking genetic engineering of plants. Figure 6, which contrasts annual corn yields for the best growers in Iowa, the average Iowa grower, and the world average, says the world grows only about 20 percent of the top Iowa farmer. Interestingly, the production ratio of the performers has not changed

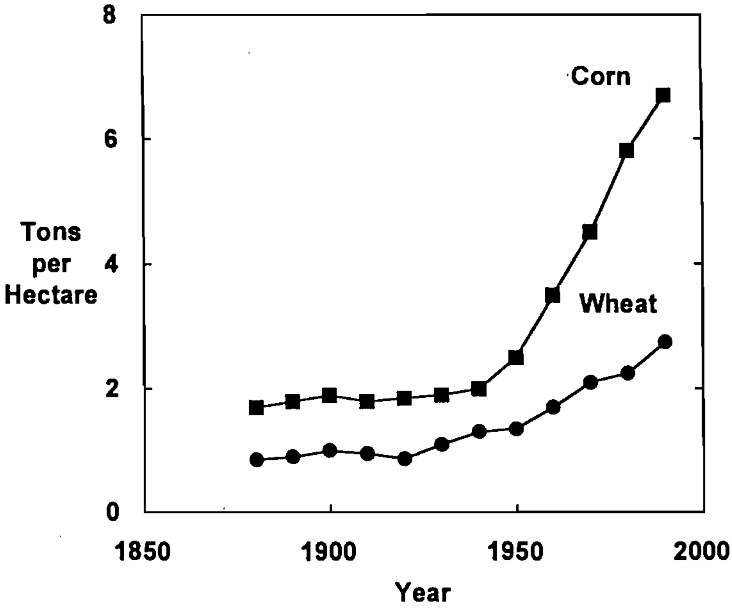


**Figure 5.** Yields of wheat and corn per hectare in the United States, 1880–1990. After Waggoner, 1994.

much since 1960. Even in Iowa, the average performer lags more than 30 years behind the state-of-the-art. While technology may progress, rates of diffusion appear to remain stable. And conservative.

Though societies are cautious in adopting new practices, recall that the doubling of the pre-industrial level of $CO_2$ often cited as hazardous is probably 75 or more years in the future. If we had performed a study prior to 1940 of the impacts of $CO_2$ doubling and climate change on US wheat and corn, the most easily defended assumption would have been constant yields per hectare as a baseline. Neglecting technical progress, the assumption would have brought misleading results. Modern science can now penetrate to every field, cell, and sector of society. It must be taken into account in assessing costs and benefits of strategies for mitigation and adaptation.

One of the technical quests that began about 1700 was to build efficient steam engines. As shown in Figure 7, engineers have taken about 300 years to increase the efficiency of the generators to about 50 percent. Alternately, we are about mid-way in a 600-year struggle for perfectly efficient generating machines. What is clear is that the struggle for energy efficiency is not something new to the 1980s, just the widespread recognition of it.

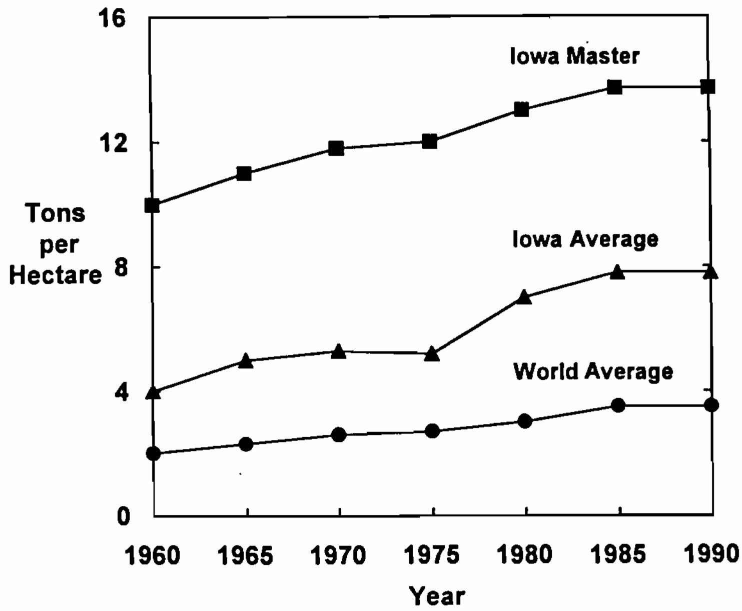


**Figure 6.** Corn yields, Iowa and world, 1960–1991. "Iowa Master" refers to the winner of the annual Iowa Master Corn Growers Contest. Source: Waggoner, 1994.

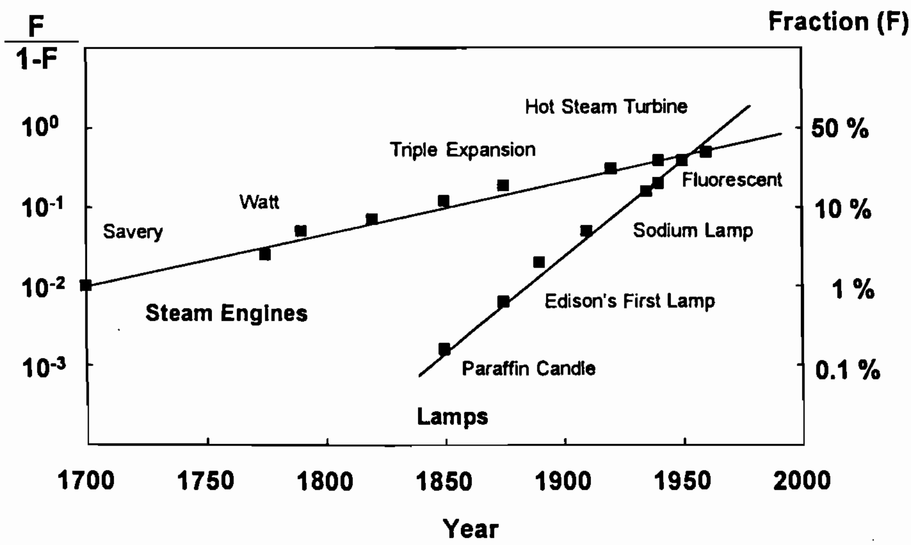


**Figure 7.** Efficiency of energy technologies. Sources: Starr and Rudman, 1973; Marchetti, 1979.

Figure 7 also explains why we have been changing many light bulbs recently. We have been zooming up a one-hundred year trajectory to increase the efficiency of lamps. The struggle with the generators is measured in centuries. The lamps glow better each decade. The current pulse will surely not exhaust our ideas for illumination. The next century could well reveal new ways to see in the dark, just as quantum computing, linear motors, and bioengineering will reshape our calculations, travel, and food.

The "cost" of reducing greenhouse gas emissions cannot be properly estimated without understanding the directions in which technical change will drive the energy sector anyway, with regard to preferred primary fuels as well as efficiency. What appear as costs in our current cost-benefit calculus for mitigating, and adapting to, the greenhouse effect may largely be adjustments that will necessarily occur in any case.

This possibility is illustrated by the final technological trajectory discussed here, that of *decarbonization*, or the decreasing carbon intensity of primary energy, measured in tons of carbon created per kilowatt year of electricity (or its equivalent) (Figure 8). As is evident, the global energy system has been steadily economizing on carbon. Without gloomy climate forecasts or dirty taxes.

In a peculiar choice of words, the Intergovernmental Panel on Climate Change in 1990 designated as "Business-as-Usual" its scenario which stifled and even reversed the 130-year trend. "Business-as-Usual" was a scenario of technical regression. It essentially ignored the scientific and technical achievement of the past 300 years, including the achievements that make identification and estimation of the greenhouse effect possible. Mr. Duell would have been quite at home with the 1990 IPCC.

For contrast, consider the "methane economy" scenario which essentially squeezes carbon out of the energy system by 2100 (Ausubel *et al.*, 1988). It is perfectly consistent with the technical history and evolution of the energy system. In its 1992 scenarios the IPCC reluctantly began to reflect that society is a learning system and that we are learning to leave carbon.

## 3. Conclusions

The essential fact is that technological trajectories exist. Technical progress in many fields is quantifiable. Moreover, rates of growth or change tend to be self-consistent over long periods of time. These periods of time are often of the same duration as the time horizon of climatic change potentially induced by additions of greenhouse gases. Thus, we may be able to predict

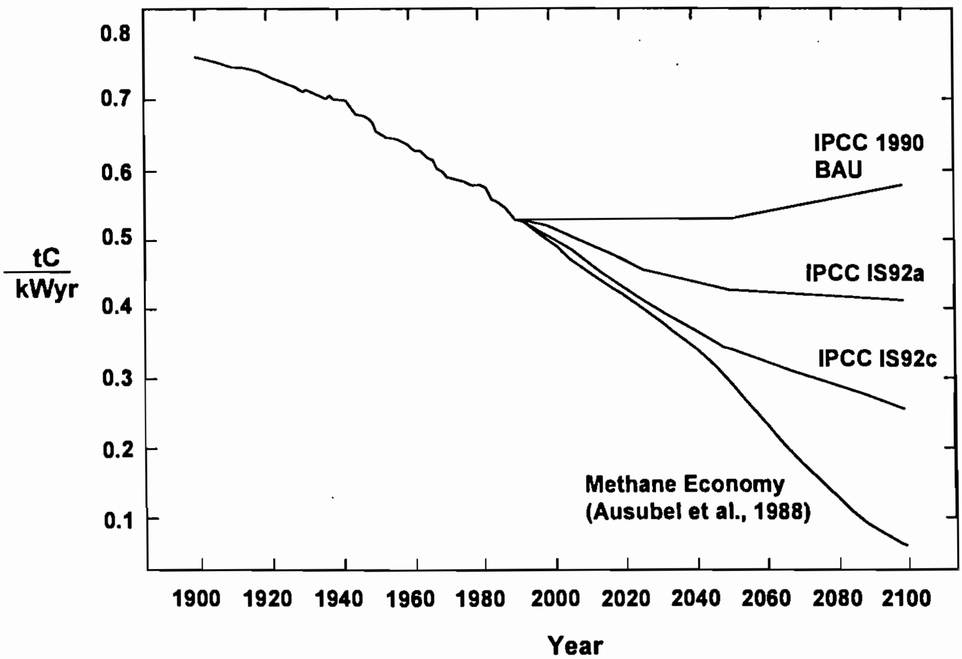


**Figure 8.** Carbon intensity of primary energy, 1860–1990, with projections to 2100. The projection stopping the historic trend of decarbonization is the IPCC 1990 "Business-as-Usual" (BAU) scenario; IPCC a and c are high and low energy scenarios from the 1992 Supplement. Sources: Intergovernmental Panel on Climate Change (IPCC), 1990, 1992; Ausubel *et al.*, 1988.

quite usefully certain technical features of the world of 2050 or 2070 or even 2100.

The hard part may be believing that in a few generations our major socio-technical systems will perform a thousand or a million or a billion times better than today.

If we accept that we are not at the end of the history of technology, surely our cost structure for mitigation and adaptation changes. In some cases it may be possible to summarize improving performance in a simple coefficient, such as that used for "autonomous energy efficiency improvement" (Nordhaus, 1992). The need is to have a long and complete enough historic record from which to establish the trend. Most prognosticators live life on the tangent, projecting on the basis of the last 15 minutes of system behavior. Our methods must advance to encompass long time frames.

A complicating factor is that technologies form clusters to reinforce one another and create whole new capabilities. Imagining how the clusters will affect lifestyles and restructure the economy, and thus affect emissions and vulnerability to climate, is a tremendous intellectual challenge. Lotka saw cars and compressors, but he probably could not envision vast air-conditioned cities and suburbs growing in Arizona, Texas, and Florida.

We also do not understand well the malleability of the time constants or rates of technical change. The technical clock ticks. The West did something a few centuries ago to set the whole machine in motion. Over the last 100 years the United States and other countries have gone much further in establishing systems for research and development. The global research and development enterprise is now about $200 billion annually. Will higher investments speed up the clock? Or, are they required just to maintain current rates of progress, with each increment coming at greater cost? The question is open.

Some object to the trajectories of technology because they limit freedom. In fact, they point out promising channels for society to explore. Discovery and innovation can be costly games. Scientists and engineers should be grateful for signs pointing in the right directions and make mitigation and adaptation for climate change cheap.

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# Optimizing Climate Change Abatement Responses: On Inertia and Induced Technology Development

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## Abstract

This paper reviews evidence that technical change in the energy sector has historically responded to external pressures (rather than being an autonomous process) and presents a preliminary analysis of how optimal responses to climate change may alter if abatement efforts induce technology development. This is linked with the inertia that characterizes energy system dynamics.

An optimizing model is developed which takes these dimensions explicitly into account in a highly simplified manner. The model optimizes the emissions trajectory given abatement costs which are related explicitly to both the degree and the rate of abatement. Altering the coefficients associated with each of these two dimensions reflects different perspectives on the inertia of change, relative to the ultimate technical and behavioral flexibility of society. Low inertia and high absolute costs (no induced technology development) reproduces the kind of results found in other optimizing cost–benefit studies. But if the major costs are those associated with the rate of abatement rather than the absolute degree – i.e., high transitional costs but an optimistic perspective on the ultimate potential of technology and/or behavioral patterns to adapt to such constraints – the optimal strategy and long-run prospects are radically altered. In this case, abatement rises within a few years above the level incurred in the "conventional" case, and long-run stabilization of atmospheric concentrations may be approached after some decades, at moderate costs, as an optimal response even for moderate values for the climate damage function.

The analysis thus highlights the importance of considering these dimensions of systemic inertia and induced technical and behavioral adaptation that have been neglected in previous quantitative studies of optimal abatement responses.

# 1. Introduction

How much effort should we make to control climate change? How do the benefits of early moves to limit emissions compare against the costs? Is there any prospect of stabilizing global emissions – or beyond that even atmospheric concentrations, which the Climate Convention states as the ultimate goal - without incurring very high costs? How do actions taken today fit in the context of a problem which involves cumulative and irreversible changes over centuries?

Cost/benefit studies of the climate problem seek to address these questions explicitly, by attaching monetary values to benefits and costs and comparing them in terms of present values. Great uncertainty surrounds the values adopted, but this paper is not concerned directly with these uncertainties. Rather, it seeks to illustrate in a simplified way the potential impact upon abatement costs and optimal strategies of two factors which have not been explicitly included in cost–benefit studies to date.

These issues are, respectively, inertia in the systems which generate greenhouse gases, and the role of technological and behavioral adaptation to abatement efforts – "responsive" (or induced or endogenous) "technology" (or systemic) development. It is shown that these factors can be captured in a simplified cost–benefit framework, and that doing so can substantially alter conclusions concerning optimal abatement trajectories and costs. Comparing optimal emission trajectories under differing assumptions about inertia and technology development points to the importance of starting to reflect these factors in models, and of seeking to understand better how to characterize these factors. Other possible research applications of the models developed are also outlined.

# 2. A Brief Review of Cost/Benefit Modeling Studies

The first published attempt at a cost-benefit modeling analysis of the climate problem was that by Nordhaus (1991). This sought to treat the problem in a classical static cost–benefit framework, adapted for the climate problem by developing a series of equations to link emissions with global temperature change. Together with assumptions about the cost imposed by a given temperature change, and the cost associated with a given emission reduction, this yielded an estimate of the emission reductions which would be optimal in a "steady-state" of constant emissions and concentrations.

In later work, Nordhaus (1992) developed an alternative, numerical model ("DICE") for optimizations in which emissions and concentrations could change over time. Both studies, using Nordhaus' cost assumptions, suggested that only modest abatement efforts were justified. Kolstad (1992) developed a stochastic version of DICE to explore the impact of uncertainty upon the optimal emissions path. Peck and Teisberg (1992) coupled an energy model (a simplified version of the Global 2100 model) to an atmospheric model to examine the trade-off between abatement costs and reduced climatic impacts.

Schlesinger and Jiang (1991) adopted a different approach, focusing upon the changes implied by delaying emission responses by ten years. They concluded that the impact of such a delay would be small, so that delaying policies to await greater scientific certainty would be rational. In subsequent interchanges, they drew upon Nordhaus' analyses to defend their conclusions (Schlesinger, 1992).

Many of the criticisms made of these analytic studies focus on arguments that they greatly underestimate the damage or risks associated with changing the atmosphere's radiative properties (e.g., Cline, 1992; Ayres and Walters, 1991; Grubb, 1993). Some dispute that the cost–benefit framework can be used at all because the climatic uncertainties are too profound and the inertia too great. For example, Swart and Hootsmans (1991) argue that there may be major instabilities in the global system and that by the time we can see evidence of this it will be too late to stop, leading to proposed "safety limits" on atmospheric change.

This paper is not directly concerned with such issues. Rather, it adopts the cost–benefit framework, along with the inevitable caveats about valuing climatic damage, and focuses upon issues concerning the abatement side of the process which are not reflected in the above studies.

The optimizing cost–benefit analyses cited above have assumed that abatement costs are a direct function of the degree of abatement only, and that they are unrelated to the *rate* of abatement. This is unrealistic. Clearly, abatements costs do depend upon the rate at which emissions depart from the baseline trend – more rapid changes incur higher costs, for several independent reasons noted below. In short, the systems which emit greenhouse gases are characterized by great *inertia.* This may be expected to affect strategy particularly under conditions of high uncertainty and learning, features which certainly characterize the climate problem.

A second important issue is that technology may be expected to develop. Indeed, a technologically optimistic outlook, such as that argued in the immense study of renewable energy technologies and applications edited by Johansson *et al.* (1993), is that emissions could be reduced below current levels in the long term with *no* long-term additional costs; it is argued that technologies already visible on paper could develop to the point at which they can deliver sufficient useful energy at similar overall costs to fossil fuels. While some authors suggest that technologies for extensive low-cost abatement are abundant now, for supply substitution in particular most authors invoke the argument that costs will fall greatly if and as alternative technologies are developed and deployed on a large scale. Recently, some economists have begun to emphasize the importance of considering such technology issues, notably Anderson and Bird (1992), and Hourcade (1993).

The key issue concerning technical change in this context is whether or not it is responsive or *induced*, i.e., whether it responds to trends and pressures. This contrasts with *autonomous* technological change, which is projected to occur irrespective of other developments. The distinction is critically important. If technical change is induced, efforts to limit emissions help to stimulate technical and other developments, including economies of scale and learning, which in turn help to lower the costs of further abatement efforts. If technical change is autonomous, the costs associated with abatement are constant irrespective of policy, the history of abatement efforts, and the size of markets for lower carbon technologies.

In modeling terms, these may be termed respectively *endogenous* (i.e., embodied within the model as a function of other factors) and *exogenous* (i.e., defined external to the model) technical change. Any model can be designed and run to encompass exogenous technical change, by lowering assumptions about the future costs of lower carbon technologies, and/or by using higher values for "autonomous" efficiency improvements. But no model yet applied to the cost–benefit problem, of which the author is aware, embodies technical development as a response to the abatement or other circumstances, although Anderson and Bird (1992) come close in linking the unit costs of carbon-free technologies to the scale of deployment.

The issues of inertia and induced technical change are distinct, but related. Technology studies such as those collected in Grübler (1991), have emphasized the way in which technologies tend to generate "clusters" of interlocking systems. Hourcade (1993) points out the implication that gradual change, developing a new and self-reinforcing trajectory of interrelated technical change, may be relatively cheap and self-sustaining, with little cost difference from an alternate "business-as-usual" trajectory which leads ultimately to a wholly different pattern of emissions and technologies. Rapid change, however, may require large-scale adoption of technologies not well suited to current systems, incurring high transitional costs which decline only as the relevant supporting systems develop.

## 3. Inertia and Induced Technology Development in Energy Systems: The Evidence

The evidence for inertia in energy systems scarcely needs elaboration. Whatever the benefits, change is rarely costless, and the faster the change the greater the costs tend to be. At the most simple level, this reflects past investment in capital stock which may be rendered worthless; the OECD among others have pointed to the importance of including this effect with "putty semi-putty" or other capital stock modeling (Hoeller *et al.*, 1993). Rapid structural changes also generate macro-economic disequilibria costs, as capital cannot be automatically switched from one sector or kind of investment to another. In social terms, sensitivity to the rate of change may be still higher, e.g., if it forces job losses much faster than feasible under natural turnover or even voluntary redundancy schemes. Rapid action may thus be much more expensive than action at a similar absolute level, phased over a longer period.

Technology development is an altogether more complex issue. The process of innovation is not understood – given the high level of failure, it has been characterized as "the triumph of action over analysis" (Ausubel, 1991). Various technology diffusion studies emphasize the complexity of factors which determine whether or not technological ideas are developed and adopted, and it is clear that this does depend heavily upon external conditions (Freeman, 1986). The author's own study of "Emerging Energy Technologies" which seem likely to have significant market impact over the next decade or two also concluded that "most of technologies considered reflect primarily a process of 'demand pull' rather than 'supply push' " (Grubb and Walker, 1992, Chapter 14).

Three specific examples, at successively greater levels of aggregation, illustrate the extent to which developments in technologies and energy systems are not autonomous, but reflect market and other external pressures.

First, when oil companies started operating in the deeper waters of the North Sea, it was on the basis of projections of oil prices rising to levels of \$50/bbl or more. In the early 1980s, it was estimated that the cost of oil from new deep water platforms would be around \$25/bbl. Yet as the oil price declined, companies responded with strenuous attempts to cut costs, leading to radical innovations in platform design and project management. Today, deep-water fields are still being developed by companies that believe that oil prices may not rise above \$20/bbl for many years, probably with production costs on the order of \$10/bbl. Such developments required extensive efforts and commitment of investment in new techniques; it would not have occurred to anything like the same degree without the need to survive in response to declining oil prices.

A second example concerns the uptake of energy efficiency investments. In 1980, the UK Department of Energy carried out an assessment of the potential for energy efficiency improvements in UK industry. They concluded that industrial energy intensities could be reduced by 20% over the following 20 years with cost-effective investments. In 1990, a new assessment concluded that the potential identified had in fact all already been exploited; but that, despite the lower energy prices, a further 20% of cost- effective efficiency improvements could be identified. The greater interest and investment in energy efficient techniques – in the UK and elsewhere – had apparently helped to generate greater development of more efficient techniques. Indeed, it seems a curious feature of energy efficiency studies that they seem regularly to identify cost-effective potentials for improvement of around 20-30% of current demand, almost irrespective of the potential already exploited. There is a continual process of developing new options. It is hard to judge how much of this is driven by energy price changes and greater investment in energy efficient techniques, but the persistence of such results suggests that investing in greater energy efficiency helps itself to stimulate and identify previously overlooked options.

A third example concerns the macroeconomic response to the energy price shock and subsequent decline in energy prices. In real terms, energy prices in some sectors and countries are lower than they were before the 1973 oil shock. Traditional econometric models based on price elasticities suggest that response to the price rise, marking a sharp decline in the trend of energy consumption especially outside the heavy industrial sector, should be mirrored by an equivalent rise after the price fall (after allowing for autonomous trends). In fact, although energy demand has started to rise again in most countries and sectors, the change has been nothing like as great as would be expected if there were indeed a "symmetric" response. Energy economists have in the last five years begun to discuss the need for "asymmetric" elasticities to model the observed the behavior, with the decline in consumption in response to price rises being much greater than the equivalent rise in response to price falls.[1] The argument is advanced that the price rises resulted in technology development, infrastructural investments, and behavioral changes which were not "unlearned" when the prices fell.

But this is the very meaning of endogenous technology development.[2] This example also helps to illustrate that the term "technology" development is really shorthand for a much broader phenomena; it is about the overall development of technology, infrastructure, and habits of human behavior and social systems as affected by perceptions of the cost and availability of different resources.

At all three levels therefore there is overwhelming evidence that 'technology' development in the energy sector is not purely autonomous, but responds to external pressures.[3] The data of the past 20 years is itself leading energy economists increasingly to recognize a central role to the phenomena of endogenous development. The pity is that, with the partial exception of the studies by Anderson and Bird (1992) and Hourcade (1993), none of this insight is yet embodied in models of how we should respond to climate change.

This paper does not seek to develop a means of "endogenizing" technical change in a fully consistent way; that would constitute a major disciplinary research effort. Rather, it seeks merely to show that it is possible to formulate a cost–benefit analysis which can mimic the possible impact of both inertia and endogenous technical change, and explores some of the possible implications of these phenomena for optimal abatement strategies.

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[1] For example, Dargay (1993, note 2) cites no less than nine studies which address the issue of irreversibility or asymmetry in energy demand – in addition to his own empirical studies which encompass France, Germany, and the UK.

[2] Dargay (1993) clarifies his study of asymmetric responses as "challenging two of the common assumptions made ... that a return to low energy prices ... would eventually restore demand to what it would have been had prices never risen ... not only does this not seem to be happening, but it also appears highly unrealistic. It is obvious that high energy prices induced the development and application of considerably more energy-efficient technologies in all sectors of the economy, many of which will remain economically optimal despite falling prices."

[3] Note that this is not the same issue as that of "embodied" technical change discussed for example in Berndt *et al.* (1993), which refers to the persistence of technological change as embodied in the unmalleable capital stock.

# 4. Basic Structure of the Model

The first stage is based directly upon the problem as framed by Nordhaus (1991). The analysis concentrates upon $CO_2$ emissions (although it can be applied to other gases), as the major long-term contributor to radiative change and the central source of concern about the impact and timing of any constraints. Equations link emissions with concentration changes in the atmosphere and hence ultimately to climate impacts. The simplest forms used in Nordhaus (1991) are adopted; more sophisticated models of the linkages can be brought to bear, but such refinement is not important in this context. The relevant equations are as follows.

*The physical system.* The atmospheric concentration of greenhouse gases at time t, M(t), is given by:

$$M'(t) = E(t) - sM(t) \tag{1}$$

where $M(t)$ is the concentration (mass) of the greenhouse gas in the atmosphere; $M'(t)$ is the rate of change in atmospheric concentration; $E(t)$ is the greenhouse gas emission rate at time $t$; $s$ is a "sink rate" removal constant.

This equation assumes that carbon is removed from the atmosphere at a rate in direct proportion to the atmospheric concentration. This is an adequate approximation for the present purposes; for longer-term changes in particular, it may be optimistic in that it does not recognize any saturation of the natural sinks. Given the simplification in the atmospheric model noted above (i.e., carbon removal proportionate to concentration), the equation yields a direct expression for the concentration remaining at date $t$:

$$M(t) = e^{-st}\left(M_0 + \int_0^t E(\tau)e^{s\tau}d\tau\right) \tag{2}$$

The parameter $s$ may be evaluated from past data. Given a conservative estimate that only a third of anthropogenic $CO_2$ emissions accumulated in the atmosphere during the mid-1980s, for $CO_2$ $s$ is approximately 3.7%/yr.[4]

*Objective.* The overall objective may be considered as maximizing the global utility $V$, discounted over time at a rate $\rho$:

$$Maximize\ V = \int_0^\infty U\{C(t)\}e^{-\rho t}dt \tag{3}$$

[4] $s = 2M'/M = 2*1.5/(350\text{-}270) = 0.037$ (carbon accumulation taken for convenience in ppm).

where time $t$ is set such that $t = 0$ represents the present, and $C(t)$ is the global consumption at time $t$; $U\{\}$ is the total utility associated with consumption $C(t)$; $\rho$ is the social rate of time preference.

In pursuing his analysis, Nordhaus (1991) described a physical "steady state" analysis, in which a baseline consumption increases exponentially at rate $h$. This is then reduced by the cost incurred by a steady-state reduction in emissions, and the damage arising from the constant temperature increase above natural levels. By assuming this steady state, Nordhaus was able to derive the optimal degree of abatement for the assumed cost functions.

The analysis here differs in several important respects. First, the analysis does not assume a physical steady state. To avoid this very limiting constraint, Nordhaus (1992) subsequently moved to a discrete mathematical programming model with non-linear optimization. Here, it is shown that an analytic solution to the dynamic problem, in which emissions and concentrations are made an explicit function of time, is possible given certain simplifying assumptions.

*Emissions control.* Emissions at time $t, E(t)$, are taken to deviate from a reference path $E_r(t)$ in which there are no abatement efforts, according to a control parameter $\varepsilon(t)$:

$$E(t) = E_r(t)[1 - \varepsilon(t)] \tag{4}$$

The consumption at time $t, C(t)$, is then assumed simply to be depressed from a reference level $C_r(t)$ by the costs imposed by climate change, and by the efforts to limit emissions. Using initially generalized cost functions denoted by $g\{.\}$, the consumption path may then be written as:

$$C(t) = C_r(t)[1 - g_a\{\varepsilon(t)\} - g_I\{M(t)\}] \tag{5}$$

where $C_r(t)$ is a reference consumption path in the absence of any costs from either climate change or abatement; $g_a\{\varepsilon(t)\}$ is the cost, as a fraction of global consumption, associated with emissions abatement level; $\varepsilon(t)$ is as defined in (4); $g_I\{M(t)\}$ is the cost arising from the impacts of the concentration change $M(t)$.

Here the abatement cost $g_a\{\varepsilon(t)\}$ and the impact cost $g_I\{M(t)\}$ may be understood in a general sense, as including a monetized reflection of non-GDP losses. The functional forms are in fact very uncertain, and we have considerable freedom in choosing them. Exploring the impact of different forms is a central point of interest as discussed below.

The key general point in Equation (5) is that the concentration change $M(t)$ is ultimately a function of the emissions control parameter $\varepsilon(t)$. The question is therefore: is it possible to find explicit expressions for $\varepsilon(t)$ which maximize the total utility?

## 5. Analytic Principles: The Key Steps

In principle at least the answer is yes, and for some useful functional forms the results appear to be tractable. Adopting the common economic assumption that utility is an approximately logarithmic function of consumption, the objective then may be written as:

$$Maximize\ V = \int_0^\infty e^{-\rho t} \ln[C_r(t)(1 - g_a\{\varepsilon(t)\} - g_I\{M\{\varepsilon(t)\}\})]dt \qquad (6)$$

For evaluating optimal abatement responses, we are not seeking to evaluate the integral itself, but rather, the path of emissions control $\varepsilon(t)$ which will minimize it. By applying the identity $\ln(AB) = \ln(A) + \ln(B), \ln\{C(t)\}$ is separable and the optimal emissions trajectory is independent of the reference consumption path $C_r(t)$. By expanding the logarithm and taking the first-order terms (costs of abatement and impacts are considered small enough to neglect second-order terms, i.e., $g_a << 1$ and $g_I << 1$), this leaves the objective as:

$$Minimize \int_0^\infty e^{-\rho t}(g_a\{\varepsilon(t)\} + g_I\{M\{\varepsilon(t)\}\})dt \qquad (7)$$

This makes sense: it states that the optimal emissions path is one which minimizes the discounted total fractional loss of consumption.

The key step is then to apply the variational principle, which states that this function is at an extreme point (maximum or minimum) when the derivative of the integrand F with respect to the control variable ($\varepsilon(t)$) satisfies:

$$\frac{\partial F}{\partial \varepsilon_t} = \frac{d}{dt}\left(\frac{\partial F}{\partial \varepsilon_t'}\right)$$

$$F = e^{-\rho t}(g_a\{\varepsilon(t)\} + g_I\{M\{\varepsilon(t)\}\})dt \qquad (8)$$

This is an explicit if complex equation for the emissions control parameter $\varepsilon(t)$.

## 6. Cost Functions and Manipulation

With sufficiently powerful numerical techniques for solving integral equations, it should be possible to derive direct solutions of the optimizing condition (8), by substituting (2) and (4), for a wide range of cost functions. With some simplifying assumptions, the complexity may be greatly reduced and even an analytic solution achieved, clarifying the results and greatly simplifying the computation.

*Abatement costs.* The central purpose of this analysis is to examine how optimal abatement strategies may alter when inertia and endogenous behavioral and technical changes in the systems producing greenhouse gases are taken into account. We therefore let the abatement cost function take a form which depends explicitly on both the *degree* and the *rate* of abatement. In both terms, the costs are clearly likely to rise non-linearly, and can be written as a general power relationship as:

$$g_a\{\varepsilon(t)\} = \frac{2C_a}{a+1}\varepsilon(t)^{a+1} + \frac{2C_b}{b+1}\varepsilon'(t)^{b+1} \tag{9}$$

where $\varepsilon(t)$ is the first derivative (i.e., the rate of change of abatement level); $a$ and $b$ are power coefficients which relate the abatement cost respectively to the degree and rate of abatement, defined such that a value of 1 implies a quadratic dependence; and $C_a$ and $C_b$ are the corresponding proportionality coefficients. Numerical values are developed below. This simple form for the cost function is in fact the heart of the new issues captured in the model. The first term is equivalent to the abatement cost function in existing aggregated cost-benefit studies such as DICE. The second is a direct reflection of *inertia*, in which costs depend on the rate of abatement.

Endogenous technical change is captured implicitly by lowering $C_a$ relative to $C_b$. A lower $C_a$ indicates that the long-run costs of abatement are lowered by induced technological development; the system starts adapting to abatement. If $C_a$ declines and $C_b$ rises, abatement costs are increasingly dominated by the inertia of moving from one state to another, relative to the recurring costs of staying at any given abatement level; and optimal response is determined by the tension between the rising transitional costs of overcoming inertia and the declining absolute costs associated with technological adaptation.

The quadratic form of (9), i.e., with $a = 1$ and $b = 1$, is the most illuminating form which the authors have found analytically tractable to date, and is the form applied in this paper. The abatement cost is then simply:

$$\text{Abatement cost } = C_a\varepsilon(t)^2 + C_b\varepsilon'(t)^2$$

Some other forms of this cost function, with arbitrary integral power coefficients for one of the terms, are analytically tractable if the other term is linear. The quadratic case is, however, the most plausible, and usefully illustrates the key points.

*Impact costs.* The actual impacts of changing the atmospheric concentration are extremely uncertain, in form as well as degree. Most studies have assumed that impact costs are determined by the degree of temperature change, in various ways, and that this will occur smoothly as determined by the radiative forcing and oceanic heat reservoirs.[5] In practice, such idealized temperature change is itself a rough guide. Other studies appear to suggest that interference with the radiative balance may more directly affect climate costs by creating instabilities, and it is likely that there is also some dependence directly upon the *rate* of temperature change, i.e., disruption to existing patterns, e.g., of agricultural production.

The problem is greatly simplified here simply by assuming that the impact cost is proportional to the *concentration* change:

$$g_I\{M(t)\} = \frac{C_I M(t)}{m} \tag{10}$$

where $M$ is the pre-industrial amount of the greenhouse gas in the atmosphere; and $C_I$ is a proportionality coefficient reflecting the severity of climate impacts such that $C_I$ is the cost associated with a doubling of atmospheric concentrations.

If temperature change is taken as determined by a single-parameter heat lag system, this relationship is equivalent to assuming the impact costs depend on both the degree and rate of that temperature change, in a particular combination.[6] It is, of course, highly uncertain whether (10) or any other

[5] Nordhaus (1991) appears implicitly to assume a linear dependence of costs upon temperature change. Cline (1992) suggests a power-law increase. Peck and Teisberg (1992) compare a linear with a cubic dependence of costs upon temperature change.

[6] The global average temperature at time $t$, $T(t)$ lags the changes in atmospheric concentrations by several decades because of the thermal inertia of the oceans. In the single lag model, this is approximated as:

$$T'(t) = \alpha[T\{M(t)\} - T(t)]$$

where $\alpha$ is a temperature lag coefficient, and $T\{M(t)\}$ is the equilibrium temperature change which would finally be reached at a constant atmospheric concentration $M(t)$.

particular form is a reasonable approximation to climatic damage, but even very different forms are unlikely to alter conclusions about the rôle of inertia and technology development in abatement derived from this model.

Emission trends in the absence of abatement efforts are uncertain, but as for population, nearly all studies project declining rates of exponential growth which can be well approximated by simple linear projections.[7] The uncertainties in the actual rate of growth far outweigh any constraints imposed by this form. We therefore let

$$E(t) = E(0)(1 + \zeta t) \tag{11}$$

where $\zeta$ is the average projected growth rate in emissions, in the absence of any abatement efforts, as a fraction of 1990 emissions.

Given these definitions, the total cost may be expressed as:

$$\begin{aligned}
&\textit{Total discounted cost} = \\
&= \int_0^\infty e^{-\rho t}\left\{C_a\varepsilon(t)^2 + C_b\varepsilon'(t)^2 + \right. \\
&\left.\frac{C_I}{m}\left[M_r - E(0)e^{-st}\int_0^t e^{s\tau}(1+\zeta\tau)\varepsilon(\tau)d\tau\right]\right\}dt
\end{aligned} \tag{12}$$

Here $M_r$ is the path of concentration in the reference case, and the term involving $M_r$ is the damage arising from emissions in the reference path (i.e., without any abatement action), which, as noted above, is not relevant to the optimization. Dropping this and commuting the integral (integrating by parts) leaves the cost to be minimized as:

---

Costs are directly proportional to concentrations if costs rise exponentially both as a function of the temperature change, and of the *rate* of temperature change, as:

$$g_I\{T(t)\} = C_I e^{T(t)} e^{T'(t)/\alpha}$$

Given that impact costs are likely to be related both to absolute temperature change and the rate of change, and arguably to the product of them, and given that many analysts expect the costs to rise rapidly with the degree of each, this is not a wholly inappropriate functional form. It is however chosen for its mathematical convenience, not because of any more pressing evidence that impact costs will be in such a form.

[7]Excluding those which (i) assume exponentially growing rates by construction (e.g., relating emissions directly to an exponentially growing GNP), or (ii) build in assumptions that emissions will be drastically curtailed in the reference case. Emission trends in the last forty years (1950–1990) are surprisingly close to a linear trend, and projections of $CO_2$ emissions by the World Energy Council (1992) in three different scenarios to the year 2020 all project linear increases.

$$\int_0^\infty e^{-\rho t}\left\{C_a\varepsilon(t)^2 + C_b\varepsilon'(t)^2 - C_c(1+\zeta t)\varepsilon(t)\right\}dt$$

$$\text{where} \quad C_c = C_I\frac{E_0}{m}\frac{1}{\rho+s} \tag{13}$$

Applying the variational principle (8) yields the equation to stationarize (minimize) the integral as:

$$C_a\varepsilon + \rho C_b\varepsilon' - C_b\varepsilon'' = \frac{C_c}{2}(1+\zeta t) \tag{14}$$

This is a second-order differential equation, with solution (satisfying the limit condition $\varepsilon(0) = 0$):

$$\varepsilon(t) = \frac{C_c}{2C_a}\left[\left(1 - \frac{\rho C_b}{C_a}\zeta\right)\left(1 - e^{\frac{\rho t}{2}\left(1-\sqrt{1+\frac{4C_a}{\rho^2 C_b}}\right)}\right) + \zeta t\right] \tag{15}$$

This equation describes the optimal degree of abatement $\varepsilon(t)$ at time $t$, given the assumed quadratic dependence of abatement costs upon both $\varepsilon(t)$ and $\varepsilon'(t)$, with the weight accorded to each determined by the constants $C_a$ and $C_b$. The following section presents results for specific values of the various parameters and interprets their implications.

## 7. Results

For illustrative purposes, results are presented for the following basic values:

| | |
|---|---|
| rate of time preference | 3%/yr |
| carbon removal rate $s$ | 3.7%/yr |
| pre-industrial concentration $m$ | 550GtC |
| damage from doubling $CO_2$ concn $C_I$ | 4% of Gross World Product |
| initial emissions *E0* | 7.5GtC/yr |
| emissions growth without abatement | 2%/yr |

The central purpose of the present paper, other than introducing the issues and the model, is to examine how the optimal trajectory varies as the costs of abatement are increasingly dominated by the tension between the inertia and induced technology development, as represented in Equation (9). An immediate issue arises as to how to make the trade-off between the declining "absolute" costs, determined by $C_a$, against the rising transitional costs associated with the rate of change, determined by $C_b$.

In this study, these costs are parameterized by assuming that the total abatement costs associated with a linear abatement schedule rising to 50% below baseline projections over a period of 30 years are constant:

$$\int_0^T \left[C_a \varepsilon(t)^2 + C_b \varepsilon'(t)^2\right] dt = Constant \tag{16}$$

where for this analysis, $T$ is taken as 30 years and the constant is 0.2, implying abatement costs at a level roughly equivalent to a purely fixed (exogenous) abatement cost function in which the cost incurred from a 50% emissions reduction is 2% of GDP/yr.

This parameterization defines the trade-off between $C_a$ and $C_b$. A high $C_b$ in this context reflects a view which still accepts the results from the major global top-down energy models as valid over the next few decades, but interprets most of these costs as transitional, and sees abatement costs beyond this being brought down steadily by the endogenous process of systemic adaptation to emission constraints. We examine three cases:

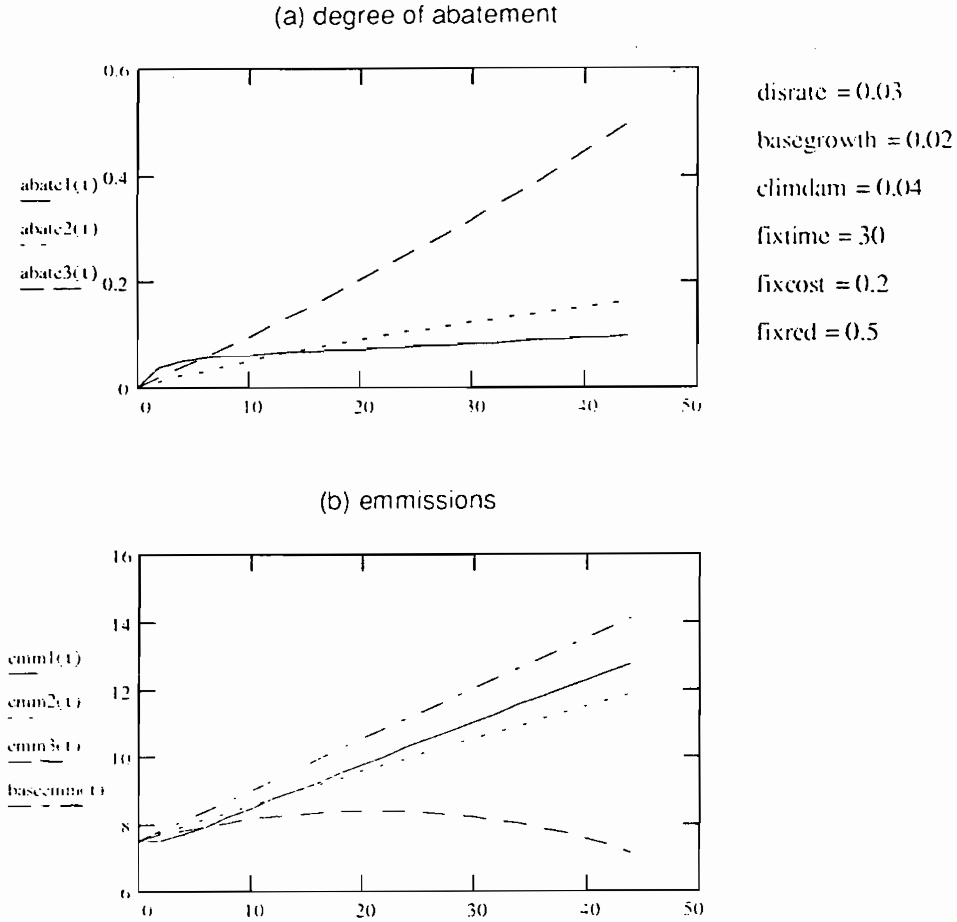
1. *Low inertia, technology exogenous* in which 99% of the costs in (16) are associated with $C_a$ – the conventional perspective.
2. *Half and half*, in which the costs in (16) are divided equally between the two terms.
3. *High inertia, technology endogenous* in which 99% of the costs in (16) are associated with $C_b$.

The results are shown in Figure 1: *abate1(t)* [Figure 1(a)] and *emms1(t)* [Figure 1(b)] show respectively the optimal control and total emissions profile when 99% of the abatement cost factors can be attributed to "absolute" costs $C_a$ (Case 1). *Abate2(t)* and *emms2(t)*, and *abate3(t)* and *emms3(t)*, show the corresponding results for cases 2 and 3.

For the classical technology exogenous/low inertia case, abatement jumps to an optimal level of about 6% emissions reduction, and then increases very slowly owing to the rising baseline emissions; this is basically the Nordhaus result, in form as well as order of magnitude.[8]

For the half-and-half case, when the abatement costs in the parameterization Equation (16) are divided equally between transitional and absolute

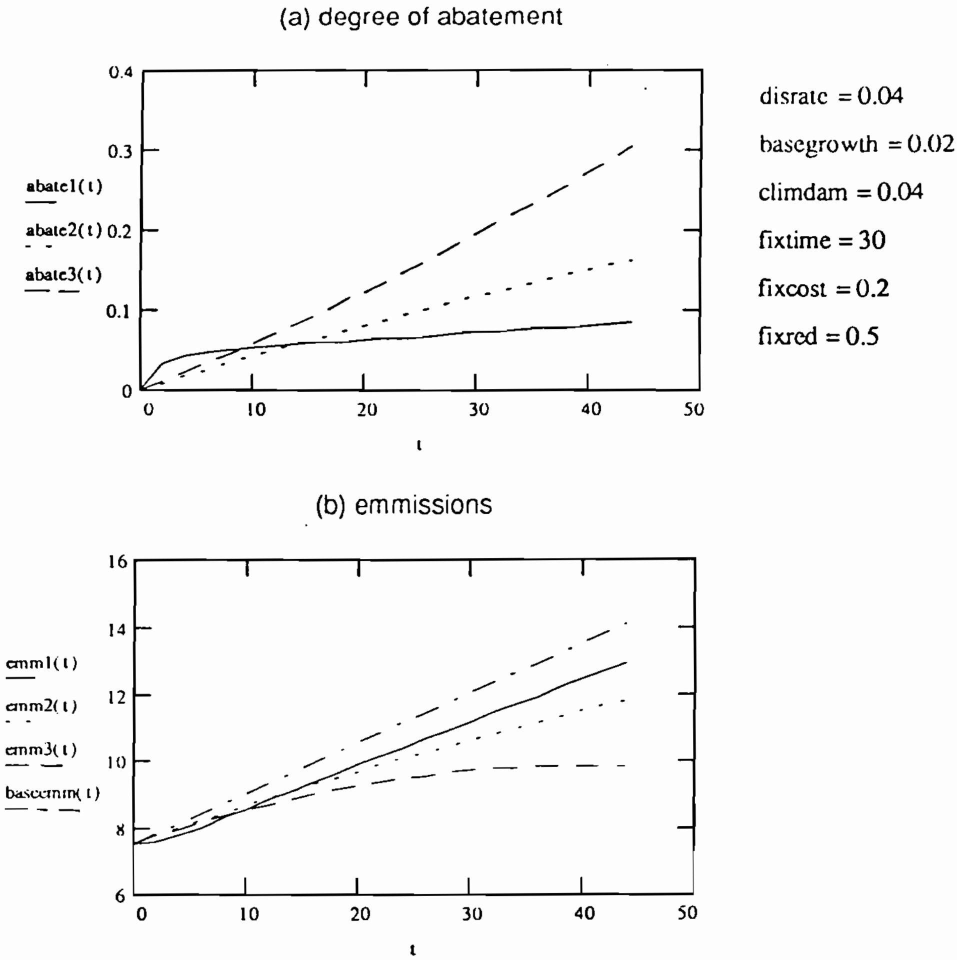
[8] In fact, Nordhaus uses a significantly lower estimate of climate damages, but a cubic cost function for abatement costs; his results reflect a trade-off at lower assumed impact and abatement costs, at such modest abatement levels, but his costs for much more extensive abatement rise very rapidly.




Case 1: Low inertia/transition costs, fixed abatement costs (exogenous technology)
Case 2: Half-and-half
Case 3: High inertia/transition costs, fully endogenous technology development

**Figure 1.** Optimal (a) abatement responses and (b) emission trajectories under differing assumptions about technology development processes (3%/yr rate of time preference).

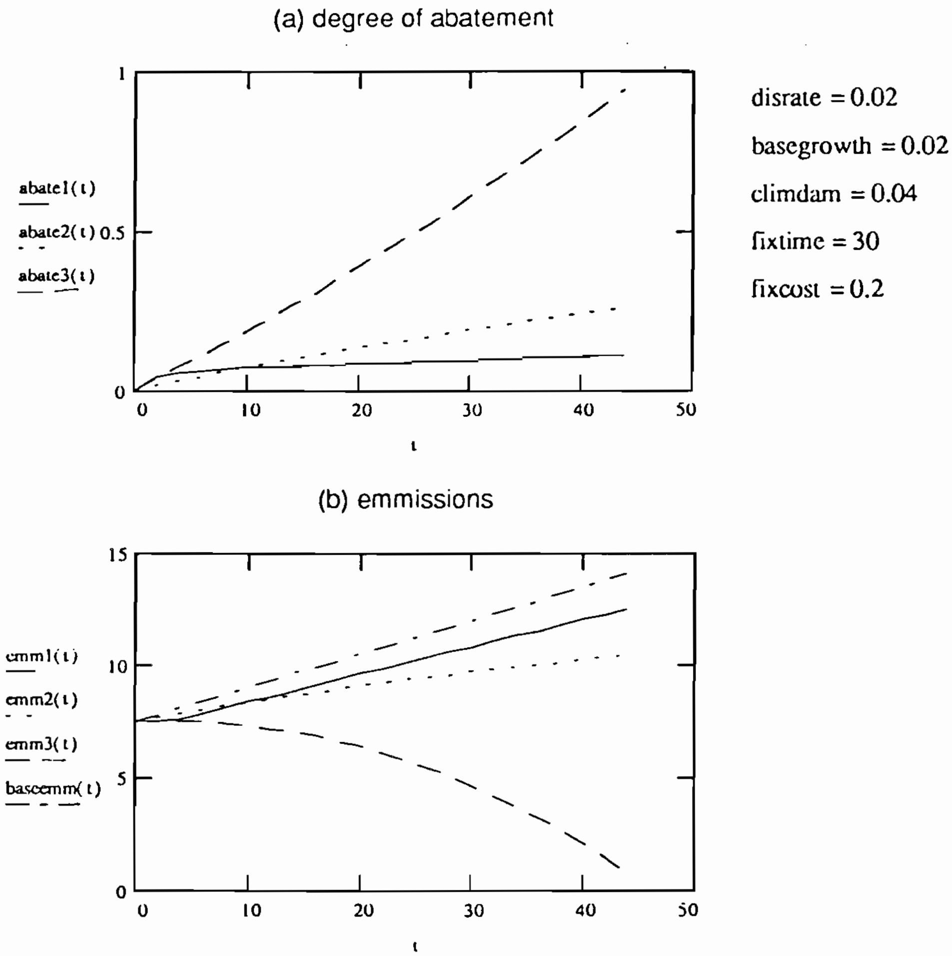
costs, abatement rises much more slowly. After about 11 years, however, it exceeds the "ceiling" level of the classical case, and carries on rising to nearly twice that level.




Case 1: Low inertia/transition costs, fixed abatement costs (exogenous technology)
Case 2: Half-and-half
Case 3: High inertia/transition costs, fully endogenous technology development

**Figure 2.** Optimal (a) abatement responses and (b) emission trajectories under differing assumptions about technology development processes (4%/yr rate of time preference).

In the endogenous technology/high inertia case, abatement rises to exceed the steady state level of case 1 after about 6 years, and it carries on rising at a rate which does not slacken in the period examined (in fact it accelerates fractionally owing to the rising baseline).




Case 1: Low inertia/transition costs, fixed abatement costs (exogenous technology)
Case 2: Half-and-half
Case 3: High inertia/transition costs, fully endogenous technology development

**Figure 3.** Optimal (a) abatement responses and (b) emission trajectories under differing assumptions about technology development processes (2%/yr rate of time preference).

The absolute impact on total emissions is shown in Figure 1(b). In the classical case, after the initial depression, global emissions carry on rising, shadowing the baseline increase. In the half-and-half case, the trajectories gradually diverge, though not enough to stabilize global emissions. For the technology endogenous case, however, emissions start to diverge rapidly; after 35 years global emissions have returned to the starting value, and are on a sharply declining trend towards stabilization of atmospheric concentrations.

It is emphasized again that this result is an optimal path for the parameter values chosen, which can hardly be considered extreme. It is not a result driven by assumptions of very high climatic damage or fixed climate thresholds, or a very low rate of time preference; nor does it reflect particularly low estimates of the cost of abatement technologies as currently perceived. It is a result driven by the consequences of endogenous technical change in which the act of limiting emissions in the first decade lowers the cost of abatement in the next, in a recurring process of technological and behavioral adaptation to the requirements of abatement.

The absolute values of course depend upon the assumptions used. Many of the key sensitivities are readily apparent from the form of the mathematical result (equation 15). Thus, the optimal degree of abatement at all points is proportional to the assumed costs of climate impacts: doubling the climate damage function doubles the optimal degree of abatement. Similarly, for a constant ratio $C_a/C_b$, the optimal abatement is inversely proportional to the cost of abatement.

As the rate of time preference is lowered, placing more weight upon future impacts, the optimal degree of abatement clearly rises, but the relationship is complex. Figures 2 and 3 show results corresponding to those above for rate of time preferences of 4%/yr and 2%/yr. In the former case, even with fully endogenous technology development, global emissions are barely stabilized at the end of four decades given the other values used. In the latter case – the value promoted by Cline (1992) – emissions decline so rapidly that atmospheric concentrations would probably be stabilized after three or four decades.

## 8. Discussion

The first conclusion of this exploratory study then is a message of relative optimism. If the process of technology development is in fact responsive to the extent modeled in case 3 above, there may be solutions to the problem of climate change, with optimal responses stabilizing the atmosphere over a period of some decades at very moderate cost. This possibility is, of course, in sharp contradiction to the conclusions of most previous cost–benefit modeling studies which have argued that the costs of stabilizing even emissions, let alone concentrations, would be high and continually increasing.

This is not a surprising conclusion when the basic hypothesis of endogenous technological change in the form modeled here is understood. Rather less intuitive is the rate of response in the first decade. It might be supposed that the rate of initial responses would be progressively depressed as the weight accorded to inertial/transitional costs increases. The results in Figure 1 illustrate that this is not the case beyond a certain point; for the high inertia, technology endogenous case (case 3), the abatement response is more rapid than in the half-and-half case.

The reason for this lies in the long-run impact on technological trajectories. Initial abatement stimulates technology and infrastructure development, and behavioral changes, which lower the cost of further abatement. As long as there is a substantial component of "absolute" abatement costs – fixed and not susceptible to endogenous cost reduction – the benefit of any endogenous cost reduction is capped after a couple of decades by the absolute component of abatement costs. If technology development is highly endogenous, however, the benefits are greater not only in terms of faster embodied cost reduction, but they also extend much further – the initial moves carry through to a pattern of more extensive abatement spanning over decades. The cost of more rapid action rises, but the benefits rise faster; and thus, it is optimal to act faster to maximize the benefits of induced technological development.

This interpretation is supported by the sensitivity studies with the discount rate. When technology development is fully endogenized, the rate of abatement rises disproportionately faster for the lower rate of time preference, reflecting the high value attached to the long-term benefits of starting early upon a "self-sustaining" abatement trajectory.

The paper has not sought to examine in depth the process of responsive or induced technology development implicit in such "endogenization"; it is a complex and poorly understood issue. The paper has, however, advanced observational evidence to suggest that technical change in the energy sector has to an important extent been of this character.

All these results point to the fact that a better understanding of the issue of endogenous technological change is essential in devising rational responses. For example, Schlesinger (1993) argued on the basis of his modeling work that:

"Rather than squabbling about near-term policies, the effects of whose differences are only minor, we should focus attention on the long-term major problem of providing energy worldwide".

This paper has demonstrated that if technology development is indeed highly responsive to market conditions (such as abatement requirements), the logic in this quotation is perverse and self-defeating: it may be the act of abatement itself which starts to generate the possibility of long-term solutions to the energy/climate problem. In this case, delaying response would not only incur marginally higher costs of climatic impact from the interim emissions; it would delay the whole schedule of feasible abatement, and increase abatement costs, over the subsequent decades.

This issue of the cost of delay under differing assumptions about technology processes is obviously one which can be examined directly with models such as the one developed here. Another and related issue is the impact of uncertainty upon optimal strategies under conditions of high inertia and/or endogenous technical change. Such work is, however, beyond the scope of this present paper, which has sought merely to introduce for scrutiny the issues and the basic modeling concept developed.

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# No-Regret Potentials and Technical Innovation: A Viability Approach to Integrated Assessment of Climate Policies

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## Abstract

This paper aims to demonstrate the advantages of a sequential approach to decision making in climate policies. This sequential approach is necessary because of the uncertainties regarding both the avoided costs of climate change and the costs of GHG emission abatement.

A stylized representation of so-called "no-regret" short-term potentials of long-term innovation trends and of backstop technologies, is used to illustrate the advantages of carrying out an integrated assessment in terms of viability criteria. This assessment focuses on the minimization of learning time, the reduction of technical and institutional inertia, and the possible unexpected nonlinearities in abatement curves.

## 1. Introduction

The integrated assessment of alternative global warming policies aims to answer two intertwined questions:

- Is any preventive action economically founded, i.e., are the benefits of slowing climate change higher than the costs of greenhouse gas (GHG) emissions abatement? What control rate of these emissions can be proved to be economically efficient?
- What would be the optimal set of actions to take? This question is in turn twofold: what is the most efficient technical option mix (energy efficiency, nuclear power, afforestation, rail transportation, etc.); what kind of economic instruments (tradable emissions permits, carbon taxes, energy taxes, environment facilities) should we use to internalize climatic risks, trigger carbon-free technical change, and encourage shifts in consumption patterns?

The state of the art of the economics of greenhouse issues is characterized by its asymmetry between the long list of quantitative studies to estimate GHG abatement costs, and the scarcity of works about the benefit of this abatement, i.e., the avoided costs of climate change. The stumbling block is obviously the difficulty of assessing these benefits over the long term. In pioneering studies, Nordhaus (1992), Fankhauser and Pearce (1993), and Cline (1992) have tried to face the challenge of removing this block, and have provided us with a first attempt at such estimates over the long and very long terms.

This paper originates in the background intuition that further progress in the integrated assessment methodology will be inhibited if due regard is not devoted to the implications of the two following statements:

1. Decision making "on actions in a sea of uncertainties" (Lave, 1991) forces us to clarify the links between two criteria defined by Pearce (1993) as "cost–benefit versus minimum surprise".[1] Related to this, it is worth noting that the Rio 1992 Climate Convention quotes both of these criteria: the "efficiency principle" and the "precautionary principle". Pearce remarks that "if the cost–benefit approach could capture all potential impacts, it would not differ from the risk aversion approach", but this formal equivalence may not be helpful in terms of policy making since it is true in practice only under perfect information, i.e., in the absence of uncertainty.
2. It is increasingly recognized that the costs of mitigation policies are not only determined by the required level of abatement, but also by the pace of this abatement in comparison with the pace of the innovation process. This is the same argument as the one developed by Grubb *et al.* (1993), in which the abatement cost function depends on both the degree and the rate of abatement.

The difficulties raised by these statements are exacerbated by the gap between a reasoning in terms of "pure economic efficiency" and what we could call the "procedural efficiency" (Hourcade, 1993). We are indeed not in a context in which a central agency launches a de-pollution program when its social return is higher than its cost; we are in a context in which governments negotiate some form of agreement on coordination procedures for decentralized actions in various economic sectors, and in countries that differ in terms of their economic wealth, their reliance on fossil fuels, their

[1] Pearce maintains the relevance of the cost–benefit analysis framework (Pearce, 1993), while giving a comprehensive picture of its "conceptual deficiencies".

endowments of alternative resources, and their technical capabilities. This means that the pure efficiency criteria over the very long run may not be able to satisfy the procedural efficiency condition if they are not weighted by a minimum degree of credibility and reliability by the negotiators.

Before proceeding further, I will illustrate with a "two drivers" metaphor both the above-mentioned background intuition and the approach to integrated assessment advocated in this paper.

The first driver is a world champion on a race circuit faced with two sharp turns, right and left, with a blind corner because of a bridge. His "objective function" is obviously to maximize his speed between the entry into and the exit from these turns. Although he has experienced this section before, he is faced with non-negligible uncertainties about the potential presence of sand or oil in the bends, the adherence of his tires at that moment in the race, and about the speed of the preceding car. His behavior can probably be best described as optimizing behavior. Implicitly he determines the optimal trajectory using some kind of probability distribution on the uncertain parameters, confident both in his capacity to assess them precisely and in his physical capacity to adapt to a potential surprise.

This is not (or should absolutely not be) the behavior of a driver on a mountain pass road in early or late winter, speculating about the presence of ice on a bend before a precipice. He also wants to maximize his speed, but if he were to try to calculate a probability distribution on the presence of ice, or on meeting an oncoming car in the bend, he would risk a crash or a fall in the case of nonzero probability of these two events. The probability distribution is too wide and the useful information would come too late given the inertia of the car. Consequently, his rational behavior is not to choose a once and for all optimized trajectory, but to release the accelerator pedal and to push slightly on the brake, ready to slow down if, as he proceeds, he sees ice in the bend, or to accelerate if the road is clear.

This metaphor renders in a simple form the nature of the decision making problem raised by the greenhouse issue: we are not faced with a "once and for all optimizing decision" over the long term, but with a "sequential decision process" where the first aim of mitigation of GHG emissions is to increase our learning time. Along this line, we will first try to clarify the connections to be maintained between the efficiency and precautionary principles and the use of works on optimized paths when one focuses on decisions taken "on time".

The sequential approach advocated here is not grounded by an axiom as widely held as the optimization approach. In a second step, a preliminary numerical exercise will thus try to demonstrate its capacity to provide guidelines for an integrated assessment of climate strategies and for a better understanding of the connections between the so-called no-regret short-term potentials, innovation strategies, shifts in consumption patterns and the efforts of the scientific research community on climate change.

## 2. Integrated Assessment: Which Criteria for Decision Making under Controversy?

We do not need to recall the scope of uncertainties involved in the greenhouse effect issue: about the contribution of each trace gas to global warming, about climate response and feedback effects, and about regional impacts. There is scientific consensus that the average surface temperature is increasing, but the scale and the pace of this process, as well as the geographical distribution of its impacts, remain largely unknown. It may be more convenient to call attention to the uncertainties which symmetrically affect the technico-economic consequences of both mitigation and adaptation policies.

The first reaction of the professional economist is to treat this collective decision problem as a classical problem of decision under uncertainty. Since von Neumann and Morgenstern (1941), these problems are treated by programs of expected utility maximization in a decision space defined by a set of possible but unknown "states of nature" (S), a set of feasible actions (A), and a set of impacts (C). Despite intrinsic well-known difficulties, an assignment of probabilities "$\pi$" to "S" is logically possible because, in most cases one accounts for "exogenous uncertainty", which means that "states of nature" are independent of actions. Modern developments of the theory account for the fact that time brings new information that can be analyzed to give a better assignment of distribution probabilities.

In the face of global warming, as for a large class of global environmental issues, this framework may be proved irrelevant for the following reasons:

1. It is not possible to postpone all decisions and wait for a satisfactory level of information. Because of the inertia of the residence time of gases in the atmosphere and of ecological mechanisms, and the slow response of technological and economic measures, decisions taken only after gathering clear-cut proofs of the risk have a high probability of being inefficient, because they would come too late. Climate change is one type of global environmental issue for which policy making "runs ahead" of the scientific knowledge needed to inform that policy making.
2. Individual and collective preferences do not result from a learning process in which agents have direct experience of a nuisance or a risk; the

risk perception and the subsequent loss of welfare are mainly determined by the way the findings, warnings and debates of the scientific community are transmitted to public opinion by mass media (Roqueplo, 1993). In a context of scientific controversies, the willingness to pay for a given level of caution reveals only the relative convincing power of each possible argument.

3. The state of the world 10 or 20 years hence cannot be held as independent of today's decisions: the set of technologies available at time $t + n$ indeed depends on R&D policies and on the set of policy instruments (taxes, tradable permits, standards) implemented at time $t$. The most challenging consequence of the non-independence between the probability distributions of (S) and (A) is the formation of irreversible or quasi-irreversible trends in technology because of lock-in effects, in consumption patterns (connection between urban planning and transportation patterns) and land use.
4. Collective action requires a prior stabilization of the institutional context by common consensus.[2] This in turn generates an obvious pressure to converge on a subset of the competing theories that seems the most able to support this minimum agreement. There is obviously no guarantee that this convergence will later be proved to be ecologically and economically well founded.
5. In this context the competition between theories or prospects about the future is part and parcel of the strategy of each actor who tries to tilt the balance in favor of the "theory" that maximizes his or her own strategic advantage. The result of the process will depend on the power of conviction of the defender of each technical or institutional project, and of its capacity to mobilize scientific support.

As suggested by Allais (1953), uncertainty is not only a difficulty with which each agent is confronted when he determines his optimum strategy; it can also become a game for some of those agents who are in a position of getting welfare gains thanks to comparative advantage either in the form of adaptive capacity or of information control. In many environmental issues, this situation leads to a configuration called "reversed risk" (*risque inversé*) by sociologist P. Roqueplo (1993): from the viewpoint of most actors the economic risk generated by a controversial solution in the name of common

[2]This does not contradict the perspective of a unilateral initiative taken by a "carbon coalition", suggested among others by Grubb and Sebenius (1991) and Hoel (1993); the aim of this coalition is to achieve a commitment by a core of countries able to *launch a demonstration effect.*

long-term interests supersedes the ecological danger. It can be demonstrated that this results in three risks:

- to do nothing and wait for more information before changing "business-as-usual" behaviors; as shown earlier, this could jeopardize the "sustainability" of long-term development;
- to act but, because of an arbitrary choice between competing "theories" about the future, in fact to "format" the short term in the name of the long term (to impose an arbitrary set of technological or economic policies); and
- to be paralyzed by a *regressum ad infinitum* of "reversed risk" perceptions, if lasting controversies impede the minimum consensus required for action.

In this context of decision "under controversy" we have to solve an underlying procedural problem of coordinating expectations;[3] to come back to our driver metaphor, the main danger stems from uncontrolled disputes among passengers of the car about the driving behavior to follow.

Among the social sciences, economics has the specific responsibility to put some rationale in these discussions. As pointed by Henry (1989), economics must keep its "Janus role" and provide a negotiation language to actors: to clarify what is really at stake, to provide a coherent analysis of the implicit assumptions behind an argument, and to describe the unexpected consequences of a given policy. The methodological issue is then to define such a language when the parameters are too loose, and when some of them have too much influence on the results.

Related to this objective, the difficulties of carrying out a cost–benefit balance of an emission path over the long run are easy to point out:

- *Nonlinearities in the links between emissions, concentrations and climate change*: The mathematically chaotic character (high sensitivity to initial conditions) of the system, confirmed by past climatic events[4] suggests

[3]This question of coordinating the expectations is addressed in many fields of modern economic theory; it has been demonstrated that different equilibria can be defined in function of the "theory" accepted as common knowledge. Both the "sunspot theories" (Guesnerie, Azariadis) of pure monetary equilibrium, and theories of common knowledge (Aumann) show how the public setting of some conventions can foster a process of mutual revision of individual expectations in a process of self-fulfilling prophecy. This is all the more important in that the economics of technical change display many examples of irreversibilities: lock-in (Arthur), path dependency, etc.

[4]Eleven times in 25,000 years there were drastic shifts from cold to warm and vice versa, with an amplitude of 7°C in some decades.

the difficulty of forecasting, if forecasting means a characterization of the climate at a given date. A frequent misunderstanding comes from the fact that existing climate models are designed to help researchers to carry out fictitious experiments (Roqueplo, 1993) or modeling experiments (Académie des Sciences, 1991), whereas the economist utilizes them as if they had some kind of capacity to predict a transient situation.

- *Nonlinearities in the impacts of climate change*: It is well known that the mean temperature provides a very weak indicator of climate change. First, the geographical distribution around this average is expected to be very wide. Second, one must account for the nonlinearities incurred by the propagation of sectoral or local shocks or disruptions. To give a simple example, a wine vintage can be totally destroyed by a short but violent hailstorm, and a doubling or a tripling of the frequency of these storms would be enough to jeopardize the economy of an entire region. Agriculture is indeed a minor and decreasing fraction of total economic output, but a tension on food supply would result in changes in relative prices that are likely gradually to affect other economic sectors (pressure for increased wages, reduced demand for other goods, regional economic disruptions). Finally, considering the fragility of arid and semi-arid areas, particularly in developing countries, a slight increase in drought is likely to exacerbate tensions due to migration (not only from South to North but also between developing countries). Consequently, the economic costs of climate change cannot be calculated without weighing them with security concerns and related geopolitical consequences.
- *Components and instabilities of the preference functions*: First, the cost–benefit balance should consider components of the agents' utility function such as risk aversion, patrimonial values or bequest values that are difficult to assess on the basis of observable data. Second, as shown by Scimemi (1988), the political life cycles of environmental crises follow neither the pace of environmental degradation nor of the progress in knowledge. They frequently evolve from periods of underconcern to crises of overconcern, where a feeling of urgency gives rise to high pressure for an immediate decision. In economic terms, this can be translated into a dramatic instability of the valuation of environmental risks in the welfare function.
- *The weight of non-directly observable parameters in the assessment of abatement costs*: These difficulties are now well identified in the literature (Dean, 1993): definition of the baseline scenario, expectations for innovation, timing of the introduction of backstop technologies, transaction costs for removing barriers to negative cost potentials, side-effects of

the recycling of carbon tax revenues, etc. In fact, any long-term scenario is the result of observed trends, technology facts, future expectations, willingness to defend a view on a given technology, arbitrary beliefs, political choices and value judgments.

The first methodological implication for the use of a cost–benefit analysis as a negotiation language is the scientific necessity for the use of several baseline scenarios that differ not only according to exogenous aggregate parameters such as demographic or economic growth, but also according to the hypotheses underlying each chosen parameter. The calculation of a cost–benefit balance then becomes a simulation of a policy experiment, but under current circumstances, there are as many results as there are scientifically non-refutable baseline scenarios, given the present state of knowledge.

This immediately raises the question of how to deal with the number of baseline scenarios which account for the combination of various possible hypotheses, often very different, on so many parameters. One might expect indeed that ongoing international scientific exchanges would gradually reduce the initial diversity; however, because of the potential bifurcations in development trends, it is impossible to expect convergence on a single baseline scenario in the foreseeable future. This is all the more unlikely since, in a negotiation process, one can expect the strategic use of information and systematic efforts on the part of each actor to refute any scenario that is unfavorable to his own interest.

Consequently, reliance on long-term cost–benefit analysis as the only negotiation language may prove to be self-defeating. This would indeed add up to make two risky bets. The first concerns our capacity to foster a cooperative process so as to minimize the strategic use of information; the second concerns the capacity of scientific research to provide in due time knowledge that is useful from a decision making point of view. Scientists insist that, during rather long periods, progress in knowledge may not be synonymous with a reduction of uncertainties; this was the case, for example, in the ozone layer issue (Mégie, 1992).

This does not imply that the use of the cost–benefit framework is of no interest. Let us return to our "car driver" metaphor: the driver in the mountains needs some information on the nonzero probability of ice and the existence of the precipice, in order to enter in the sequential decision process. In summer, for instance, he will adopt another behavior, similar to that of the racing car driver, because the temperature is too warm to expect any ice. In the same way, to enter a sequential decision process in the face of the greenhouse issue, we need some landmarks about the long term. That is why long-term optimization reasoning is necessary and useful, provided that we remember that in practice we are not in a "once and for all" decision problem. For example, a comparison of the findings of Nordhaus (1992) and of Fankhauser and Pearce (1993) shows the sensitivity of the result to the accounting of risk-aversion and the rationality of some emission curbing measures, however limited they may appear.

Sensitivity tests on long-term optimized paths will provide the required landmarks, but we cannot expect to settle the controversies about critical parameters quickly enough to translate their findings directly into concrete, immediate decisions. Fortunately, as suggested by Manne and Richels (1993) "we need not be overly concerned with our inability to predict the detailed character of the energy system several decades into the future. Uncertainty is important only to the extent that it confounds near-term decision making. Today's decisions appear to be relatively insensitive to some of the more controversial longer-term uncertainties in the greenhouse debate".

## 3. A Model of "Surprise Disclosure" to Test the Timeliness of Actions

The following model gives a stylized representation of the collective decision problem with which we are confronted, namely:

- The possibility of surprises and nonlinearities in the avoided cost curve.
- The distinction between a precautionary approach and a maximizing approach under imperfect information.
- The evolution of public concern in the face of climatic risks as a function of the space of improvement of scientific knowledge.
- The critical role of long-term innovation.
- The debate about short-term "no-regret" policies.

This model describes a "once and for all" decision over the long run and aims to assess the price to be paid for a postponed action in the case of "surprises". We must underline that the calibration of the model will require further investigations in collaboration with the Laboratoire d'Aéronomie of CNRS; in its present version it can only be used for heuristic purposes, to illustrate some logical structures of decision making to deal with climate change. This model has four components (see Figure 1):

1. *The calculation of GHG concentrations for given emission trends*, depending on the world gross domestic product (GDP). In the following numerical simulations, the GDP growth rate will be assumed to be 3% per

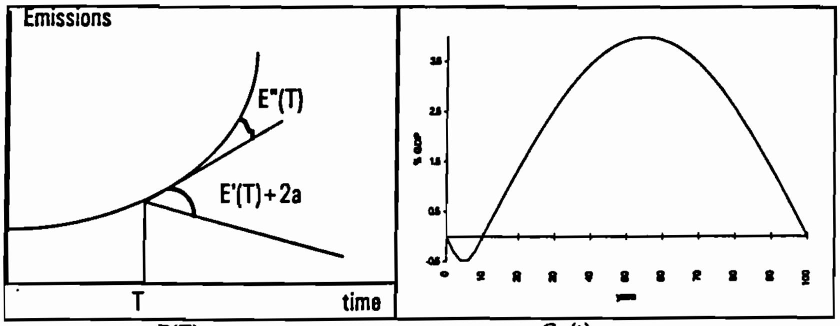
**Emissions (E)**
$E(t) = Eo \exp(\alpha\, t)$

**Concentrations (M)**
$M' = \beta\, E(t) - \delta\, M$

**Abatment Cost Curve**
$C_T(t)$ : abatement cost at time t. $C_T(t)$ is a function of the decision time T.
C(T) : actualised abatement cost.

$$C(T) = R(T) * \int_T^{\infty} C_T(t) \exp(-\theta t)\, dt$$

where $R(T) = p\,(\,E'(T) + 2\,a\,)^2 + (1-p)\,(\,E''(T)\,)^2$




R(T) $C_T(t)$

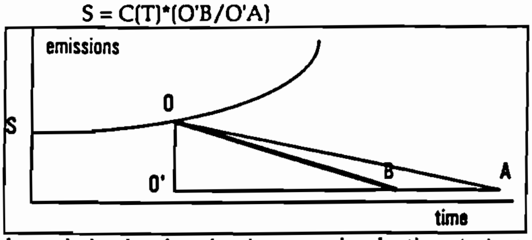
**Level of Information**
$p(T)=T/\theta$ if $T<\theta$
$p(T)=1$ if $T>\theta$

**Expected Value of the Cost of Climate Change**
$B(T) = (1-p(T)) * LC + p(T) * HC$
Where LC is the low-cost hyphothesis and HC the high-cost hypothesis

**Utility Function of Expected Value of the Cost of Climate Change**
$U(B)=(B/10\%GDP)^3$

**Decision Making Equation**
$U(B(T_d))-C(T_d)=0$

**Incremental Cost of Accelerated Abatement**
$S = C(T)*(O'B/O'A)$




SOA is the emission level under the normal reduction strategy
SOB is the emission level under the accelerated reduction strategy

**Figure 1.** Behavioral model of economy, ecology, and climate change.

year and the income elasticity of emissions of 0.66, in order to approximate to the upper bound of the IPCC 1992 scenarios.

2. *A set of abatement technologies*: It will be assumed that, at the date of the decision, a set of abatement technologies is available[5] or can be expected over the long run. This set of technologies results from the "business-as-usual" scenario developed until the launch of an emissions abatement program. In order to represent the technical and institutional inertia in the diffusion of technologies, the new trend is assumed to follow a concave parabolic function that describes a constant acceleration of the decoupling between the baseline and the abatement trends.

The costs of these technologies are assumed to be known in terms of the discounted cost of a 100-year transition program agreed on today (after 100 years a set of backstop technologies is assumed to sustain world development within an emissions constraint of 3 Gt C per year, leading to long-term stabilization of concentrations at around pre-industrial levels).[6] From this starting point, it is assumed that the total cost of the program grows as the square of the necessary abatement level.

It is then possible to calculate the curve of the abatement cost as a function of the decision date. The shape of this curve is obviously determined by the long-term discount rate, but, contrary to conventional intuition, it does not systematically turn downwards. This is the case only if the discount rate $i$ is higher than the product of the emissions growth rate and of the exponent of the abatement cost curve.[7] Within the range of parameters adopted here, this is the case only if $i > 4\%$. For $i = 5\%$ the curve increases up to 2025, and decreases thereafter.

3. *Nonlinearities in the costs of climate change*: In this simplified version of the model these nonlinearities are captured in binary form. Below a concentration of 500 ppmv, the cost is very low (0.05% of GDP), and above

[5]The concept of technology encompasses here not only carbon-free technologies, but all other abatement variables such as changes in consumption trends.

[6]This oversimplified alternative (between a business-as-usual scenario and long-term carbon-free scenario) is used only for heuristic purposes; to increase the sophistication of the model to represent less contrasted choices would be useless at this stage and would make the demonstration more fastidious.

[7]The derivative of this function is of the form:

$$C'_t = (d.Log(1+g) - i)(1+g)T_d + i.S \quad ,$$

where $T_d$ denotes the decision date, $S$ is a mathematical function of $T_d$ which is always positive, and $g, i, d$, denote the emissions growth rate, the discount rate, and the exponent of the abatement cost curve, respectively. This expression remains positive when $T_d$ infinite if $d.Log(1+g) - i > 0$, which is the case if $d.g > i$.

this level it increases to 15% of GDP.[8] This order of magnitude may look surprising when compared to other figures in the literature, but it can be explained in two ways. First, this is an easy way to figure numerically a "surprise" evolution. Second, it cannot be interpreted as a permanent loss: its order of magnitude means that the price to be paid for climate change is a freeze on economic growth for five years, or roughly the cost of a world war. In fact, the loss extends over one generation (it is absorbed mainly during the first decade) and is not a permanent loss from an optimized growth path. We think it more convenient to assume that once adaptation to climate change is completed, economic growth will recover from the "non-shock" trajectory, such as was the case after World War II. Translated into losses along a permanent regime over 100 years this comes to a loss of 2% of GDP. The difference between this estimate and that of Fankhauser and Pearce (1992), or even Nordhaus, consequently lies not in the order of magnitude of the overall loss, but in its temporal distribution.

We must insist on possible misunderstandings that may occur with this stylized representation of the climatic risks. It is obvious that we are describing here a kind of "danger line". Then, this line must not be interpreted as resulting only from some possible catastrophic changes in climate dynamics. It encompasses both this possibility and the nonlinearities in the human adaptation to slow climate changes or some local evolutions that could proceed faster than the increase in the average world temperature (e.g., problems in the adaptation of agriculture, droughts, accelerated migrations, etc.).

4. *Two decision behaviors*: It will be assumed that humanity as a whole acts as a rational economic agent under imperfect information and following two logical behaviors:

- "Precautionary behavior": the action is taken when the expected value of avoided costs of climate change exceeds the expected emissions abatement costs.
- "Optimizing behavior": the action is launched at a date which minimizes the ratio of the discounted costs of the abatement program to the discounted cumulative GDP over the same period, so as to minimize the pressure on consumption. This behavior is equivalent to the precautionary behavior for each $i < g + d$ ($g$ and $d$ denote the emissions growth

[8] A new version of this model introduces both continuous functions relating the costs of climate change to the level of concentration, and the distribution of the probabilities of these costs.

rate and the exponent of the abatement cost curve, respectively) since the discounted cost of abatement increases steadily over time.

The result of these calculations is conditional upon the level of information about climate change: it will be assumed that scientific knowledge increases linearly with time, and gives a perfect information after $\theta$ years ($40 < \theta < 100$). It is assumed that the subjective probabilities attributed to the "low-impact" hypothesis ($\pi$(li)) and the "high-impact" hypothesis ($\pi$(hi)) depend on the state of knowledge. The expected abatement cost can then be written as a function of $\theta$ (in the model runs analyzed in this paper we simulate the discovery of "surprises", consequently, when $t \rightarrow \theta$, $\pi$ (hi) $\rightarrow 1$).

The shape of the utility function of the expected value of avoided costs is designed so as to capture phases of underconcern when the expected costs are low, and phases of overconcern when these costs are high. There are many sociological and psychological grounds which can lead us to think that the actual curve will be more complex, but relating overconcern to the increase in subjectivity seems to provide an acceptable proxy at this level of abstraction.

Since this model aims to simulate the occurrence of surprises, it has no endogenous mechanism that ensures that a decision will be taken before $T_u$, the ultimate date after which a faster deceleration of the emissions is needed to avoid the "danger line"; if $T_d > T_u$, the model calculates the profile of the revised abatement program.

The economic implication of this form of surprise is the necessity to remove barriers to the penetration of abatement technologies and to accelerate the depreciation of existing capital vintages. If we assume that all abatement costs are investment outlays, it is possible to assess the order of magnitude of the incremental costs of the acceleration. The multiplier coefficient of these costs is assumed to be proportional to the ratio of the duration of the accelerated program so as to meet the 3 Gt C emission target, to that of the non-accelerated program period to achieve the same result. In fact, this coefficient is roughly equal to the ratio of the tangent angles of the corresponding emission curves in $T_d$.

## 4. Expectations and Inertia: The Narrow Windows of Opportunity

The outcome of this model is obviously very sensitive to the values of certain parameters: the proxy function of GHG concentrations as functions of emissions trends, the level of the danger line, the temporal distribution of abatement costs and avoided costs (these determine the sensitivity of the model to the discount rate), the shape of the utility function, and the linkage between progress in knowledge and the distribution of subjective probabilities. This last parameter has proved to be the most sensitive.[9]

This is not the occasion to comment on the result of this sensitivity analysis in great detail, but it seems convenient to sketch a typology of possible cases computed without resorting to extreme hypotheses. Figures 2(a) to 2(d) represent four possible scenarios if the discount rate over the long term is lower than $g + d$.

(a) The "no-problem" scenario. The decision is made before the date $T_u$; this configuration appears in particular for very low discount rates or when the research period to obtain perfect information is less than 30 years, which means that a 50% certainty about the existence of a danger line is reached within 15 years. This configuration is a no-problem one whatever decision criterion is adopted.

(b) The "no-action" scenario. The subjective value of damage remains below the abatement cost curve. This means that the speed of information build-up is too low compared with the slope of the abatement cost curve.

(c) The "window of opportunity" scenario. The abatement cost curve cuts the benefit curve at two points; at the date $t_a$ the choice is made too late and accelerated abatement is triggered, entailing additional costs (curve RC = real costs). From this date on, the abatement cost assessment is gradually revised so as to approach the true costs. At date $T_b$ the revised abatement cost curve passes irreversibly over the benefit curve. This means that, if deadlocks in the negotiation process prevent decisions being taken before this date, it will be too late to launch a preventive strategy. This is a first way to introduce the idea of a "window of opportunity"; a second one is presented in Section 5. As shown by the simulations, this window is rather narrow in most cases (less than 15 years).

(d) The "try-and-stop" scenario. This scenario is an asymptotic version of the previous scenario in which the window of opportunity goes to zero. In this case, the sunk costs already devoted to the abatement strategy are

[9]Note that in the present version of the model, the absolute level of incurred costs beyond the danger line is not the most sensitive parameter if we remain above a value of 8–10% of GDP; namely, an order of magnitude figuring some kind of "catastrophic" disruption.

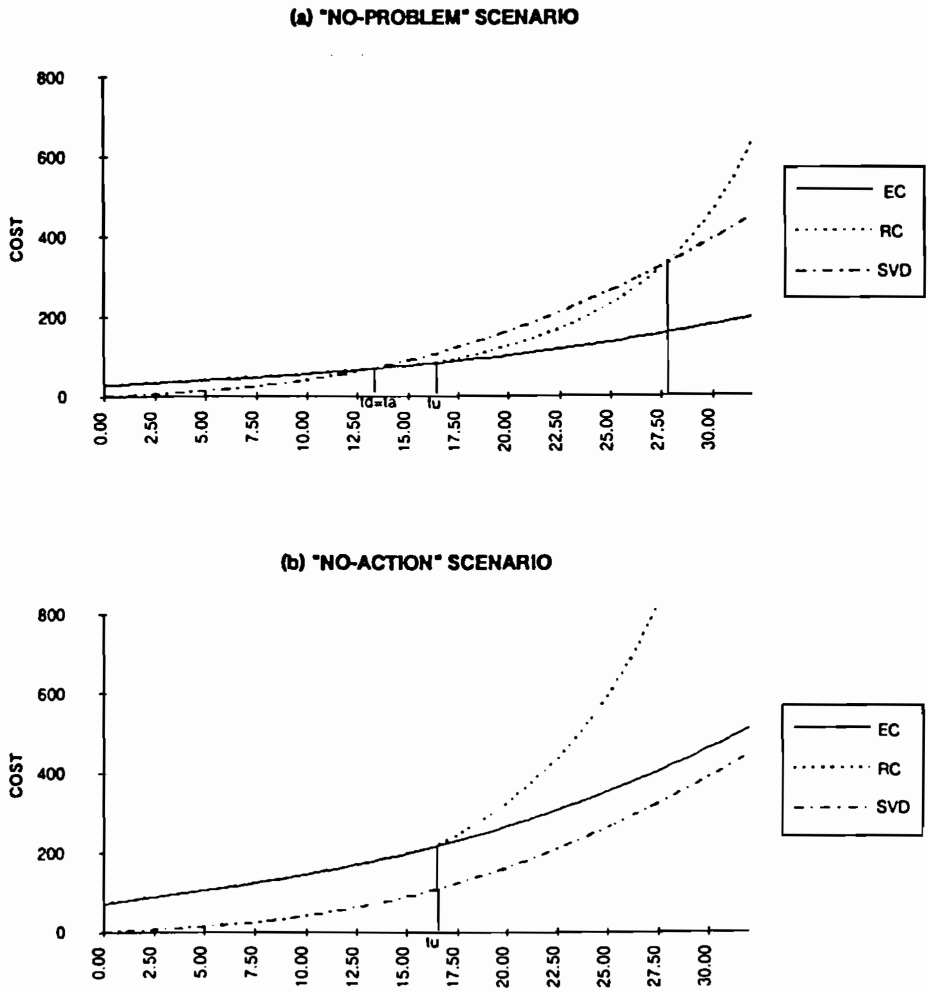
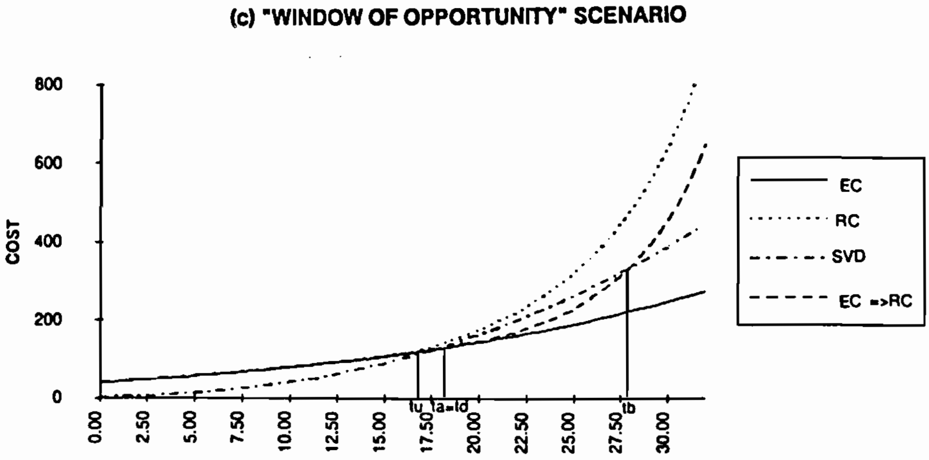



**Figure 2.** Four scenarios with a discount rate $i < g + d$. (EC: expected cost; RC: real abatement cost; SVD: subjective value of damage.)

not high enough to prevent a drop-out, considering the new appreciation of true abatement costs.

The configuration of "window of opportunity" is systematic for high discount rates. The distinction between precautionary and optimization behaviors turns out to be useful in this case. The optimal abatement decision is indeed made when the revised cost of abatement is minimal, namely when the incremental cost of acceleration supersedes the effect of the discount rate.



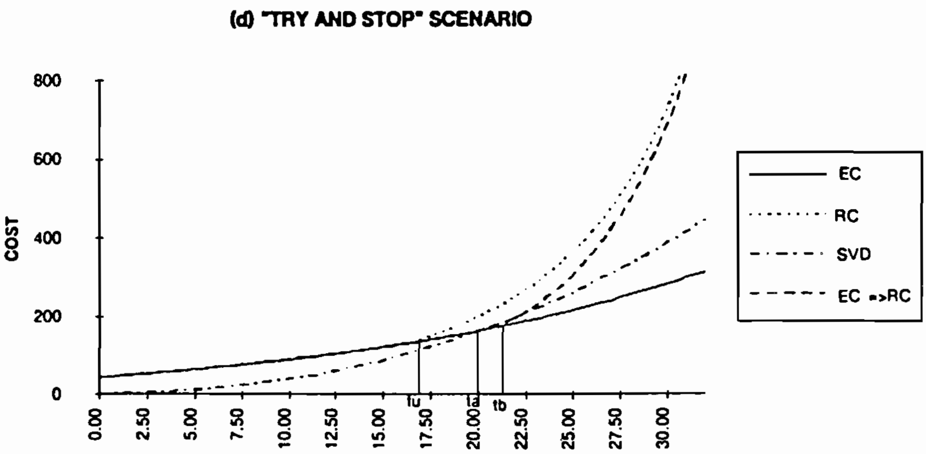




**Figure 2.** Continued.

# 5. The Costs of Inertia, the Value of Information, and Viability Criteria

To illustrate the cost of postponing decisions, Figures 3(a) and 3(b) show a scenario in the middle of the range of variation of our simulations (most of our numerical assumptions were given in Section 3). This does not necessarily imply that it can be considered to be the most probable one. It describes a "window of opportunity" case with a low discount rate.

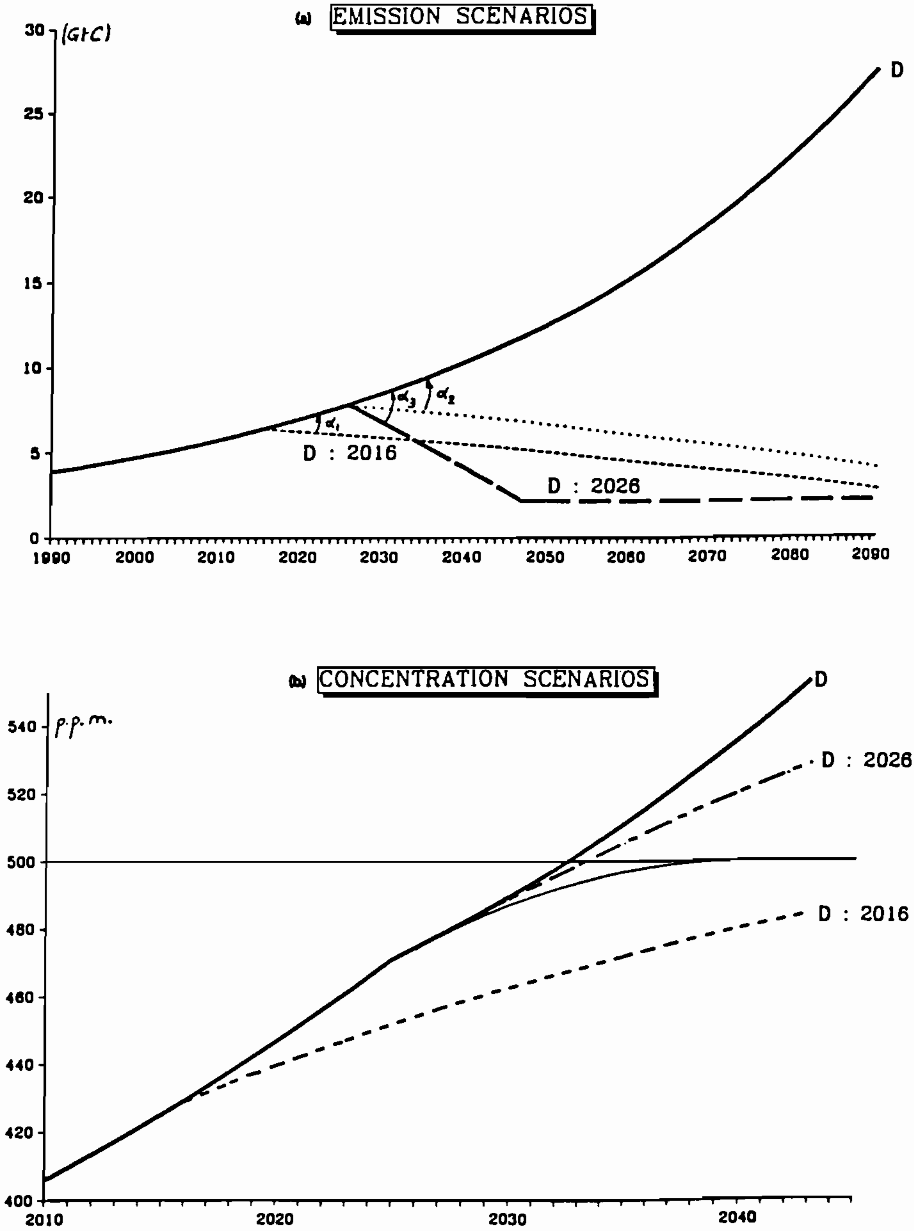



**Figure 3.** "Window of opportunity" scenario with a low discount rate.

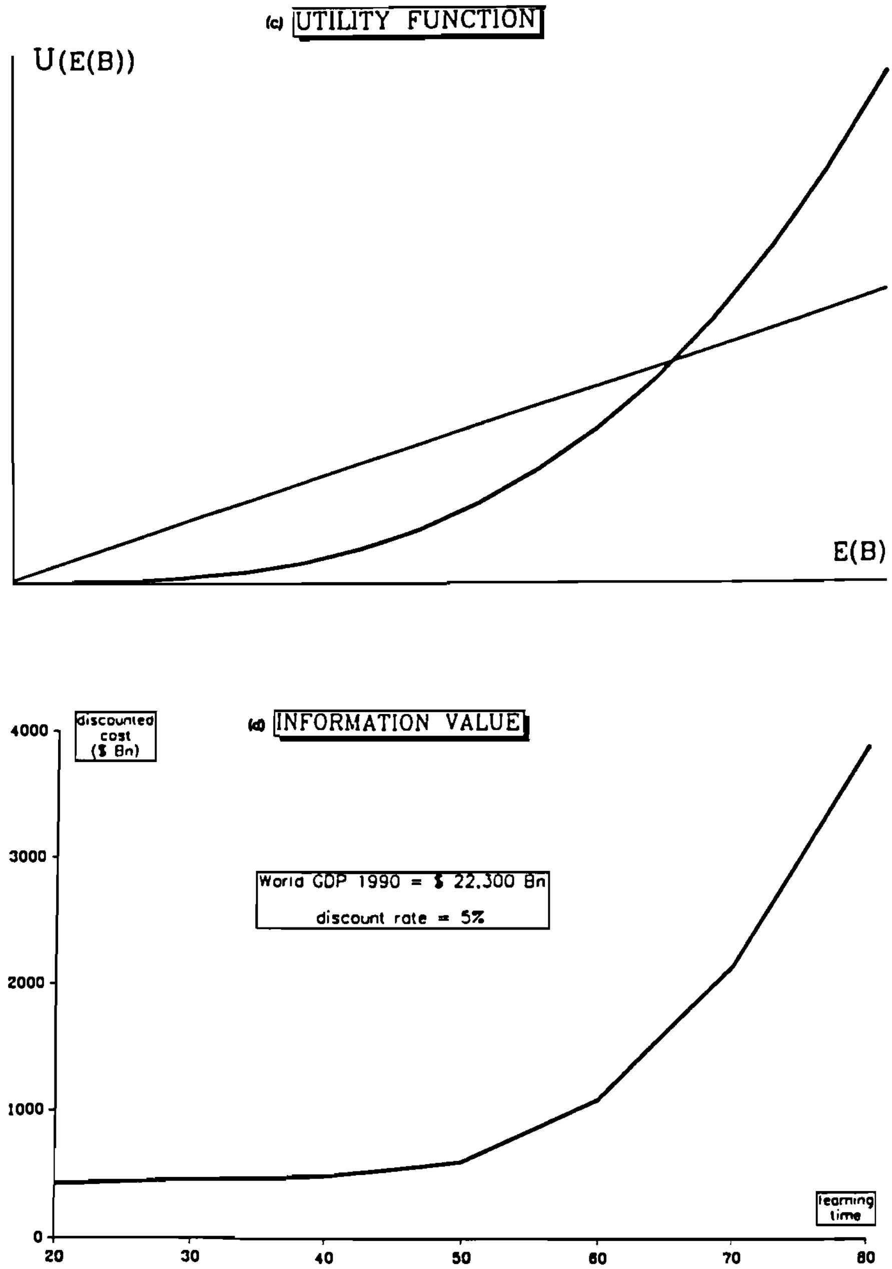



**Figure 3.** Continued.

In this case, the ultimate decision date $T_u$ (not implying accelerated abatement) is 2016, and the model calculates a decision date in 2026. The challenging outcome is twofold:

- First, the pace of abatement must be accelerated by a factor of two (see the difference between the angles $\alpha_1$ and $\alpha_2$ in Figure 3(b); the impressive result is obviously the drastic acceleration needed in the case of such a short delay, due to the fact that, roughly speaking, the concentration curve is the integral of the emission curve.
- Second, the $T_b$ emission profile falls drastically below the $T_d$ profile after about two decades. To put it in another way, to decide in $T_d$ makes it possible to maintain a relatively high level of fossil fuel consumption for 100 years or so, whereas to decide 10 years later means that it is necessary to hastily reduce this level of consumption down to a 3 Gt C emission target. This conclusion is the same as that demonstrated by Mégie (1992) for the ozone layer: had CFC abatement decisions been taken 10 years earlier, it would have been possible to maintain a 20% market share for CFCs without disequilibrium of the atmospheric system.

A first assessment of the cost of postponing decisions can be immediately observed in Figure 3(d), which describes the evolution of the true *ex post* costs calculated, *ceteris paribus*, as a function of the parameter $\theta$, the time necessary to obtain perfect information. This curve is rather flat up to $\theta < 40$ years (because, in this case, the measures are taken before $T_u$), but increases sharply for $\theta > 50$ years.[10] This can be interpreted in terms of the value of scientific information; the derivative of this cost curve gives the gains generated by shortening the time lag of perfect information by one year. Between 50 and 60 years, for instance, each year saved returns around 0.2% of GDP, and 0.76% between 70 and 80 years.

It is totally open to criticism to compare this finding with the assessment of the value of information made by Manne and Richels (1992), using a totally different approach. However, we cannot but note that, translated into \$/t C between our dates $T_u$ and $T_a$, our calculations give a value of \$17.8/t C, whereas Manne and Richels find \$15/t C in the case of high damage potential, which is exactly the case under consideration here.

A second assessment can be carried out in terms of viability criteria. The foregoing results are obviously the result of a pure mathematical artefact.

[10]Within the set of parameters used in this simulation, we enter into a no-action case when $T_a > 85$ years.

Given our modeling structure, the danger line can never be crossed except if $T_d > T_u$; the model does not constrain the acceleration of the abatement ($T_g(\alpha_2) \to \infty$), which is totally unrealistic. A simple way to reintroduce some realism into the behavior of the model is to give limits to the ratio of abatement costs to GDP; if this limit is exceeded at any moment along an abatement path, this path will be considered unsustainable since it would be impossible to reconcile environmental and economic sustainability.

To give an order of magnitude, if we assume that the abatement costs are mainly capital expenditures, and that the capital-to-output ratio is 20–25% of GDP, it can be assumed that abatement costs of 5% of GDP are a reasonable indicator of the upper limit of economic viability. When $\theta = 50$ years, for instance, the acceleration of the abatement is necessary, but the cost entailed never reaches this limit. This means that, in this case, the losses due to imperfect information are far from negligible but that the transient path is viable both with regard to the climatic and economic constraints. Conversely, if $\theta = 80$ or 70 years, the economic viability constraints are violated in 2032 and 2035. This information is important from a decision-making point of view since it demonstrates that low-cost carbon-free backstop technologies must be mature enough at that period to penetrate massively and shortcut the increase in abatement costs.

Under the current state of knowledge, there is a low probability that such a penetration is possible at that date in a "business-as-usual" perspective; gasoline from crude oil has indeed for long time had a technical and economic advantage over biofuels or electric engines, which can discourage the penetration of these technologies to reach larger market shares.

Before proceeding further, we must draw a preliminary conclusion: the investment in scientific knowledge is likely to be one of the most efficient in a preventive strategy, but it would be very dangerous to rely on this policy variable alone. Since scientists cannot commit themselves to providing useful knowledge (namely, knowledge that is useful in terms of decision making) within given time targets, and because of the additional delays to decision making due to the difficulties in the negotiation process, a mere reliance on future knowledge of climate change would be a risky bet for the timely generation of low-cost carbon-free technologies.

## 6. Precautionary Strategy, Sequential Approach, and the Value of Short-term Focused Decisions

The previous simulations confirm the extent to which the key issue is some kind of long-distance race between GHG concentrations, the development of scientific knowledge of incurred risks, and progress on carbon-free technologies. It is then possible to define, at a theoretical level, the content of the precautionary principle as the harmonization of these three kinetics. This leads us to consider the maximization of learning time as the key parameter of an integrated assessment. This in turn leads us to speculate about a core of short- and medium-term policies that could:

- slow down the rate at which we approach two symmetric dangers: premature arbitrary and costly actions, and delayed actions;
- achieve this slowing down at a low or even zero incremental cost: this does not imply a "free lunch", but the existence of a core of decisions which we will not regret even if climate warming is ultimately proven to be a harmless or nonexistent phenomenon;
- be consequently more easily negotiated and implemented, providing additional time for tougher negotiations on more costly and more controversial decisions, if they are proven necessary;
- broaden the degrees of freedom in the future and lower the cost of GHG abatement.

It is from this point of view that no-regret policies are to be examined, in connection with innovation policies. Although commonly used in literature, the no-regret concept nevertheless involves many ambiguities, and is sometimes assimilated into negative cost abatement potentials or "free lunch" policies. We will define here the no-regret policies as encompassing the negative costs technical potentials, the side-effects of removing distortionary incentive systems (taxes, subsidies), and the positive externalities of GHG reduction on issues such as regional environmental problems or security issues.

In fact, the main questions about this concept concern the order of magnitude of actual no-regret potentials if the transaction costs of their exploitation are accounted for, and the capacity of these potentials to provide in practice a sensible gain in terms of learning time. An argument against such no-regret policies is the fact that even if actual potentials could stabilize emissions for 20 years, the concentration curve would be shifted by only 8 years. This indeed brings us to conclude that these policies have no practical advantage. It is clear that this statement relies on purely physical criteria; economically it is possible to present a totally different conclusion that is more optimistic with regard to the long-term advantages of short- and medium-term, apparently limited decisions.

Coming back to the above scenario, new simulations have been carried out, assuming that, from now on, two complementary policies are launched together with higher investments on climate research:

- no-regret policies enabling to stabilize GHG emissions at an average zero cost (the sum of the negative costs offsets the sum of the entailed positive costs);
- innovation policies resulting in biased carbon-saving technical progress, which reduce the relative price of abatement technologies at a rate of 0.5–1% per year.[11]

It is then possible to compute both the reduction of abatement costs, and the date for an accelerated penetration of backstop technologies that will permit viable development. In our central case (with $\theta = 80$ years), no-regret potentials representing 20% of the overall abatement and launched in the ten following years would bring a 50% cut in total costs and would postpone the penetration of carbon-free backstop technologies by 18 years, with carbon-saving technical progress of 0.5% per year, and 62 years with a rate of 1% per year.

Even the first moderate assumption leads to an important conclusion. Indeed, the "non-viability line" is exceeded in 2032 in our central case, and whether we need large-scale carbon-free technologies by the year 2032 or the year 2050 changes the picture considerably. During this period, there is no reason why electric cars or biofuels would remain unavailable for large-scale markets if convenient innovation policies are steadily implemented. These policies would probably be helped if price signals are given to remind policy makers that the short-term prices of fossil fuels do not represent good indicators of the long-term tensions on energy. Consequently, a moderate amount of no-regret potentials launched in the short term in connection with research and development programs would totally alter the perception of our capacities to face an important but controversial risk without entailing extremely high costs in either the short or the long term.

[11] This can be interpreted as the additional technical progress beyond the average of technical progress achieved on other goods and services.

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# Mitigating Global Warming by Substituting Technology for Energy: MITI's Efforts and New Approach

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## Abstract

In the last two decades Japan has successfully overcome energy and environmental constraints despite the fragile nature of its energy and environmental structure, and has been able to maintain a high rate of economic growth. This success was achieved by means such as substituting an unconstrained production factor (technology) for a constrained production factor (energy) in a manner similar to an ecosystem. MITI's industrial technology policy functioned well in stimulating this substitution, thereby enhancing the vitality of industry.

Given the two-sided nature of $CO_2$ discharges and energy consumption, the experience of Japan can provide informative suggestions to address the current worldwide concerns regarding global warming. However, Japan may now again be facing the prospect of energy and environmental constraints following the fall in international oil prices and the subsequent "bubble economy".

This paper reviews Japan's path and MITI's efforts to overcome energy and environmental constraints by means of the substitution of technology for energy. It also analyzes the sources of the current fears concerning energy and environmental constraints and the effectiveness of MITI's new comprehensive approach in reducing such fears.

## 1. Introduction

The global environmental consequences of $CO_2$ discharges resulting from energy production and use are causing mounting concerns regarding the sustainability of our development future. The Japanese economy, despite many handicaps, achieved sustainable development in the face of various constraints by focusing efforts on improving the productivity of the relatively scarce resources of the respective era (Economic Planning Agency, 1965–1992). In the 1960s, the scarce resources were chiefly capital stock, whereas after the 1973 energy crisis they were the supply of labor, environmental capacity constraints, and then the supply of energy (Economic Planning Agency, 1965–1992). The driving force behind this achievement was the development of manufacturing industry, and the rapid enhancement of productivity levels was most typically observed in overcoming constraints in the supply of energy by means of technological development. This enhancement was achieved by substituting an unlimited resource (technology) for a limited one (energy) (Watanabe, 1992). This success suggests that the effective substitution of resources which have become scarce due to global environmental constraints by technology may be an answer to the question of how energy and environmental constraints can be overcome while maintaining sustainable development.

Section 2 describes Japan's path in overcoming energy and environmental constraints – a path which aimed to overcome the energy crises by substituting an unlimited production factor (technology) for a limited one (energy). Section 3 reviews MITI's efforts to induce this substitution, and Section 4 analyzes the sources of the current fears concerning energy and environmental constraints. Finally, Section 5 assesses MITI's new comprehensive approach for the mitigation of global warming by means of the integration of energy and environmental technologies.

## 2. Japan's Path in Overcoming Energy and Environmental Constraints

### 2.1. Comprehensive approach

Figure 1 compares trends in $SO_x$ and $NO_x$ emissions in advanced countries over the last two decades, and demonstrates Japan's significant achievement in reducing pollution. Japan's ability to minimize its emissions of $SO_x$ and $NO_x$ can be attributed to a comprehensive systems approach consisting of a mixture of incentives and regulations, and a web of industrial policies relating to technology innovation, comprehensive energy policy, industrial location policy, industrial structure policy, etc., as illustrated in Figure 2. Figure 3 analyzes trends in Japan's $SO_2$ concentration in the atmosphere over the period 1965–1989 and the countermeasures taken to reduce $SO_2$ emissions. From Figure 3 we note that the $SO_2$ concentration was reduced

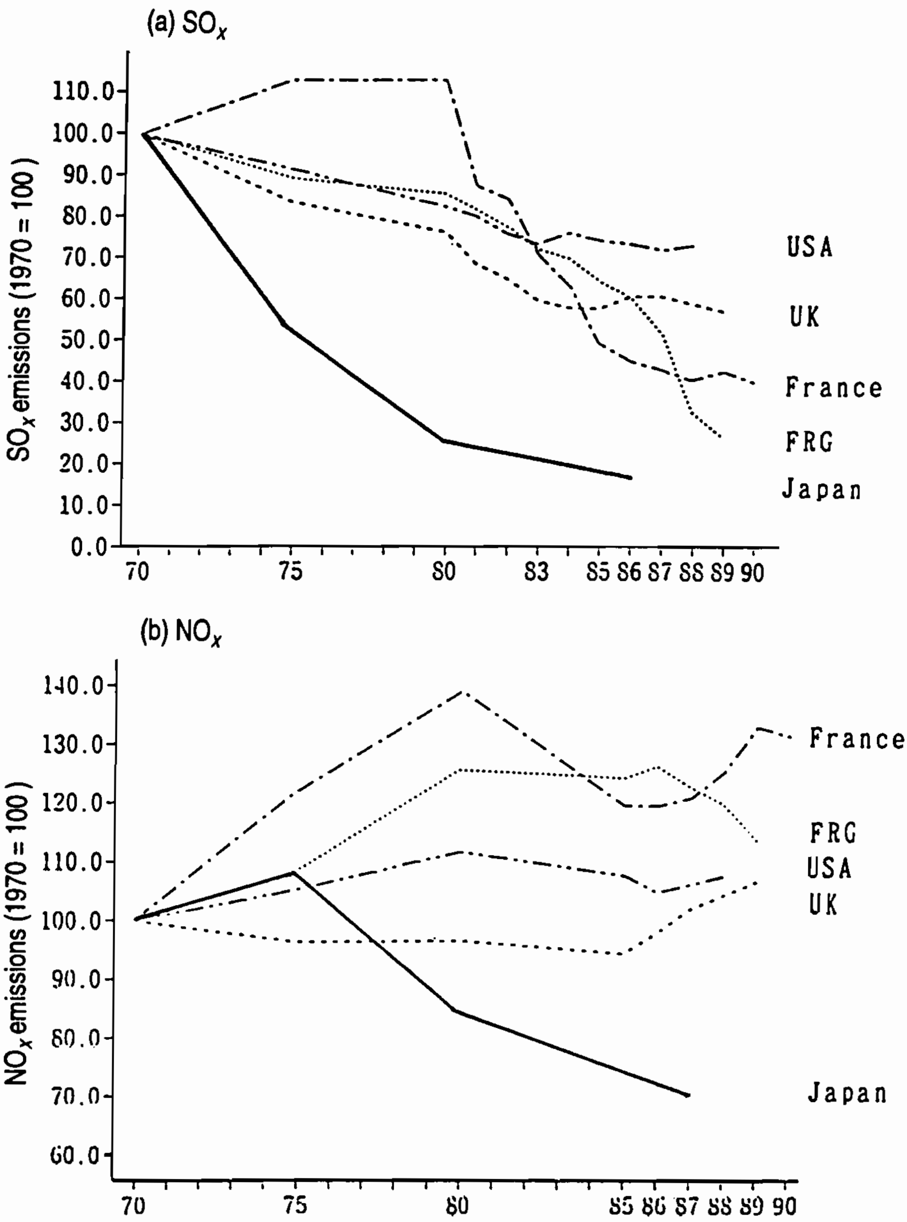



**Figure 1.** Comparison of trends in (a) $SO_x$ and (b) $NO_x$ emissions, 1970–1990. Index: 1970 = 100.

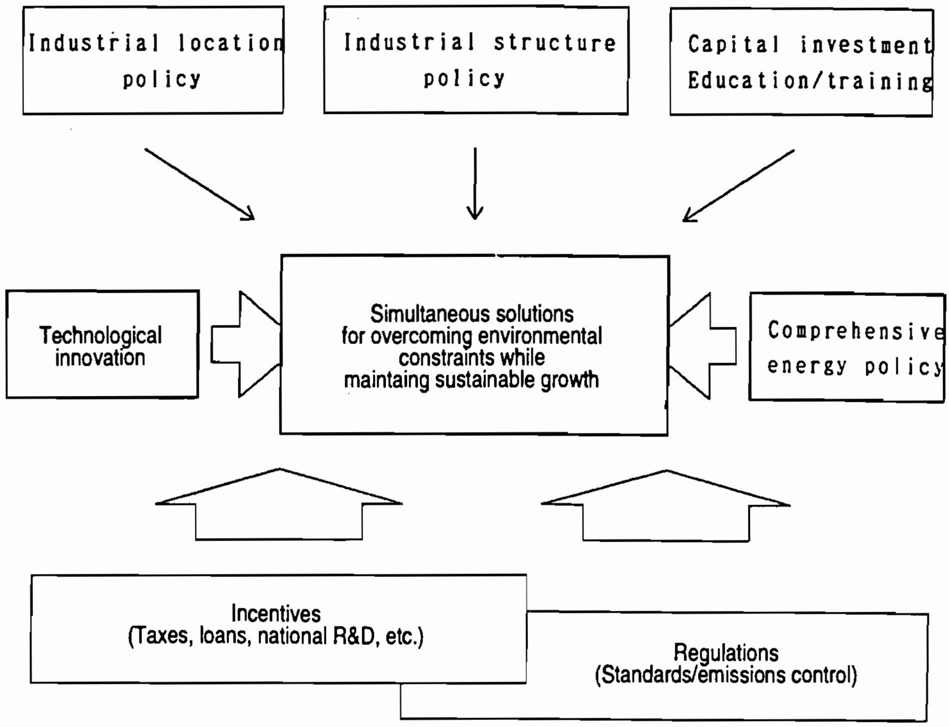



**Figure 2.** Japan's systems approach to overcome environmental constraints.

by one-sixth over 25 years. This can be attributed primarily to: (i) improvements in the quantity and quality of fuel consumption, including the development and introduction of direct heavy oil desulfurization facilities; (ii) the development and introduction of stack gas desulfurization facilities; and (iii) emissions control. Figures 4 and 5, which analyze the factors that contributed to such a dramatic reduction in $SO_x$ emissions over the period 1966–1990, indicate that before the 1973 energy crisis, 65% of the reduction in $SO_x$ discharges was due to a change in fuels; 30% to an increase in desulfurization capacity; 4% to energy conservation; and 1% to a change in the industrial structure. After the energy crisis, 40% was due to energy conservation; 38% to a change in fuels; 18% to an increase in desulfurization capacity; and 4% to a change in the industrial structure. The contribution of energy conservation became significant after the second energy crisis in 1979, representing 56% of the $SO_x$ reduction over the period 1979–1990. This analysis indicates that the dramatic reduction in $SO_x$ emissions after the energy crises was largely due to efforts to reduce Japan's energy dependency,

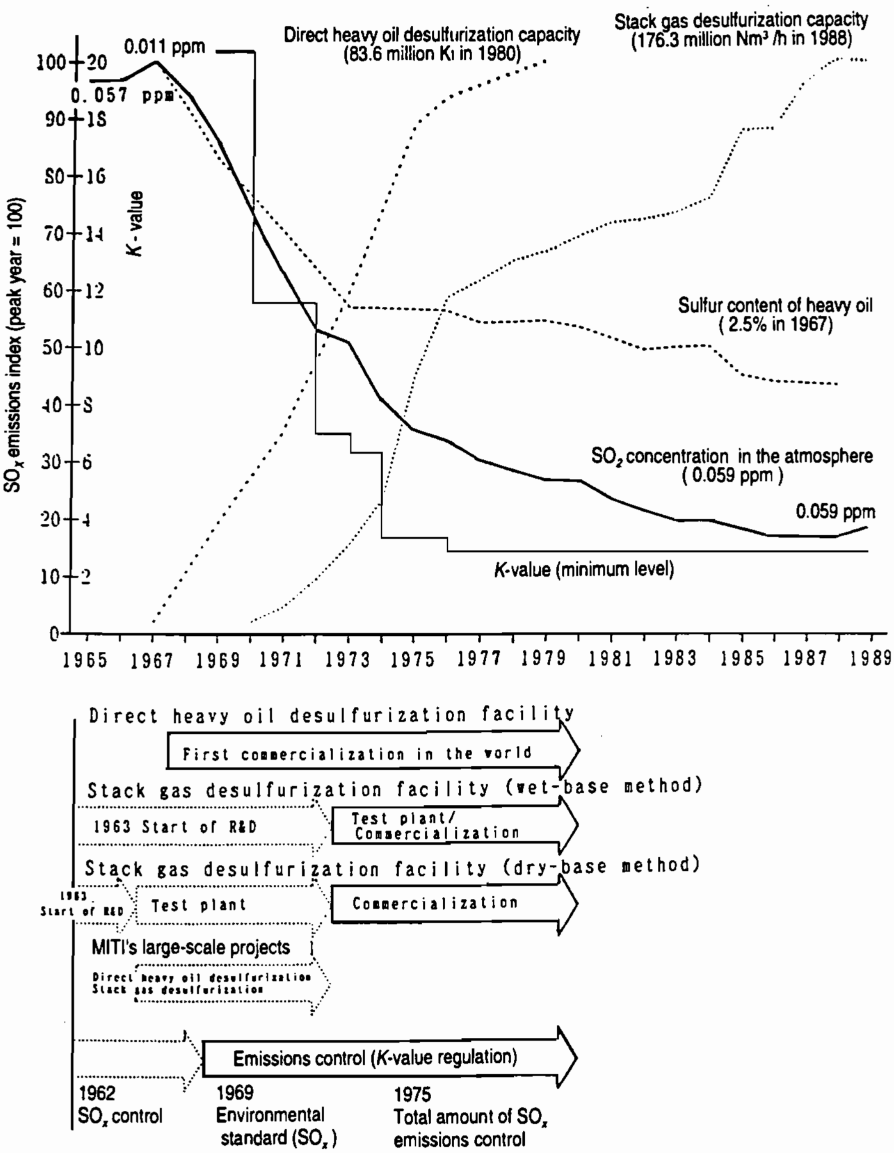
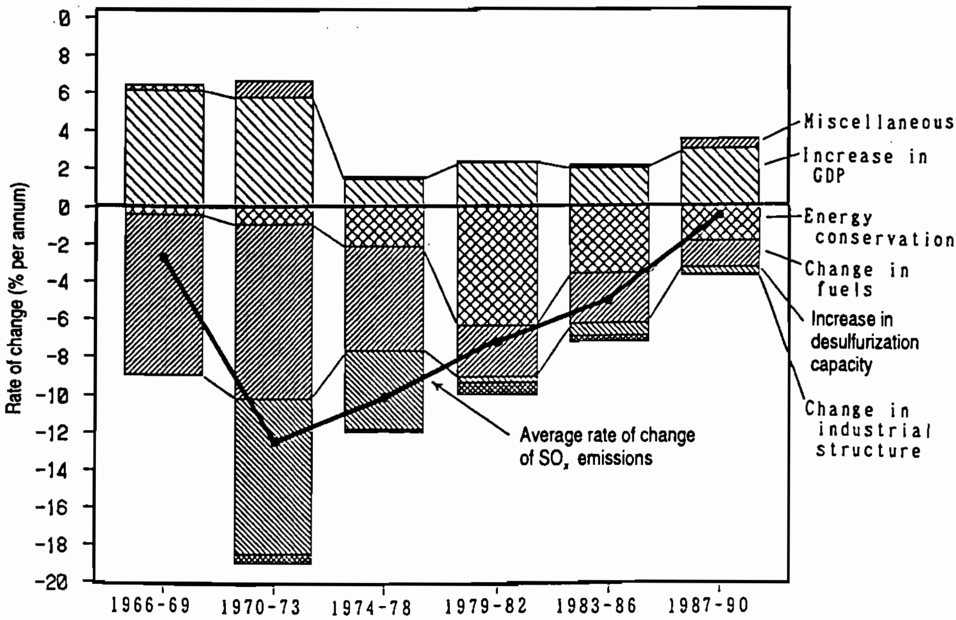



**Figure 3.** Trends in Japan's efforts to reduce $SO_x$ emissions (1965–1989). Figures in parentheses indicate peak levels.




a Magnitude of contribution is measured by the following equation (1965-1990):

$$\mathrm{Ln}\ SOx = \underset{(-23.42)}{14.99 - 0.24}\ \mathrm{Ln}\ DSF + \underset{(12.84)}{1.41}\ \mathrm{Ln}\ E/Y \qquad \text{adj. } R^2\ 0.99 \quad DW\ 1.24 \quad \text{------------------} \ ①$$

$$SOx = (SOx/E)*(E/Y)*(Y/V)*V$$

$$\mathrm{Ln}\ SOx = \mathrm{Ln}\ (SOx/E) + \mathrm{Ln}\ (E/Y) + \mathrm{Ln}\ (Y/V) + \mathrm{Ln}\ V \quad \text{------------} \ ②$$

$$(① + ②)/2$$

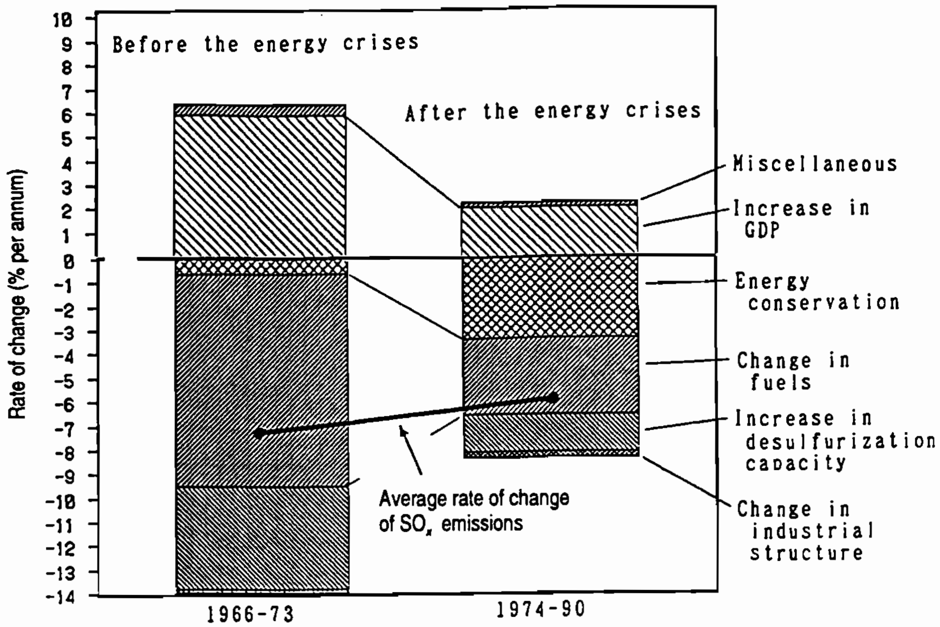
$$\mathrm{Ln}\ SOx = 7.49 + 0.50\mathrm{Ln}(SOx/E) + 1.20\ \mathrm{Ln}(E/Y) + 0.50\mathrm{Ln}(Y/V) - 0.12\mathrm{Ln}(DSF) + 0.50\mathrm{Ln}\ V$$

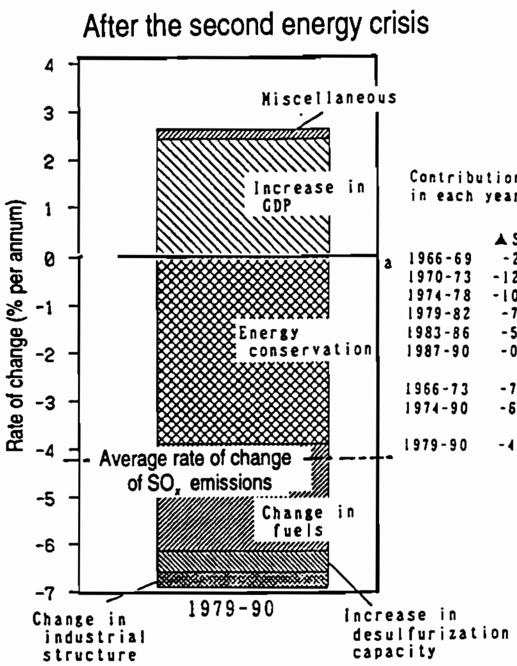
$$\blacktriangle SOx = \underset{\text{change in fuels}}{0.50\blacktriangle(SOX/E)} + \underset{\text{energy conservation}}{1.20\blacktriangle(E/Y)} + \underset{\text{change in ind. struct.}}{0.50\blacktriangle(Y/V)} - \underset{\text{desulf. capacity}}{0.12\blacktriangle(DSF)} + \underset{\text{change in prod.}}{0.50\blacktriangle V} + \underset{\text{misc.}}{\eta}$$

where E: energy, Y: production, V: value added (GDP), DSF: desulfurization capacity.

**Figure 4.** Factors contributing to the changes in $SO_x$ emissions in Japan, 1966–1990.

which in turn resulted in increased energy productivity. This demonstrates Japan's success in overcoming both energy and environmental constraints while maintaining sustainable development despite the damaging impact of the energy crises on energy supply.




Contribution of respective factors to reducing SOx emissions in each year is as folows (average change rate: %):

| | ▲SOx | ▲(SOX/E) | ▲(E/Y) | ▲(Y/V) | ▲(DSF) | ▲V | η |
|---|---|---|---|---|---|---|---|
| a 1966-69 | -2.51 | -8.56 | -0.35 | 0.26 | 0 | 6.14 | 0 |
| 1970-73 | -12.25 | -9.27 | -0.87 | -0.54 | -8.25 | 5.78 | 0.90 |
| 1974-78 | -10.44 | -5.55 | -2.08 | -0.15 | -4.20 | 1.37 | 0.17 |
| 1979-82 | -7.61 | -2.70 | -6.27 | -0.68 | -0.26 | 2.26 | 0.04 |
| 1983-86 | -5.08 | -2.66 | -3.57 | -0.26 | -0.68 | 1.96 | 0.13 |
| 1987-90 | -0.05 | -1.37 | -1.82 | -0.04 | -0.36 | 3.06 | 0.4S |
| 1966-73 | -7.38 | -8.91 | -0.61 | -0.14 | -4.13 | 5.96 | 0.45 |
| 1974-90 | -6.07 | -3.21 | -3.36 | -0.28 | -1.54 | 2.12 | 0.20 |
| 1979-90 | -4.25 | -2.24 | -3.89 | -0.33 | -0.43 | 2.43 | 0.21 |

**Figure 5.** Factors contributing to the changes in $SO_x$ emissions in Japan, 1966–1990.

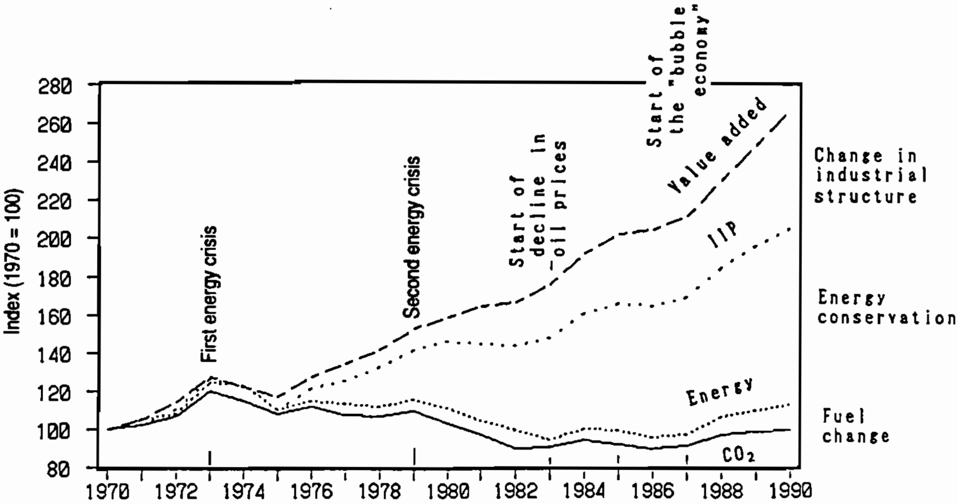



**Figure 6.** Trends in production, energy consumption and $CO_2$ discharges by Japanese manufacturing industry, 1970–1990. Index: 1970 = 100.

## 2.2. Improvement in energy efficiency

Figure 6 illustrates trends in production, energy consumption and $CO_2$ discharges by Japanese manufacturing industry over the period 1970–1990.[1] Industry was able to maintain steady development despite the damaging impacts of the energy crises on energy supply. However, despite increases in production, discharges of $CO_2$ were controlled at a relatively low level (Figure 7). Figure 8 analyzes the factors that contributed to the change in $CO_2$ discharges by manufacturing industry after the first energy crisis. While the average annual increase in production by value added between 1974–1990 was 4.55%, the average $CO_2$ discharges fell by 1.01%. Figure 8 indicates that this reduction in $CO_2$ discharges was largely due to efforts to reduce the dependence on energy (60% of this reduction can be attributed to efforts to improve energy efficiency). Indeed, Figures 9 and 10 demonstrate that Japan's efforts to reduce energy consumption after the 1973 energy crisis were more successful than those of other advanced countries. Such a dramatic improvement in energy efficiency was considered to be a response to the sharp increase in energy prices in 1973 (Watanabe *et al.*, 1991; Watanabe and Honda, 1991).

[1]Shares of Japan's $CO_2$ discharges in 1990 were as follows (including $CO_2$ in the power generation process): industry 47.6% (manufacturing industry 43.1%); residential and commercial 22.6 %; transportation 18.5 %; and others 11.3 %.

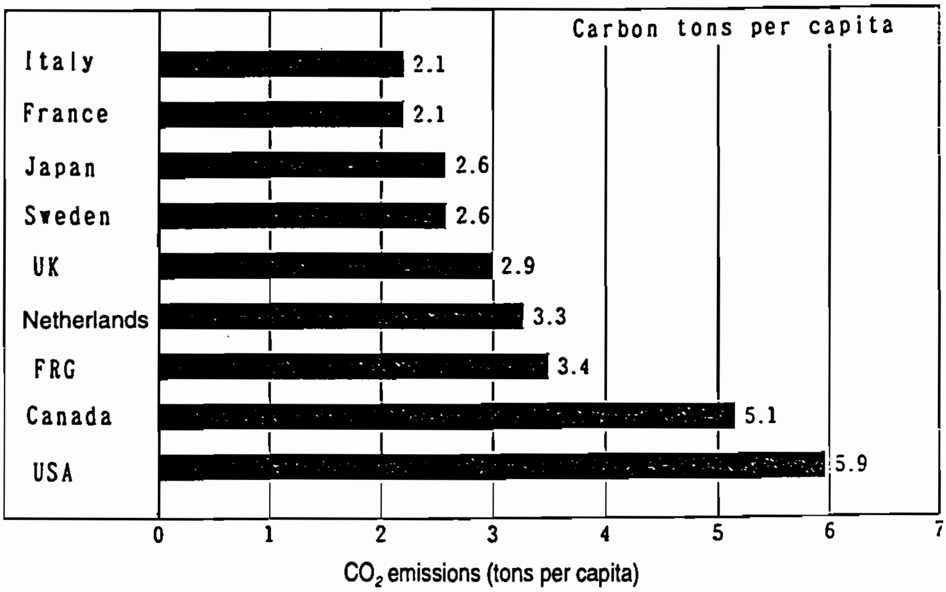


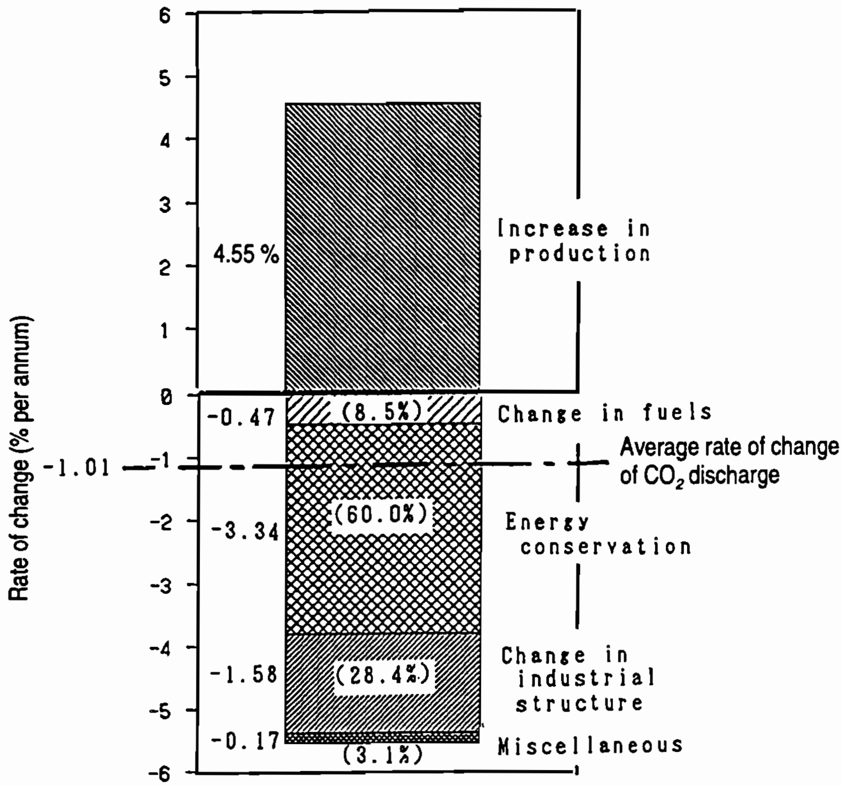

**Figure 7.** $CO_2$ emissions per capita in OECD countries, 1990.

## 2.3. Substitution of technology for energy

In order to identify the factors that contributed to this dramatic improvement in energy efficiency, I analyzed the contribution of technology, which is largely independent of the constraints of energy price increases. Table 1 compares correlations between energy efficiency improvements and (a) prices of energy, (b) autonomous energy efficiency improvements by autonomous productivity increases (AEEI), and (c) technology stock (endogenous technological change). Table 1 suggests that the contribution of technology stock to the improvement in energy efficiency was almost equivalent to the contribution of AEEI and more significant than that of energy prices.

The foregoing analysis suggests that endogenous technological change by means of an increase in technology stock made a great contribution to the improvement in energy efficiency in Japan's manufacturing industry after the energy crises.

Under the circumstances of a "constrained economy", it is generally pointed out that the majority of efforts to overcome constraints have been directed toward the substitution of a constrained (or limited) production factor by unlimited production factors (Christensen *et al.*, 1973). This is similar to an ecosystem in that, in order to maintain homeostasis (checks and balances that dampen oscillations), when one species slows down, another




a Figures in parentheses indicate shares of contribution to reducing $CO_2$ discharge.

b Magnitude of contribution is measured by the following equation:

$C = C/E \cdot E/I \cdot (V/I)^{-1} \cdot V$ where C: $CO_2$, E: Energy, I: IIP (production weight) and V: Value added.

$$\blacktriangle C/C = \underbrace{\blacktriangle (C/E)/(C/E)}_{\text{change in fuels}} + \underbrace{\blacktriangle (E/I)/(E/I)}_{\text{energy conservation}} - \underbrace{\blacktriangle (V/I)/(V/I)}_{\text{change in industrial structure}} + \underbrace{\blacktriangle V/V}_{\text{change in production}} + \eta$$

**Figure 8.** Factors contributing to the changes in $CO_2$ discharges by Japanese manufacturing industry, 1974–1990.

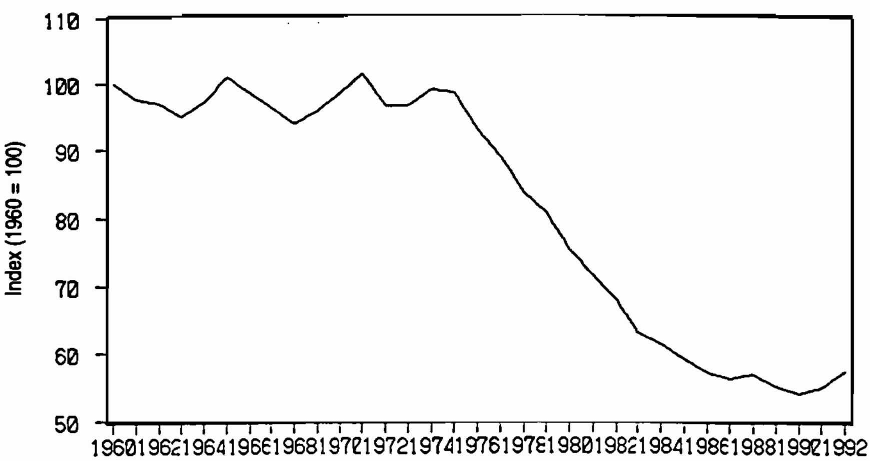



**Figure 9.** Trends in unit energy consumption in Japanese manufacturing industry, 1960–1992. Index: 1960 = 100. Unit energy consumption: energy consumption per *IIP* (production weight).

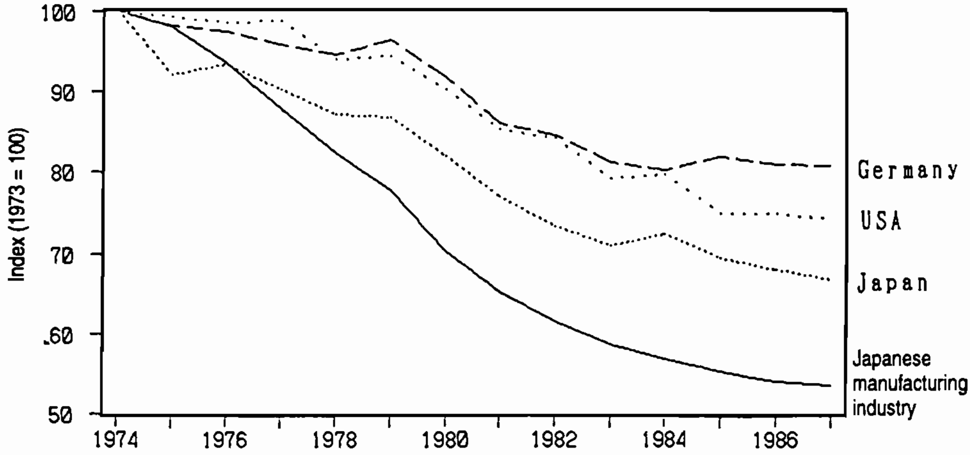



**Figure 10.** Trends in unit energy consumption in Japan, the USA, and Germany, 1974–1987. Index: 1973 = 100. Unit energy consumption, national level: energy consumption per unit GNP; manufacturing industry: energy consumption per unit value added.

speeds up in a compensatory manner in a closed system (substitution), while depending on supplies from an external system leads to a dampening of

**Table 1.** The contributions to energy productivity (*E/IIP*) improvements by autonomous energy efficiency improvements (*AEEI*) and technology stock (*T*) in Japanese manufacturing industry, 1974–1988.

AEEI

| | adj. $R^2$ | DW |
|---|---|---|
| $\ln E/IIP = 81.24 - 0.04\, t - 0.13 \ln Pe$ <br> $(-16.74) \quad (-2.68)$ | 0.984 | 1.24 |

Technology stock

| | adj. $R^2$ | DW |
|---|---|---|
| $\ln E/IIP = 3.52 - 0.50 \ln T - 0.14 \ln Pe$ <br> $(-12.19) \quad (-2.23)$ | 0.971 | 1.05 |

where t: time trend, and Pe: energy prices.

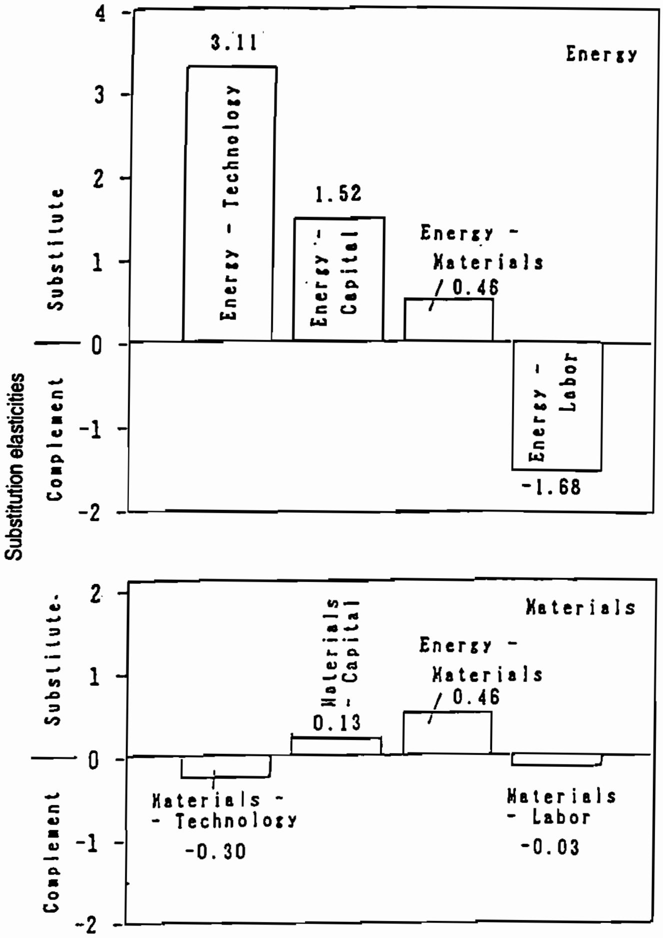
a Technology stock (T) is measured by the following equation:

$$T_t = R_{t-m} + (1-\rho)T_{t-1}$$

where $R_{t-m}$: R&D expenditure in the period $t-m$, $m$: time lag of R&D to commercialization, and $\rho$: rate of obsolescence of technology.

homeostasis (complement) (Odum, 1963). This concept of "substitution" provides informative suggestions for a "constrained economy".

In the case of Japan the constrained production factor is energy, while technology is the unlimited production factor. Figure 11 illustrates the extent of the substitution of energy by other production factors in Japanese manufacturing industry over the last two decades. In order to overcome sharply increased energy constraints due to the energy crises, while at the same time maintaining sustainable development, intensive efforts were made to substitute technology for energy (such as energy conservation and oil replacing energy technologies, and energy efficiency improvements), followed




a Substitution elasticities are measured based on the following price functions

$$
\begin{array}{llllll}
M_l = 0.1471 & + 0.0996\ln P_l & + 0.0091\ln P_k & - 0.0892\ln P_m & - 0.0277\ln P_e & + 0.0082\ln P_t \\
\quad (98.15) & (12.86) & (1.71) & (-10.30) & (-6.97) & (6.87)
\end{array}
$$

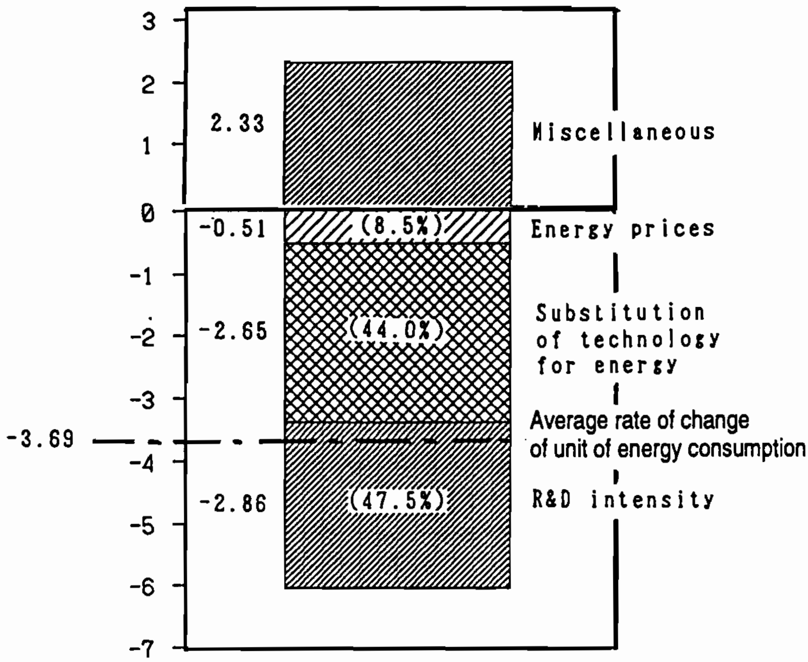
$$
\begin{array}{llllll}
M_k = 0.1591 & + 0.0091\ln P_l & + 0.0723\ln P_k & - 0.0837\ln P_m & + 0.0058\ln P_e & - 0.0035\ln P_t \\
\quad (34.84) & (1.71) & (7.72) & (-7.93) & (1.16) & (-2.47)
\end{array}
$$

$$
\begin{array}{llllll}
M_m = 0.5952 & - 0.0892\ln P_l & - 0.0837\ln P_k & + 0.2093\ln P_m & - 0.0260\ln P_e & - 0.0104\ln P_t \\
\quad (234.24) & (-10.30) & (-7.93) & (12.14) & (-5.62) & (-6.73)
\end{array}
$$

$$
\begin{array}{llllll}
M_e = 0.0831 & - 0.0277\ln P_l & + 0.0058\ln P_k & - 0.0260\ln P_m & + 0.0455\ln P_e & + 0.0023\ln P_t \\
\quad (27.97) & (-6.97) & (1.16) & (-5.62) & (12.59) & (2.78)
\end{array}
$$

$$
\begin{array}{llllll}
M_t = 0.0156 & + 0.0082\ln P_l & - 0.0035\ln P_k & - 0.0104\ln P_m & + 0.0023\ln P_e & + 0.0033\ln P_t \\
\quad (23.96) & (6.87) & (-2.47) & (-6.73) & (2.78) & (5.31)
\end{array}
$$

**Figure 11.** Average substitution elasticities of (a) energy and (b) materials in Japanese manufacturing industry, 1974–1987. Source: Watanabe, 1992a, 1992b, 1992c.




a Magnitude of contribution is measured by the following equation:

$$\sigma te = (Bte + Mt \cdot Me)/(Mt \cdot Me) = 1 + Bte(GC/GTC)(GC/GEC)$$
$$\sigma te - 1 = Bte(GC/R)(GC/E \cdot Pe) = Bte(S/R)(GC/S)(IIP/E)(GC/IIP)(1/Pe)$$
$$E/IIP = Bte \cdot (\sigma te - 1)^{-1}(R/S)^{-1}(PE)^{-1}(GC/IIP)(GC/S)$$
$$\ln E/IIP = \ln Bte - \ln(\sigma te - 1) - \ln R/S - \ln Pe + \ln (GC/IIP)(GC/S)$$
$$\blacktriangle E/IIP = -\blacktriangle(\sigma te - 1) - \blacktriangle R/S - \blacktriangle Pe + \eta$$

where $\sigma te$: substitution of technology for energy; Bte: coefficient; Mt and Me: cost share of technology and energy respectively; GC: gross cost; GTC: gross technology cost; GEC: gross energy cost; R: R&D expenditure (= gross technology cost); E: energy consumption; Pe: prices of energy; S: sales; IIP: index of industrial production ; $\eta$ : miscellaneous.

b Contribution of respective factors to reducing unit energy consumption is as follows (average change rate: %):
$\blacktriangle$E/IIP (unit energy consumption): -3.69
$\blacktriangle(\sigma te - 1)$ (substitution of technology for energy): -2.65
$\blacktriangle$R/S (R&D intensity): -2.86
$\blacktriangle$Pe (energy prices): -0.51
$\eta$ (miscellaneou)s: 2.33
(a years of 1980 is not included because of inconsistently drastic change due to the 2nd energy crisis in 1979).

**Figure 12.** Factors contributing to the changes in unit energy consumption in Japanese manufacturing industry, 1976–1990.

by efforts to substitute capital for energy (typically energy conservation investments). The substitution of energy by other production factors (chiefly technology and capital) was more effective than the substitution of materials by other production factors. This analysis suggests that the Japanese economy was able to sustain its development in the face of sharply increased energy supply constraints by substituting technology for energy. This substitution has in turn resulted in a dramatic improvement in Japan's technological level as a whole (MITI, 1988; Watanabe, 1992a, 1992b, 1992c).[2]

In order to demonstrate the contribution of technology substitution for energy to the dramatic improvement in energy productivity in Japan's manufacturing industry, I analyzed the factors contributing to the change in unit energy consumption over the period 1976–1990 (see Figure 12). The analysis indicates that 44% of the reduction in unit energy consumption can be attributed to the substitution of technology for energy, and the remainder to R&D intensity (47.5%) and energy price increases (8.5%). This supports the analysis in Table 1 and demonstrates the hypothesis that technology made a significant contribution to the dramatic improvement in energy productivity in Japanese manufacturing industry.

## 3. MITI's Efforts to Induce the Substitution of Technology for Energy

### 3.1. MITI's energy R&D policy

Japan has adopted different industrial policies in different stages in its economic development, and these policies have reflected the international, natural, social, cultural and historical environment of the postwar period (Watanabe, 1990). In the late 1940s and 1950s, Japan made every effort to reconstruct its war-ravaged economy and to lay the foundation for viable economic growth. During the 1960s, Japan actively sought to open its economy to foreign competition by liberalizing trade and the flow of international capital.

[2] In a previous analysis of trends in the substitution of production factors by technology in Japanese manufacturing industry over the last 20 years, the following conclusions were drawn (Watanabe, 1992a, 1992b, 1992c). Triggered by the sharp increase in energy prices due to the two energy crises, (i) energy has been substituted by technology and also, to some extent, by capital; (ii) the sharp increase in energy prices resulted in an increase in labor prices, which induced the substitution of labor by technology; (iii) although capital and materials have been complementary to technology, they have been shifting toward substitution by technology; thus (iv) all production factors, directly or indirectly, have been substituted by technology or have been shifting in that direction.

In the process, it achieved rapid economic growth led by the chemicals and other heavy industries. On the other hand, the concentration of such highly material-intensive and energy-intensive industries and population in Japan's Pacific belt area led to serious environmental pollution problems (Ogawa, 1991). This necessitated a reexamination of industrial policy (MITI, 1972a, 1972b).

Recognizing the need for a change in direction, MITI formulated a new industrial development plan, *MITI's Vision for the 1970s* (Industrial Structure Council of MITI, 1971), which proposed a shift to a knowledge-intensive industrial structure that would reduce the burden on the environment by depending less on energy and materials while depending more on technology.[3]

In order to identify the required basic concept of industry and the industrial technology policies that would contribute to the establishment of the industrial structure proposed in its vision, in May 1971 MITI set up a research group consisting of experts from ecology-related disciplines to define an ecological science for studying the global environment (MITI, 1972b). This research group proposed the concept of "Industry-Ecology" as a comprehensive method for analyzing and evaluating the complex mutual relations between human activities, particularly industry, and the environment.

On the basis of its extensive research work, in 1973 MITI outlined a new policy principle to be applied to its industrial policy as well as a new policy system based on the principle. Efforts were directed to further develop R&D programs to contribute to recovering the ideal equilibrium of the ecosystem by creating an environmentally friendly energy system (MITI, 1970–1990).

The first energy crisis occurred a few months later, which urged the reduction of redundancy by taking ecological considerations into account. The majority of MITI's efforts focused on securing energy supplies in the face of a dramatic increase in oil prices. Given such circumstances, a new policy was initiated based on the Basic Principle of Industry-Ecology aiming at securing a solution to basic energy problems by means of R&D on new and clean energy technologies. This policy led to the establishment of a new program, the Sunshine Project (R&D on New Energy Technology), which was initiated in July 1974.

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[3]In order to establish a knowledge-intensive industrial structure, the plan stressed the significant role of innovative R&D that would reduce Japan's dependency on materials and energy in the process of production and consumption. It also stressed that such reduced dependency could be achieved by means of intensive conservation and recycling of resources (materials and energy) in a long-term, global, and *ecological* context, and that R&D aiming to develop "limit-free energy technology" (technology-driven clean energy) was required.

The Basic Principle of Industry-Ecology suggests that substitution among available production factors in a closed system should be the basic way to achieve sustainable development under certain constraints (Odum, 1963). The Sunshine Project initiated this approach by enabling substitution of technology-driven energy which has unlimited potential, for limited energy sources, chiefly oil. Further substitution efforts should be made not only in the energy supply field but also in the field of energy consumption. Improved energy efficiency by means of technological innovation would reduce dependency on energy, and this process is simply the substitution of technology for energy. In line with this policy consideration, the Moonlight Project (R&D on Energy Conservation Technology) was initiated in 1978 (MITI, 1970–1990).

The second energy crisis occurred in 1979, and MITI was able to implement policies capable of enhancing industrial vitality for sustainable development in the face of the damaging impact of the energy crises by means of the substitution of an unlimited resource, technology, for a limited resource, energy.[4]

MITI's budget for the Sunshine and Moonlight Projects represented 14% of MITI's total R&D budget in 1979, and this increased to 29% in 1982, compared with only 5% in 1974. Table 2 summarizes Japan's R&D expenditures on energy technologies in 1990. As can been seen, out of the nation's total energy R&D expenditures of ¥ 915 billion, MITI expended ¥ 130 billion (14.2% of the total).[5] Of this, ¥ 51 billion was used for the Sunshine and Moonlight Projects, and ¥ 79 billion was used for coal, oil and gas, electric power and nuclear R&D.

## 3.2. Stimulation of industry's energy R&D

MITI's efforts to stimulate the substitution of technology for energy and also for limited energy sources encouraged industry also to invest in energy

[4]The mechanism of MITI's policy for such an inducement can be summarized as follows (Watanabe and Honda, 1991): (i) penetration and identification of future prospects and strategic areas; (ii) formulation and publication of visions; (iii) provision of policy measures to stimulate substitution in order to induce industries to increase their R&D intensity; (iv) identification of the potential for further technological development increases as the degree of R&D intensity increases; (v) raising expectations on the outcome of technological development among industries; (vi) inducing further investment in R&D activities; and (vii) building up dynamism conducive to technological development.

[5]MITI's energy R&D can be categorized as follows: Unconstrained energy resources: energy conservation, hydrogen, solar, ocean, coal conversion, coal, nuclear. Constrained renewable energy resources: geothermal, wind, biomass, hydro. Constrained conventional energy resources: oil and gas.

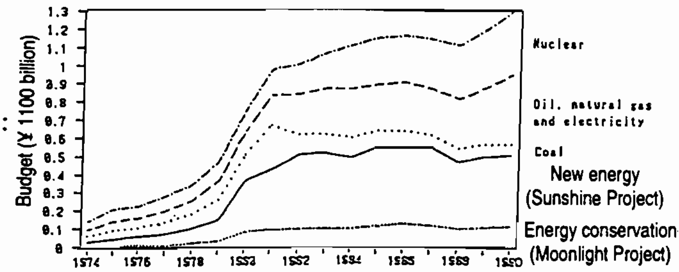
**Table 2.** R&D expenditures on energy and environmental technologies in Japan, 1990 (¥ 100 million).

| | Ind. (Manf. Ind.) | Research Inst.[a] | University | Total |
|---|---|---|---|---|
| Energy Technology | 3492 (2819) | 5241 | 417 | 9150 |
| Nuclear | 827 ( 660) | 2922 | 272 | 4021 |
| Non-Nuclear | 2665 (2159) | 2319 | 145 | 5129 |
| Energy Conserv. | 1882 (1693) | 1754 | 66 | 3702 |
| Renewable | 145 ( 120) | 86 | 52 | 283 |
| Coal | 172 ( 117) | 185 | 8 | 365 |
| Oil & Gas | 294 ( 177) | 198 | 10 | 502 |
| Electric Power | 172 ( 52) | 96 | 9 | 277 |
| Environmental Tech. | 1428 (1360) | | | |

a Research institutions are those organizations established by central or local governments or by private organizations which perform R&D.

b Total R&D expenditure in 1990 (natural sciences): 11993.5 billion yen (industry 9267.2; research institutions 1401.2; universities 1325.2).

c Trends in MITI's energy R&D budget are as follows (100 bill. yen at current prices):




MITI's Energy R&D (SSML+nSM) 1299

Manufacturing Industry's Energy R&D (ERT) 2819

SSML 512
- Moonlight(ML) 116 — Energy Conservation (ML) 116
- Sunshine (SS) 396
  - Hydrogen (SSH) 1
  - Renewable
    - Solar (SSS) 74
    - Geothermal(SSG) 54
    - Wind/Ocean(SSO) 18
  - Coal Conversion (SSC) 249

nSM 787 Coal/Oil/Nucl/Elc.
- Coal (MC) 66
- Oil/Gas (MOG) 256
- Electric Power (ME) 119
- Nuclear (MN) 346

Conservation (ERS) 1693
Renewable (ERR) 120
Coal (ERC) 117
Oil and Gas (EROG) 177
Electr. Power (ERE) 52
Nuclear (ERN) 660

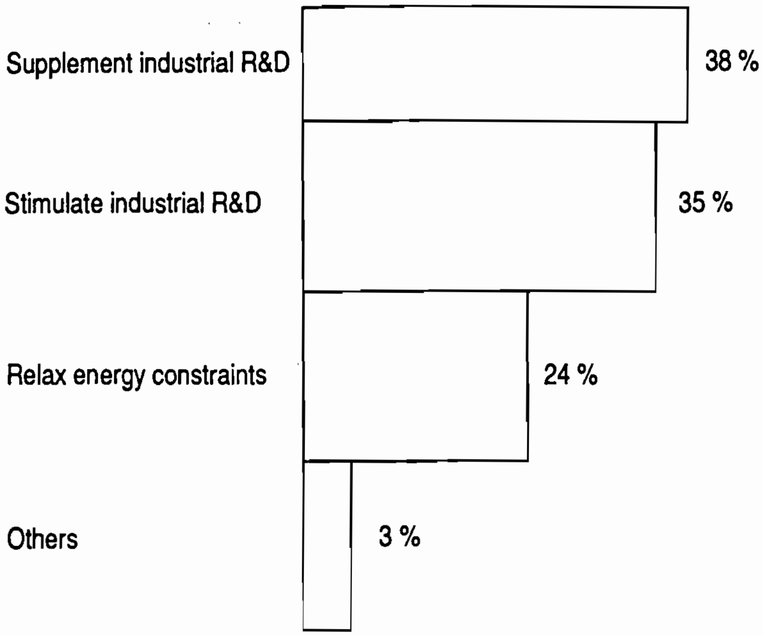



**Figure 13.** Expectations of MITI's energy R&D (based on a questionnaire survey of 54 manufacturing firms involved in MITI's energy R&D program; AIST of MITI, June 1993).

R&D. Figure 13 summarizes the outcome of a survey of the expectations of manufacturing firms involved in MITI's energy R&D program projects. In addition to supplementing industry's own R&D activities, a significant number of firms expressed the strong expectation that such projects would stimulate industrial R&D in relevant fields.

Table 3 summarizes the results of an analysis of correlations between MITI's energy R&D expenditures and those initiated by Japanese manufacturing industry. From Table 3 we can observe strong correlations between the R&D efforts of industry and MITI with respect to energy conservation, renewable energy and coal technologies led by both the Moonlight and Sunshine Projects, while those with respect to constrained conventional energy resources technologies such as oil and gas R&D are relatively weaker. This analysis demonstrates that MITI's Sunshine and Moonlight Projects have functioned well as means of inducing industry to initiate related R&D activities. Table 4 summarizes the outcomes of an analysis of the inducing impacts of MITI's R&D. From Table 4 we can observe strong correlations

**Table 3.** Inducing impacts of MITI's energy R&D expenditures and those initiated by Japanese manufacturing industry, 1976–1990.

| | adj. $R^2$ | DW | D |
|---|---|---|---|
| **Energy R&D Total** | | | |
| $\ln(ERT) = 3.43 + 0.45 \ln(SSML) + 0.24 \ln(nSM) - 0.65\,D$ | 0.978 | 0.96 | 1976 = 1 |
| $\qquad\qquad\qquad (4.21) \qquad\qquad (1.31) \qquad\qquad (-5.67)$ | | | |
| **Energy Conservation** | | | |
| $\ln(ERS) = 3.84 + 0.72 \ln(ML+SSH) - 1.43\,D$ | 0.975 | 1.28 | 1976 = 1 |
| $\qquad\qquad\qquad (12.82) \qquad\qquad (-8.36)$ | | | |
| **Renewable Energy** | | | |
| $\ln(ERR) = 0.09 + 0.98 \ln(SSS+SSG+SSO)$ | 0.957 | 1.75 | |
| $\qquad\qquad\qquad (17.59)$ | | | |
| **Coal** | | | |
| $\ln(ERC) = -5.86 + 0.50 \ln(SSC) + 1.13 \ln(MC)$ | 0.972 | 2.18 | |
| $\qquad\qquad\qquad (18.07) \qquad\qquad (12.06)$ | | | |
| **Oil and Gas** | | | |
| $\ln(EROG) = 0.46 + 0.92 \ln(MOG) - 1.01\,D$ | 0.780 | 0.95 | 1976 = 1 |
| $\qquad\qquad\qquad (4.41) \qquad\qquad (-2.24)$ | | | |
| **Nuclear** | | | |
| $\ln(ERN) = 3.17 + 0.56 \ln(MN)$ | 0.848 | 2.16 | |
| $\qquad\qquad\qquad (8.88)$ | | | |
| **Electric Power** | | | |
| $\ln(ERE) = -2.59 + 1.53 \ln(ME) + 1.34\,D$ | 0.870 | 1.07 | 1979 = 1 |
| $\qquad\qquad\qquad (9.76) \qquad\qquad (2.54)$ | | | |

between (i) MITI's energy and non-energy R&D and manufacturing industry's R&D intensity (adjusted $R^2 = 0.977$); (ii) MITI's energy R&D and energy prices and manufacturing industry's substitution of technology for energy (adjusted $R^2 = 0.945$); and (iii) MITI's energy R&D and manufacturing industry's technology stock of energy R&D (adjusted $R^2 = 0.998$). This analysis demonstrates the significant impact of MITI's R&D on R&D

**Table 4.** Inducing impacts of MITI's R&D on R&D intensity, substitution of technology for energy, and technology stock on energy R&D initiated by Japanese manufacturing industry.

1. Structure of MITI's R&D Budget in 1990
   (100 million yen in current price)

MITI's R&D (MRD) 2498.3
- Energy R&D (MER) 1299.3
  - New Energy (SS) 395.9
  - Ene. Conserv.(ML) 116.0
  - Other Energy (nSM)787.4
- non Energy R&D (NER) 1199.0

2. R&D Intensity (1979-1990)

$$\ln R/S = -2.07 + \underset{\substack{(15.1)\\ \text{MITI's energy R\&D}}}{0.28\ \text{Lag5}\ (\ln MER)} + \underset{\substack{(2.0)\\ \text{MITI's non energy R\&D}}}{0.08\ \text{Lag2}\ (\ln NER)}$$

adj. $R^2$ 0.977 DW 1.98

3. Substitution of Technology for Energy (1977-1990)

$$\underset{\text{Internal Substitution Factors}}{\ln[(\sigma-1)Pe]} = 5.14 + \underset{\substack{(15.6)\\ \text{MITI's energy R\&D}}}{0.19\ \ln MER}$$

adj. $R^2$ 0.945 DW 1.28

$$(\sigma-1) = Bte(GC/R)(GC/E\cdot Pe)$$ (see footnote of Fig. 12)

4. Technology Stock of Energy R&D (1978-1990)

$$\ln TE = 3.07 + \underset{\substack{(5.6)\\ \text{New energy}}}{0.12\text{Lag4}(\ln SS)} + \underset{\substack{(10.5)\\ \text{Energy conserv.}}}{0.34\text{Lag2}(\ln ML)} + \underset{\substack{(2.4)\\ \text{Other energy}}}{0.25\text{Lag2}(\ln nSM)} + \underset{\substack{(6.5)\\ \text{Dummy}\\ (1981,90=1)}}{0.13D}$$

adj. $R^2$ 0.998 DW 2.29

$$\ln TE = 0.11 + \underset{(41.8)}{0.98\ \text{Lag2}(\ln MER)} + \underset{\substack{(4.6)\\ 81,\ 90=1}}{0.14D}$$

adj. $R^2$ 0.993 DW 1.72

$$TE_t = (\Sigma\ ERS,\ ERR,\ ERC,\ EROC,\ ERN,\ ERE)_{t-m} + (1-\rho)TE_{t-1}$$

intensity, the substitution of technology for energy, and the technology stock of energy R&D initiated by Japan's manufacturing industry.

# 4. The Prospect of Energy and Environmental Constraints

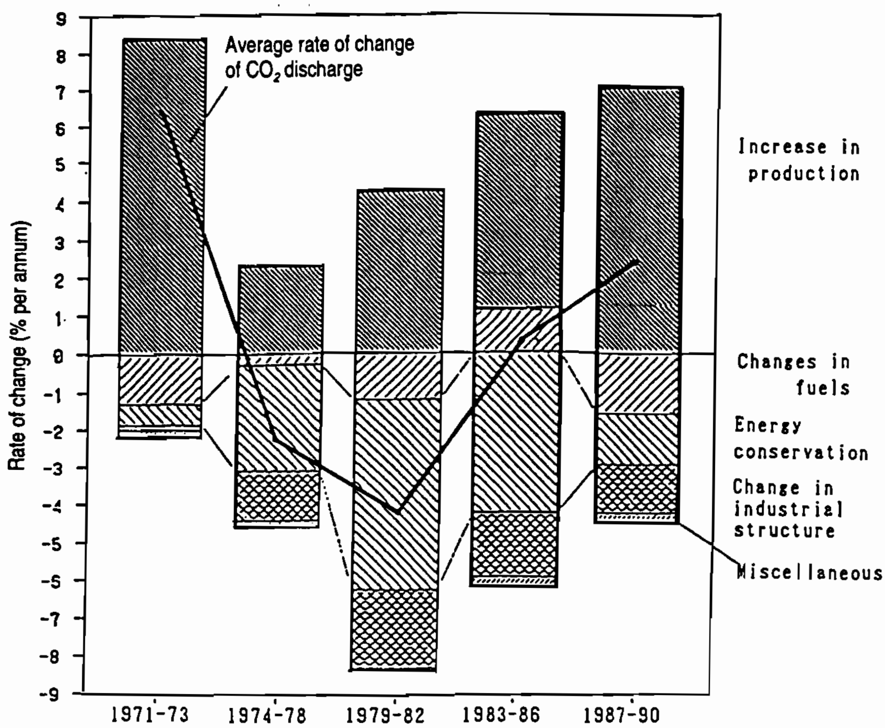
## 4.1. Factors contributing to changes in energy and environmental constraints

Figure 14 analyzes the factors that contributed to changes in production, energy consumption, and $CO_2$ discharges by Japanese manufacturing industry over the period 1970–1990. Looking at the trend of $CO_2$ discharges and the contributing factors in each time period, we find that the $CO_2$ discharge level fell dramatically after the first energy crisis in 1973, in line with an increase in energy conservation efforts. This was largely the result of the substitution of technology (energy conservation technology) and capital (energy conservation facility) for energy (see Figure 11), while the contribution of a fuel change (which also represents the outcomes of similar substitutions involving oil alternative technologies and capital investment) is less significant. This is considered to be due to the increased dependency on coal as a promising alternative to oil. Figure 14 shows that $CO_2$ discharges began to increase again after 1983 (when international oil prices began to fall) due to the increased use of coal and reduced energy conservation efforts. The reduction in energy conservation efforts after 1987, the year of the start of Japan's so-called "bubble economy" (Figure 15), resulted in an increase in $CO_2$ discharges (Figure 16), and a decrease in marginal energy productivity, as illustrated in Figure 17. Figure 12 suggests that such a decrease in energy conservation efforts was due primarily to decreases in the R&D intensity and the substitution of technology for energy (which can be attributed to the technology stock of energy R&D).[6]

The R&D intensity has a strong correlation with the share of R&D investment in total investment with a one to two year time-lag, and considering the decreasing trend in R&D investment share of total investment in the period of the "bubble economy" (Watanabe, 1992a, 1992b, 1992c) as

[6] The contribution to a decrease in dependency on energy in Japanese manufacturing industry over the period 1971–1990 can be identified by the following correlations:

$$\text{Ln } E/IIP = 0.968 - \underset{(-5.61)}{0.325} \text{ Ln } R/S - \underset{(-15.92)}{0.199} \text{ Ln } TE. \qquad \text{adj. } R^2\ 0.987 \text{ DW } 1.09$$




a Magnitude of contribution is measured by the following equation:

$C = C/E \cdot E/I \cdot (V/I)^{-1} \cdot V$ where C: $CO_2$, E: Energy, I: IIP (production weight) and V: Value added.

$$\blacktriangle C/C = \underbrace{\blacktriangle(C/E)/(C/E)}_{\text{change in fuels}} + \underbrace{\blacktriangle(E/I)/(E/I)}_{\text{energy conservation}} - \underbrace{\blacktriangle(V/I)/(V/I)}_{\text{change in industrial structure}} + \underbrace{\blacktriangle V/V}_{\text{change in production}} + \eta$$

b Shares of contribution to reducing $CO_2$ discharge in each period are as follows:

| | 1971-1990 | 1971-73 | 1974-78 | 1979-82 | 1983-86 | 1987-90 |
|---|---|---|---|---|---|---|
| Energy conservation | 58 | 27 | 61 | 61 | 83 | 30 |
| Change in ind. struc. | 27 | 6 | 29 | 24 | 33 | 30 |
| Change in fuels | 12 | 60 | 6 | 14 | -21 | 35 |
| Miscellaneous | 3 | 7 | 4 | 1 | 5 | 5 |
| Total | 100% | 100% | 100% | 100% | 100% | 100% |

**Figure 14.** Factors contributing to changes in $CO_2$ discharges by the Japanese manufacturing industry, 1971–1990.

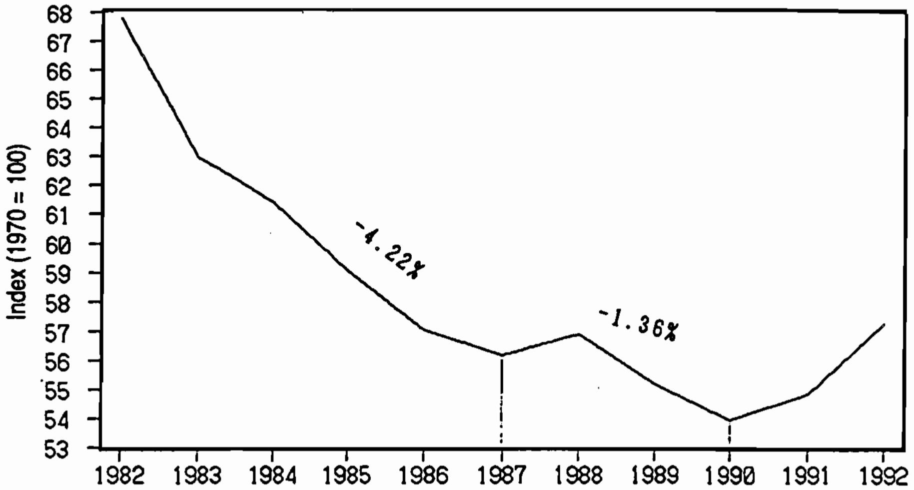



**Figure 15.** Trends in unit energy consumption (*E/IIP*) by Japanese manufacturing industry, 1982–1992. Index: 1970 = 100.

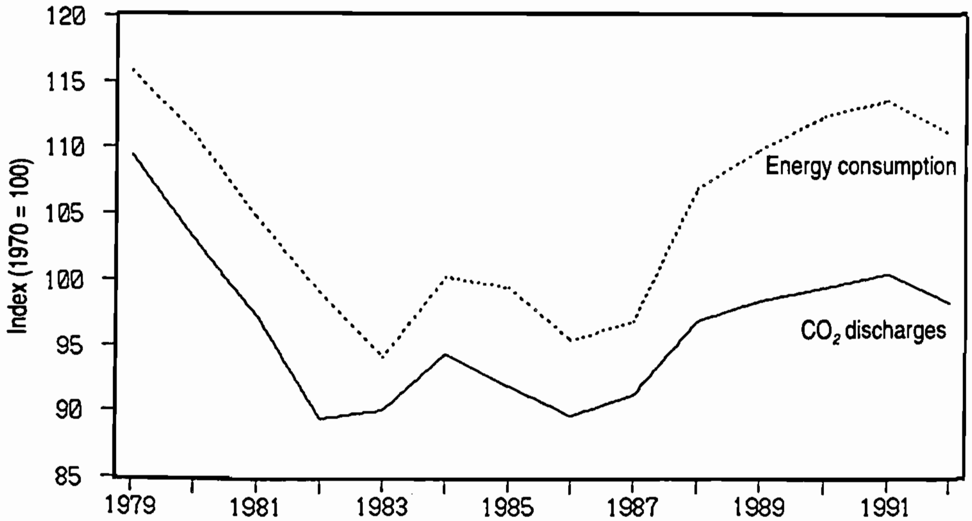



**Figure 16.** Trends in energy consumption and $CO_2$ discharges by Japanese manufacturing industry, 1979–1992. Index: 1970 = 100.

illustrated in Figure 18, it is strongly feared that R&D intensity may decrease further due to the bursting of the "bubble economy" (since 1991) and the consequent economic stagnation. Such a decrease in R&D intensity may have had significant impacts on the "quality" of R&D activities.

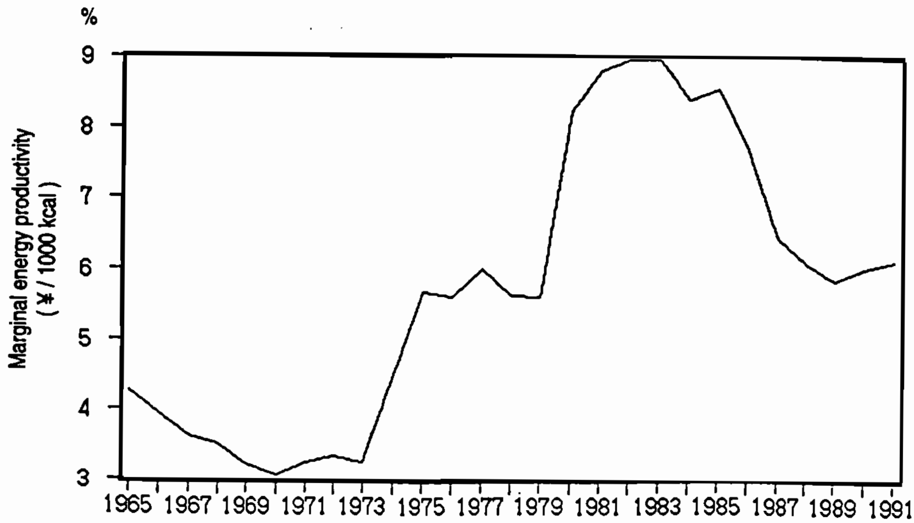
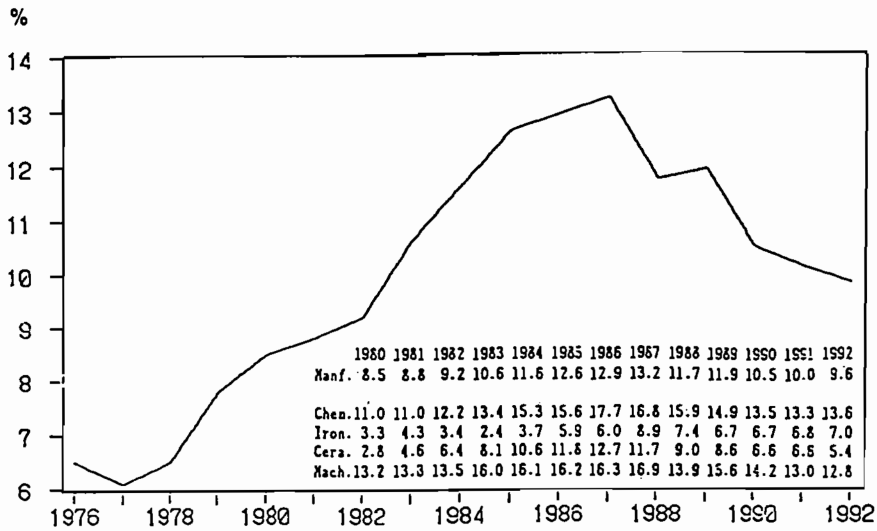



**Figure 17.** Trends in marginal energy productivity of Japanese manufacturing industry, 1965–1991. ¥/1000 kcal, 1985 constant prices. Marginal energy productivity = $\alpha Y/E$, where $Y$ = production, $E$ = final energy consumption, $\alpha$ = cost share of energy.

Table 5 compares the factors stat stimulated R&D for energy, environmental protection, and information technology in Japanese manufacturing industry in the period 1976–1990. We can note that R&D for energy and environmental protection are sensitive to the level of R&D intensity, in contrast with R&D for information technology. The analyses in Figure 18 and Table 5 suggest that the R&D intensity of Japanese manufacturing industry has stagnated, resulting in a decrease in energy R&D. Thus, due to the fall in international oil prices after 1983 and a decline in R&D intensity, energy R&D efforts have stagnated, resulting in a stagnation of the technology stock of energy R&D, as illustrated in Figures 19 and 20.

Changes in the technology stock of energy R&D have both quantitative and qualitative impacts on the total technology stock. Quantitatively, the technology stock of energy R&D is a part of the total technology stock and its stagnation results in a stagnation of the total technology stock. Qualitatively, it induces the technology stock of non-energy R&D. Figure 21 analyzes this inducement; we can note that the trend of marginal productivity of the technology stock of energy R&D to the total technology stock has begun to decrease. This analysis suggests that a stagnation of the technology stock of energy R&D results in a slower rate of increase in the total technology




| | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | 1992 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Manf. | 8.5 | 8.8 | 9.2 | 10.6 | 11.6 | 12.6 | 12.9 | 13.2 | 11.7 | 11.9 | 10.5 | 10.0 | 9.6 |
| Chem. | 11.0 | 11.0 | 12.2 | 13.4 | 15.3 | 15.6 | 17.7 | 16.8 | 15.9 | 14.9 | 13.5 | 13.3 | 13.6 |
| Iron. | 3.3 | 4.3 | 3.4 | 2.4 | 3.7 | 5.9 | 6.0 | 8.9 | 7.4 | 6.7 | 6.7 | 6.8 | 7.0 |
| Cera. | 2.8 | 4.6 | 6.4 | 8.1 | 10.6 | 11.8 | 12.7 | 11.7 | 9.0 | 8.6 | 6.6 | 6.6 | 5.4 |
| Mach. | 13.2 | 13.3 | 13.5 | 16.0 | 16.1 | 16.2 | 16.3 | 16.9 | 13.9 | 15.6 | 14.2 | 13.0 | 12.8 |

a Correlations between R&D investment share out of total investment (IR) and R&D intensity (RS) in the Japanese manufacturing industry are as follows (1978-1990):

| | | adj.$R^2$ | DW |
|---|---|---|---|
| Manufac. total | $\ln RS = 0.81 + 0.17\,\text{Lag2}(\ln IR) + 0.22\,D$ <br> (20.30) (2.86) <br> 90=1 | 0.975 | 1.41 |
| Chemicals | $\ln RS = -0.02 + 0.52\,\text{Lag2}(\ln IR)$ <br> (12.96) | 0.933 | 2.53 |
| Iron & steel | $\ln RS = 0.07 + 0.30\,\text{Lag1}(\ln IR) + 0.21\,D$ <br> (7.36) (4.14) <br> 85-87=1 | 0.907 | 1.58 |
| Machinery | $\ln RS = -0.24 + 0.58\,\text{Lag2}(\ln IR) + 0.06\,D$ <br> (8.74) (2.66) <br> 80.90=1 | 0.886 | 1.51 |

**Figure 18.** Trends in R&D investment share of total investment in Japanese manufacturing industry, 1976–1992.

**Table 5.** Inducing factors for R&D on energy, environmental protection, and information technology in Japanese manufacturing industry, 1976–1990.

**Energy R&D** — adj.$R^2$ DW D

$$\ln ERT = 2.12 + \underset{(2.64)}{0.77} \ln ENERS + \underset{(3.70)}{1.50} \ln RS + \underset{(1.29)}{0.45} \ln PE + \underset{(1.34)}{0.12} D \qquad 0.918 \quad 1.54 \quad D_{1990}=1$$

**R&D for Environmental Protection**

$$\ln ENVRD = 2.86 + \underset{(7.94)}{1.07} \ln ENVRS + \underset{(8.97)}{2.08} \ln RS + \underset{(1.57)}{0.21} \ln PE - \underset{(-1.77)}{0.14} D \qquad 0.847 \quad 1.85 \quad D_{1986}=1$$

**R&D for Information Technology**

$$\ln INFRD = 2.75 + \underset{(23.10)}{1.53} \ln INFRS + \underset{(6.25)}{0.87} \ln RS + \underset{(4.92)}{0.27} \ln PE \qquad 0.999 \quad 2.44$$

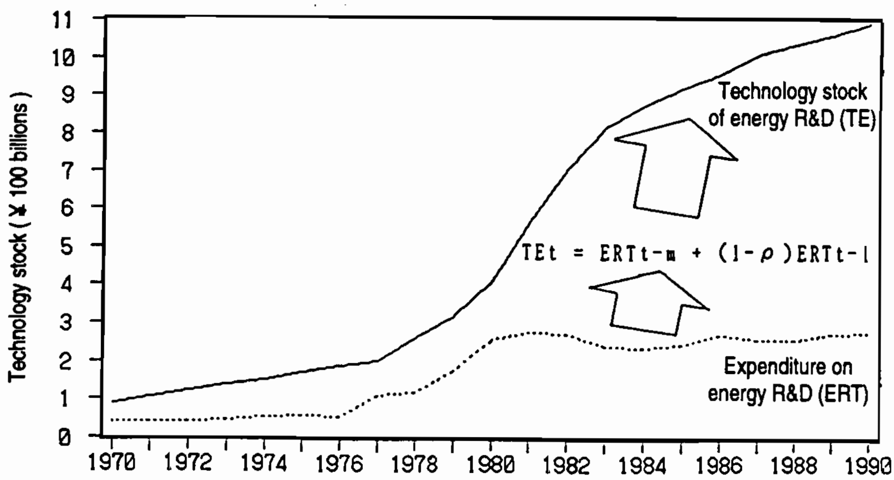
Multipliers of Inducing Factors

| | R&D Share by Objectives | R&D Intensity | Energy Prices |
|---|---|---|---|
| Energy R&D | 0.77 | 1.50 | 0.45 |
| R&D for Environmental Protection | 1.07 | 2.08 | 0.21 |
| R&D for Information Technology | 1.53 | 0.87 | 0.27 |

a Firms with capital of more than 100 million yen.
b ERT, ENVRD and INFRD: R&D expenditures for energy R&D, R&D for environmental protection and R&D for information technology respectively.
ENERS, ENVRS and INFRS: The ratio of R&D expenditures for energy, environmental protection and information technology respectively.
RS: R&D intensity.
PE: Prices of energy.
c All 1985 constant prices.

stock, which in turn results in not only a decrease in production but also in the marginal productivity of technology stock to production, as analyzed in Figure 22.

These analyses provide a warning that despite its success in overcoming energy and environmental constraints in the 1960s, 1970s and the first half of the 1980s, the Japanese economy once again faces the prospect of energy and environmental constraints and consequent stagnation following the fall in international oil prices and the succeeding "bubble economy" (Industrial Structure Council of MITI, 1992).




a TEt = ERTt-m + (1-ρ)ERTt-l
where m: time lag of R&D to commercialization (2 years), and
ρ: rate of obsolescence of technology (20%).

**Figure 19.** Trends in technology stock of energy R&D in Japanese manufacturing industry, 1970–1990. ¥ 100 billion, 1980 constant prices.

## 4.2. Trends in inducing impacts of MITI's energy R&D

MITI's energy R&D budget was influenced by its overall R&D budget and also by trends in energy prices.[7] As international oil prices fell and the global environmental consequences gave rise to mounting concerns regarding the sustainability of our development future, MITI's priority for energy R&D shifted to other policy fields such as the Global Environmental Technology Program, initiated in 1989 (Watanabe and Honda, 1992). Together with government financial constraints after the energy crises, MITI's budget for energy R&D has stagnated since 1982, as illustrated in Table 2. Considering the significant impacts of MITI's energy R&D on R&D intensity, the substitution of technology for energy and the technology stock of energy R&D initiated by manufacturing industry as indicated in Table 4, such stagnation has discouraged manufacturing industry's efforts to increase R&D intensity,

[7]MITI's energy R&D budget ($MER$) is influenced by its overall R&D budget ($MRD$) and energy prices ($Pe$) as follows:

$$\text{Ln } MER = -6.66 + 1.02 \text{ Ln } MRD + 1.02 \text{ Ln } Pe + 0.36\ D. \qquad \text{adj. } R^2\ 0.975\ DW\ 1.51$$
$$\qquad\qquad (8.55) \qquad\qquad (4.59) \qquad\qquad (3.42)\ 78{=}1$$

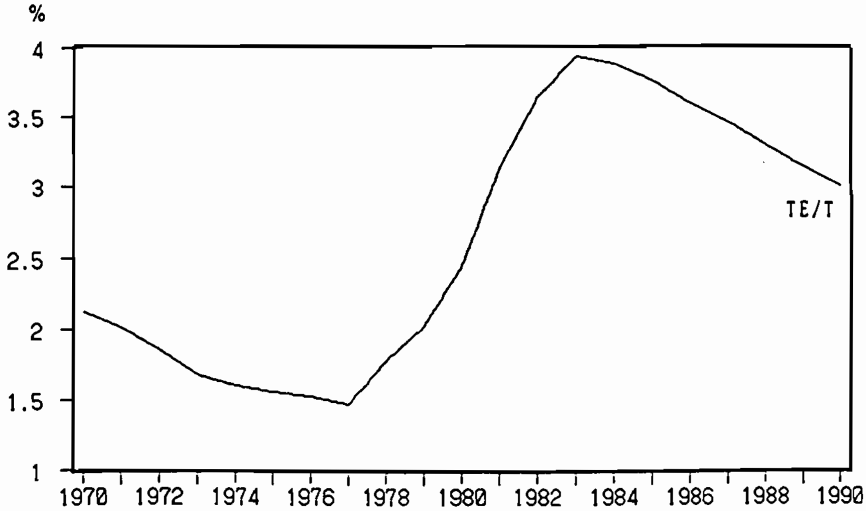
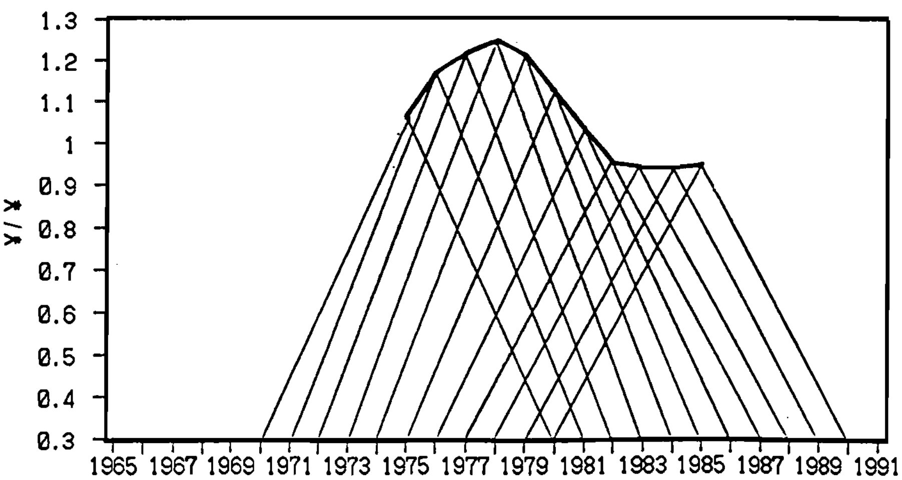



**Figure 20.** Trends in the ratio of technology stock of energy R&D ($TE$) to total technology stock ($T$) in Japanese manufacturing industry, 1970–1990.

the technology stock of energy R&D and technology substitution for energy, which were the main sources of the decrease in energy productivity in Japan's manufacturing industry, as indicated in Figure 12. As MITI's budget stagnated, its return on investment to R&D intensity and the technology stock of energy R&D decreased, as analyzed in Figures 23 and 24. This is a clear warning that evolution of manufacturing industry's R&D intensity and the technology stock of energy R&D will structurally stagnate in the near future.

### 4.3. Sources of the current fear

During the period of the "bubble economy", the R&D intensity of Japan's manufacturing industry began to stagnate as shown in Figure 18, which resulted in a decrease in energy R&D (Table 5). Thus, due to the fall in international oil prices after 1983 and a decline in R&D intensity, energy R&D efforts stagnated, resulting in a stagnation of the technology stock of energy R&D (Figures 19 and 20). This stagnation caused a reduction in the total technology stock, in terms of both quantity and quality (see Figure 21), and in turn a decrease in the rate of substitution of technology for energy. A dramatic improvement in energy productivity (which was the main

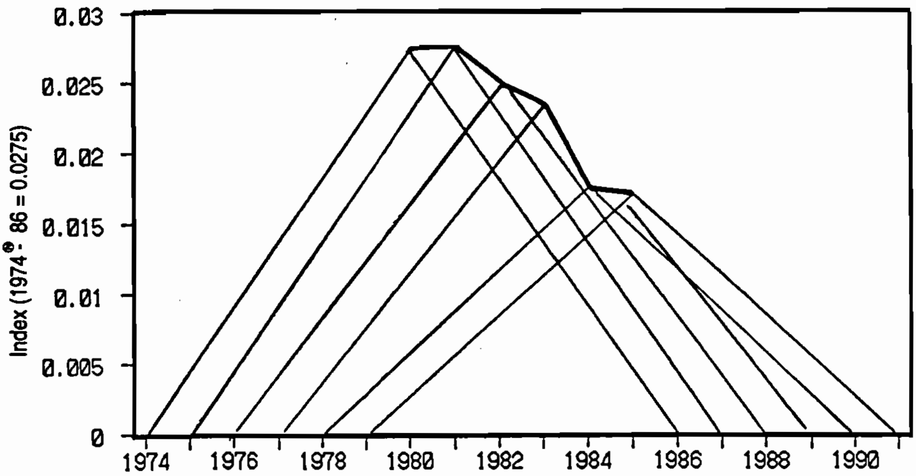



a Marginal productivity (MP) is measured by the following equation:
$T = A*TE^{\alpha}*TNE^{\beta}$ $T = TE + TNE$
Where T: total technology stock, TE: technology stock of energy R&D, TNE: technology stock of non-energy R&D, A: scale factor.
$MP = \sigma T/\sigma TE = \alpha T/TE$

b MP and correlation among TE, TNE and T in the respective period is as follows:

| | MP | | adj. $R^2$ | DW |
|---|---|---|---|---|
| 1970-80 | 1.06 | LnT = 0.135 + 0.031LnTE + 0.969LnTNE | 0.999 | 1.88 |
| | | (42.12) (1302.05) | | |
| 1971-81 | 1.17 | LnT = 0.143 + 0.035LnTE + 0.966LnTNE | 0.999 | 1.37 |
| | | (24.27) (506.83) | | |
| 1972-82 | 1.22 | LnT = 0.159 + 0.038LnTE + 0.962LnTNE | 0.999 | 0.96 |
| | | (19.33) (277.59) | | |
| 1973-83 | 1.25 | LnT = 0.185 + 0.041LnTE + 0.958LnTNE | 0.999 | 0.77 |
| | | (16.02) (167.87) | | |
| 1974-84 | 1.21 | LnT = 0.204 + 0.042LnTE + 0.955LnTNE | 0.999 | 0.70 |
| | | (12.70) (110.30) | | |
| 1975-85 | 1.12 | LnT = 0.188 + 0.042LnTE + 0.957LnTNE | 0.999 | 0.65 |
| | | (10.00) (81.92) | | |
| 1976-86 | 1.04 | LnT = 0.167 + 0.041LnTE + 0.960LnTNE | 0.999 | 0.70 |
| | | (11.22) (95.51) | | |
| 1977-87 | 0.95 | LnT = 0.178 + 0.042LnTE + 0.958LnTNE | 0.999 | 0.77 |
| | | (14.70) (134.86) | | |
| 1978-88 | 0.94 | LnT = 0.207 + 0.046LnTE + 0.952LnTNE | 0.999 | 0.89 |
| | | (23.62) (243.18) | | |
| 1979-89 | 0.94 | LnT = 0.217 + 0.049LnTE + 0.949LnTNE | 0.999 | 1.26 |
| | | (31.36) (384.14) | | |
| 1980-90 | 0.95 | LnT = 0.220 + 0.052LnTE + 0.946LnTNE | 0.999 | 1.89 |
| | | (46.64) (726.91) | | |

**Figure 21.** Trends in the marginal productivity of technology stock of energy R&D to total technology stock in Japanese manufacturing industry, 1970–1990, by moving correlations with 8 degrees of freedom (¥/¥).




a Marginal productivity (MP) is measured by the following equation:

$Y = A\ L^{\wedge}\alpha * K^{\wedge}\beta * ME^{\wedge}\gamma * T^{\wedge}\delta$

$\text{Ln } Y = -0.45 + 0.22\text{Ln } L + 0.19\text{Ln } K + 0.60\text{Ln } ME + 0.08\text{Ln } T$ (1974-1991)
(1.88) (1.69) (5.00) (1.91)

adj. $R^2$ 0.999 DW 1.52

Where Y: production, L: labor, K: capital stock, ME: materials and energy, T: technology stock, A: scale factor.

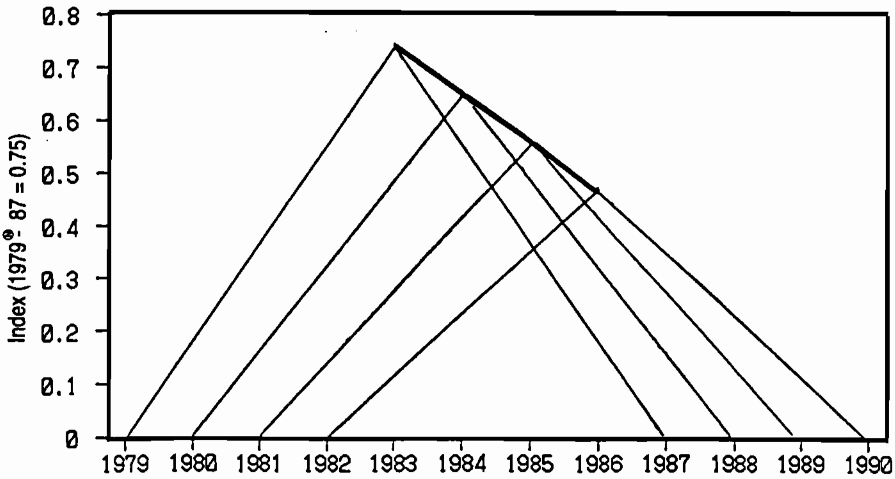
$MP = \sigma Y/\sigma T = \delta Y/T$

b $\delta$, Y/T and MP in the respective period is as follows:

| | $\delta$ | Y/T | MP |
|---|---|---|---|
| 1974-1986 | 0.098 | 0.28 | 0.0275 |
| 1975-1987 | 0.115 | 0.24 | 0.0276 |
| 1976-1988 | 0.109 | 0.23 | 0.0251 |
| 1977-1989 | 0.102 | 0.23 | 0.0235 |
| 1978-1990 | 0.080 | 0.22 | 0.0176 |
| 1979-1991 | 0.081 | 0.21 | 0.0170 |

**Figure 22.** Trends in the marginal productivity of technology stock to production in Japanese manufacturing industry, 1974–1991, by moving correlations with 8 degrees of freedom. Index: 1974–1986 = 0.0275.

reason for the reduced discharges of $CO_2$) was largely due to R&D intensity and the substitution of technology for energy, as analyzed in Figure 12. Therefore, decreases in both R&D intensity and technology substitution for energy urged Japan's manufacturing industry to increase its energy independence, which resulted in an increase in $CO_2$ discharges. A stagnation of technology stock resulted in a decrease in production, which resulted in decreased sales. Change in R&D expenditure is a function of changes in R&D



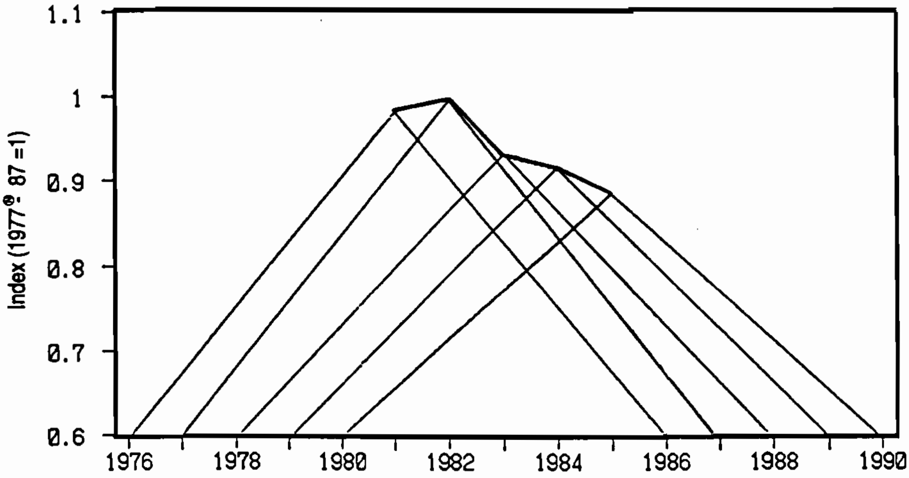

a Return of investment (RI) is measured by the following equation:
$Ln\ RS = a + \alpha\ Lag5(Ln\ MER) + \beta\ LAG2(Ln\ MNER)$
$RI = \sigma RS/\sigma MER = \alpha RS/Lag5(MER)$
Where RS: R&D intensity, MER: MITI's energy R&D, MNER: MITI's non energy R&D, $\alpha$ : multiplier of RS induced by MER, $\beta$ : multiplier of R&D induced by MNER.

b RI and correlation between MER and RS are as follows:

| | RI | | adj. $R^2$ | DW |
|---|---|---|---|---|
| 1979-87 | 0.75 | LnRS=-2.36+0.29Lag5(LnMER)+0.12Lag2(LnMNER) | 0.975 | 2.22 |
| | | (15.03) (2.60) | | |
| 1980-88 | 0.65 | LnRS=-2.26+0.28Lag5(LnMER)+0.10Lag2(LnMNER) | 0.960 | 1.71 |
| | | (12.29) (1.92) | | |
| 1981-89 | 0.56 | LnRS=-1.80+0.27Lag5(LnMER)+0.05Lag2(LnMNER) | 0.966 | 2.33 |
| | | (14.14) (1.01) | | |
| 1982-90 | 0.46 | LnRS=-1.80+0.25Lag5(LnMER)+0.05Lag2(LnMNER) | 0.966 | 2.66 |
| | | (12.47) (1.60) | | |

**Figure 23.** Trends in return on investment of MITI's energy R&D to R&D intensity in Japanese manufacturing industry, 1979–1990, by moving correlations with 6 degrees of freedom. Index: 1979–1987 = 0.75.

intensity and sales. Therefore, decreases in R&D intensity and sales led to a decrease in technology stock, which resulted in a decrease in production. Increased energy dependency also resulted in a decrease in production (a decrease in marginal energy productivity) as analyzed in Figure 17. Thus, Japan's manufacturing industry appears to have fallen into a negative spin cycle, as illustrated in Figure 25.




a Return of investment (RI) is measured by the following equation:
$\ln TE = a + \alpha \, Lag2(\ln MER)$ $RI = \sigma TE / \sigma MER = \alpha TE / Lag2(MER)$
Where TE: technology stock of energy R&D, MER: MITI's energy R&D,
$\alpha$ : multiplier of TE induced by MER.

b RI and correlation between MER and TE are as follows:

| | RI | | adj. $R^2$ | DW |
|---|---|---|---|---|
| 1976-86 | 0.98 | $\ln TE = -0.24 + 1.03\, Lag2\, (\ln MER)$ (17.60) | 0.969 | 1.65 |
| 1977-87 | 1.00 | $\ln TE = -0.29 + 1.04\, Lag2\, (\ln MER)$ (16.20) | 0.963 | 1.07 |
| 1978-88 | 0.93 | $\ln TE = 0.28 + 0.95\, Lag2\, (\ln MER)$ (25.47) | 0.985 | 1.33 |
| 1979-89 | 0.92 | $\ln TE = 0.47 + 0.93\, Lag2\, (\ln MER)$ (22.37) | 0.980 | 1.52 |
| 1980-90 | 0.89 | $\ln TE = 0.74 + 0.89\, Lag2\, (\ln MER)$ (14.87) | 0.957 | 1.09 |

**Figure 24.** Trends in return on investment of MITI's energy R&D to technology stock of energy R&D in Japanese manufacturing industry, 1976–1990, by moving correlations with 9 degrees of freedom. Index: 1977–1987 = 1.

MITI's energy R&D contributed to induce industry's R&D efforts as analyzed in Tables 3 and 4. However, such an inducement has stagnated as analyzed in Figures 23 and 24. Faced with the prospect of energy and environmental constraints, and also a stagnation of sustaining development, MITI needs to initiate intensive energy R&D to stimulate improvements in the quality and quantity of the total technology stock. This will in turn help to overcome the current fears in this time of economic stagnation.

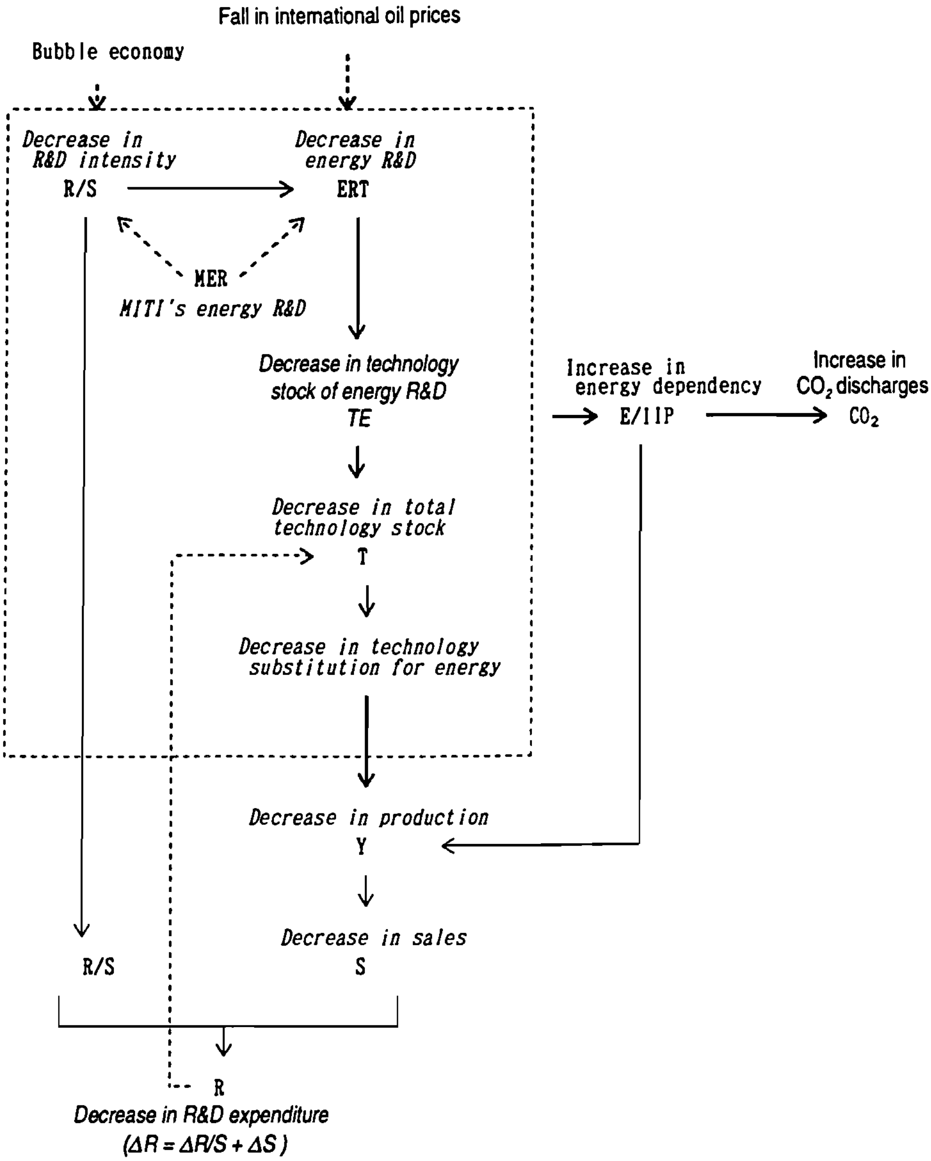



**Figure 25.** Impacts of the fall in international oil prices and the succeeding bubble economy on energy and environmental constraints and sustainable growth in Japanese manufacturing industry.

# 5. MITI's New Comprehensive Approach: The New Sunshine Program

## 5.1. Integration of energy and environmental technologies

The above urges MITI to provide effective policy measures to reactivate efforts directed toward substituting technology for constrained production factors such as energy and environmental capacity. Given the two-sided nature of the issue of the global environment and energy consumption, MITI should develop a comprehensive approach based on the integration of related programs for strong and effective measures to address the mounting concerns regarding the sustainability of the world's development future in the face of increasing energy and environmental constraints (Industrial Technology Council of MITI, 1992).

To respond to these concerns, a comprehensive approach based on R&D programs on new energy technologies, energy conservation, and environmental technology, could lead to sustainable development by overcoming both energy and environmental constraints simultaneously (Industrial Structure Council of MITI, 1992).

In April 1993, MITI therefore decided to establish the New Sunshine Program (R&D Program on Energy and Environmental Technologies) by integrating the Sunshine and Moonlight Projects and the Global Environmental Technology Program (Industrial Technology Council of MITI, 1992). Through the integration of these R&D activities, effective and accelerated achievement of R&D in the fields of energy and environmental technologies is expected by means of co-utilization and supplementation of such key technologies as catalysts, hydrogen, high-temperature materials and sensors common to new energy, energy conservation and environmental protection. The New Sunshine Program is also expected to provide a new concept for an environmentally friendly technology system and to inspire a new principle to be pursued under global environmental constraints.

## 5.2. Structure of the development program

The New Sunshine Program comprises three R&D programs in the field of energy and environmental technologies:

1. The Innovative R&D Program, which aims to accelerate R&D on innovative technology essential for achieving the goal of the Action Program to Arrest Global Warming – to stabilize per capita $CO_2$ emissions at 1990 levels by the year 2000.

2. The International Collaboration Program for Large-Scale R&D Projects, which aims to initiate large-scale international R&D projects, is expected to make a significant contribution to the achievement of the goal of "New Earth 21" – to restore the Earth over future decades through the reduction of greenhouse gases.
3. The Cooperative R&D Program on Appropriate Technologies, which aims to develop and assimilate appropriate technologies in developing countries through cooperative R&D on technologies originating from the Sunshine and Moonlight Projects.

Priority projects in the New Sunshine Program can be classified into two basic types:

1. Acceleration projects, which are expected to lead to practical use in the near future by means of a "virtuous spin cycle" (to reduce costs by technological improvements, which will increase demand, which will further reduce costs through mass production) triggered by an acceleration of R&D. Examples include photovoltaic and fuel cell power generation.
2. Innovative synthetic system projects, which are expected to achieve an extremely high level of breakthrough by means of the synthesis of key technologies. Examples include a broad area energy utilization network system and an international clean energy network using hydrogen conversion (the WE-NET project).

The schedule of the New Sunshine Program's projects which will be undertaken in conjunction with the Action Program "New Earth 21", is illustrated in Figure 26.

# 6. Implications for Mitigating Global Warming

Increasing energy and environmental constraints, especially the global environmental consequences of $CO_2$ discharges resulting from energy use, are causing mounting concerns around the world, and it is widely warned that such constraints may be "limits to the sustainability of our development future".

Japan's success in overcoming the energy crises while maintaining economic growth by means of the substitution of technology for energy, which resulted in a dramatic improvement in technological level, could provide useful suggestions to the question of how technology can be utilized to sustain development. The way in which Japan's technological development succeeded by focusing on efforts to overcome the limitations of scarce resources

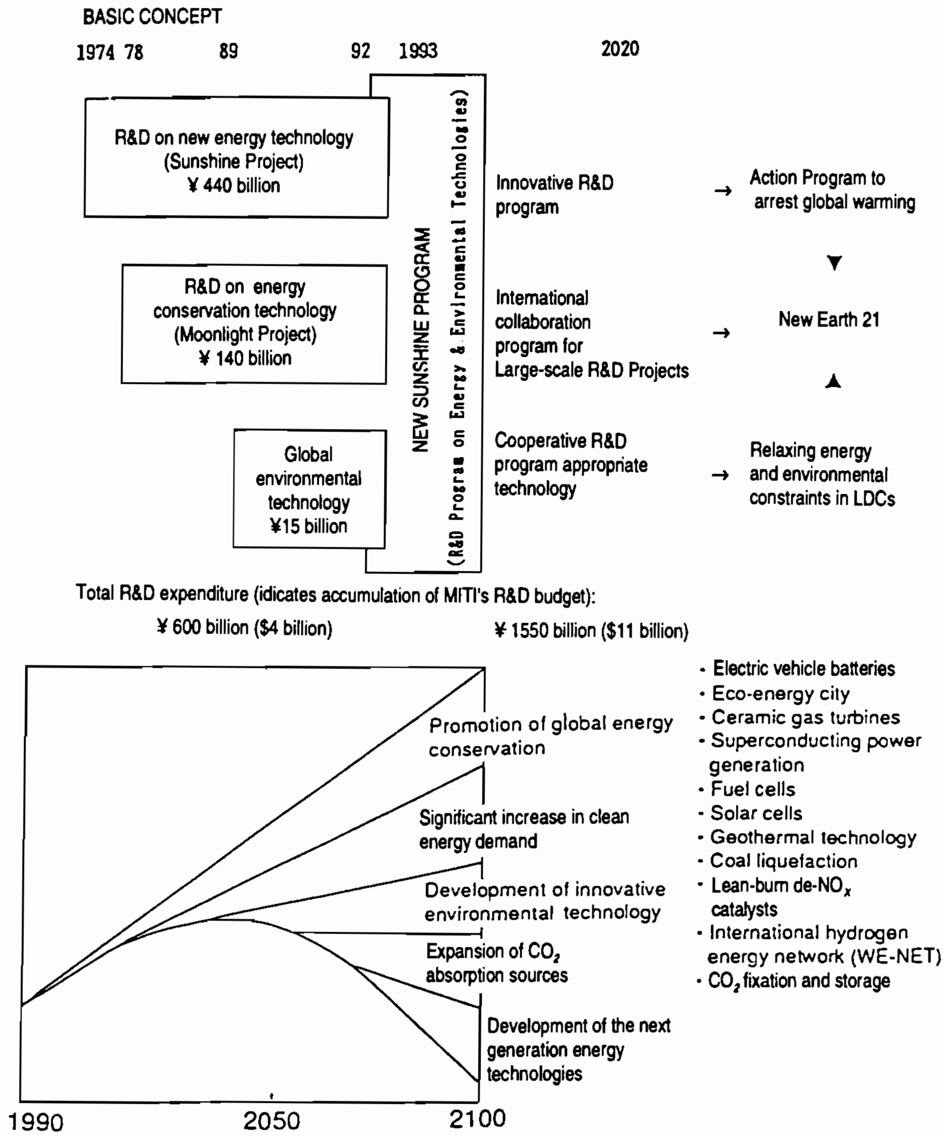



**Figure 26.** Schedule of the New Sunshine Program's projects, which will be undertaken in conjunction with the Action Program "New Earth 21".

in the 1970s and 1980s may be particularly instructive since it strongly suggests that a comprehensive approach that challenges the limits of sustainable development by substituting new technology for energy and environmental constraints could lead to a new frontier.

Given the above, MITI's industrial technology policy in the 1970s and early 1980s is instructive because it functioned well in stimulating such substitution, thereby enhancing the vitality of industry. However, following the fall in international oil prices and the succeeding "bubble economy" in the late 1980s, Japan may once again face the prospect of energy and environmental constraints as various indicators warn that Japan's economy has been falling into a negative spin cycle. In order to avoid this, while also facing a stagnation of industry's R&D efforts due to the bursting of the "bubble economy", MITI's new comprehensive approach is expected to lead to the reconstruction of a virtuous spin cycle for the effective stimulation of sustainable substitution of technology for energy.

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# Joint Implementation

# Benefits and Costs of Climate Measures Under Joint Implementation

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## Abstract

This paper discusses some general problems related to the assessment of costs and benefits of joint implementation projects. Joint evaluation of alternative projects in different countries adds some problems to the well-known list of difficulties in assessing the net social benefits from projects. These problems may to some extent be related to the kind of system of international cooperation for actions taken to mitigate climate change. This paper focuses on the effects of differences in the preferences between countries, possibilities of changes in the terms of trade between groups of countries, and uncertainty with respect to future targets imposed on receiving countries. These effects mainly consist of long-term macroeconomic effects, and may be taken into account when choosing a discount rate for joint implementation projects.

## 1. Introduction

The UN Framework Convention on Climate Change (FCCC) signed in Rio in June 1992 strongly emphasizes the goal of cost effectiveness in the assessment of measures to mitigate climate change to be undertaken by single nations. One way of obtaining cost effectiveness, explicitly mentioned in the Convention, is to encourage joint implementation of the convention. This means that countries that commit themselves to targets for future emissions of greenhouse gases are given an opportunity to finance projects abroad against some allowance for domestic emissions.

The motivation for joint implementation is straightforward. Countries that make efforts to mitigate climate change gain some benefits from reducing the speed of accumulation of greenhouse gases in the atmosphere. Taken isolated, these benefits accrue independently on where in the world the reductions of the emissions of greenhouse gases take place. If the reductions can be attained at lower costs abroad than the least cost domestic project, the country should initiate projects in other countries in order to minimize the costs. If the receiving country has no commitments regarding future emissions, they have nothing to loose if the additional cost of the joint implementation project is covered by the investing nation. Thus, joint implementation may lead to Pareto improvements.

However, many countries and organizations have reacted with scepticism to the idea of joint implementation. One reason may be the fact that the idea has been advocated mainly by industrial countries for which the advantage is quite evident. What developing countries that do not commit themselves to targets at the present stage may gain is more difficult to see. Secondly, especially non-governmental organizations in developing countries fear that joint implementation will only give developing countries an opportunity to "buy themselves out of the problems", partly at the expense of developing countries, and that the ultimate global reduction in the accumulation of greenhouse gases will be negligible under such a regime.

This scepticism is to some extent of political nature and may be explained by mistrust to the true willingness to mitigate climate change in the governments of the industrial countries. On the other hand, many questions as to how the system will evolve are open. There is great uncertainty about the ultimate effects on the relative development between rich and poor countries and also about global warming. The difference between the text-book like effectivity argument on which joint implementation is based and the real world often turns out in disfavor of certain interests. Both developing countries and environmentalists may have reasons to think twice when faced with simple market economic arguments.

The aim of this paper is to shed light over some (rather arbitrarily) chosen issues that may affect the evaluation of projects subject to joint implementation. As a point of departure, I assume that some countries have committed themselves to binding targets for future emissions of greenhouse gases, and that some have not. This implies a strengthening of the present content of the FCCC, which does not bind any of the participants with respect to emissions. I concentrate on the possible macroeconomic effects of a more or less extensive world- or region-wide system of joint implementation activities. Since macroeconomic effects only exceptionally can be attached to single projects, one has to account for them implicitly. The approach taken here is to assess the optimal growth path for an economy under alternative regimes, and study the effect on the social rate of discount. Thus, the analysis gives an indication of how to choose a proper rate of discount for joint implementation projects.

The paper is organized as follows: In Section 2, the basic argument supporting joint implementation is presented, together with some of the assumptions on which it is based. In Section 3, the criteria for choice among projects, based on cost-benefit analysis, are given including the definition of the so-called incremental cost. The importance or necessity of pre-assessments of the incremental cost is questioned, and the role played by the choice of utility functions is shown. In Section 4, the intertemporal aspect of a joint implementation regime is addressed from the angle of the possible change in terms of trade between receiving and investing countries. Section 5 discusses the account for anticipated future targets in receiving countries under uncertainty. Some concluding remarks are given in Section 6.

## 2. The Basic Argument

Consider a country, or a group of countries, where the welfare, $W_0$, is taken to depend on material welfare derived from consumption, $c_t$ ($t$ is the time indicator) and global emissions of greenhouse gases $e_t$.

$$W_0 = \int_0^\infty w(c_t, e_t, t)dt. \tag{1}$$

One single product $x_t$ is produced with capital $k_t$ as the only input,

$$x_t = f(k_t). \tag{2}$$

Capital formation in this economy is

$$\dot{k}_t = \delta k_t + i_t, \tag{3}$$

where $\delta$ is a constant expressing capital depreciation and the control variable $i_t$ is investment. To avoid unnecessary use of variables, assume $\delta = 0$. Output is used for investments, consumption $c_t$, and abatement activities $a_t^A$ and $a_t^B$, where $A$ denotes abatement activities carried out domestically and $B$ represents financial support of abatement activities in other countries. In other words, this is regarded a closed economy, but there is an opportunity to make investments in joint implementation projects.

Emissions of greenhouse gases $e_t^A$ in this country is linked to the production process, i.e.

$$e_t^A = G(x_t, a_t^A) = g(k_t, a_t^A), \tag{4}$$

where $g'_k > 0$ and $g'_a < 0$ (accents denote partial derivatives). Total emissions of greenhouse gases, which is what matters for the welfare of this country is

$$e_t = e_t^A + e_t^B, \tag{5}$$

where $e_t^B$ is emissions from other countries. As indicated above, these may be controlled to some extent by the country if it engages in joint implementation projects, i.e.

$$e_t^B = h(a_t^B). \tag{6}$$

With a known initial amount of capital, the optimal level of consumption and abatement activities can be found by maximizing welfare (1), subject to the model (2) – (6). The following first order conditions are obtained,

$$g_a' w_e' = h_a' w_e' = w_c'. \tag{7}$$

$$-\frac{\dot{\lambda}_t}{\lambda_t} = \frac{g_a'}{g_k'} + f_k', \tag{8}$$

where $\lambda_t$ is the cojoint variable of the control problem. Note that $g_a'$ in (8) may represent both domestic abatement and joint implementation projects, since $g_a' = h_a'$ in optimum according to (7).

The argument supporting joint implementation is provided by the first equality in (7) which states that the optimal abatement policy is to allocate activities in such a way that the marginal effect of one dollar spent on domestic abatement equals the marginal effect of one dollar spent in financial support of abatement activities through joint implementation. Thus, one may say that within this context, joint implementation is a precondition for optimal development. Furthermore, (7) describes the "static" optimum and may be interpreted as providing a principle for the allocation of the domestic product. The marginal effect on welfare from consumption and products spent on abatement, either domestically or abroad, should be equal. Roughly speaking, in optimum, at each $t$ one unit of $x$ withdrawn from consumption implies the same welfare loss as the gain from an additional unit of $x$ spent on some abatement activity.

Equation (8) assesses the intertemporal condition for optimum. $\lambda_t$ can be interpreted as the social shadow price on the restriction on the use of capital in the economy. Compared with ordinary national accounting practice, this is the shadow price of savings. The rate of change in $\lambda_t$, expressed in (8), is therefore the social discount rate. The social discount rate includes two terms. $g_a'/g_k'$, which is negative, expresses the relative effect on emissions from a substitution between capital and abatement. $f_k'$ is the ordinary rate of return in the economy, which again conforms with the rate of interest.

The discount rate diverges from the rate of interest because the environment matters to welfare. For the evaluation of an average investment project in the economy described here, the project should yield an additional return to the society, compared with the usually required one. Abatement activity has to be implemented as a result of the investment. To finance these activities, a gap between the social return and the return on the investments is required. This reflects the principle put forward by Arrow and Kurtz (1970), that in order to assess the proper discount rate for a project, all the impacts should be evaluated in the light of social optimization.

## 3. Evaluation of Projects

The optimality of engagements in joint implementation projects shown in the previous section emerged as a result of an isolated analysis of one country committing itself to restrict emissions of greenhouse gases. The question arises, of course, what about the country that provides projects advantageous to the investing country? We assume as a starting point that this country, henceforth called the receiving country, has so far made no commitment to reduce the emissions of greenhouse gases. Strictly interpreted, this implies that emissions of greenhouse gases do not enter the receiving country's welfare function. Thus, the optimal solution for this country's economic policy is unaffected by foreign investments in abatement activities. This is obvious since these activities are of no interest to them, and the solution can easily be checked with the model presented in the previous section by omitting $e_t$ from the welfare function.

Accepting this, however, the question arises how much should the investing nation pay for the abatement activity, and what should be regarded as the effect on emissions from this activity? To the first part of this question, FCCC states that the amount to be financed through joint implementation projects should *at least* cover the additional cost that accrue as a result of carrying out the joint implementation project, rather than the receiving country's first choice. This works fine as a principle, but turns out to be problematic when applied for practical decisions. A formal analysis may be helpful in order to establish a tool for analyzing the social implication of a given choice. The following analysis is based on Drèze and Stern (1987).

We take the ideal point of departure and assume that it is possible to make judgements about projects in which *all* information of relevance to the evaluation of projects is embodied. Denote by $s$ a vector of variables representing the social state which gives signals that summarizes all information needed to determine the behavior of private agents in the receiving country. Let $E$, with element $E_j$ represent private agent's demand for commodities, and

$$E : s \rightarrow E(s).$$

Let $z$ with element $z_j$ denote the vector of supplied commodities. We may limit the scope of analysis by restricting $z$ to commodities under control by the public sector, for instance. Equilibrium is represented by the restriction

$$E(s) - z = 0, \tag{9}$$

$$s \in S, \tag{10}$$

where $S$ denotes the opportunity set.

Projects can be defined within subsets of the supply of public goods and services, $z \in Z$ where $Z$ is the (public sector) production set. In this section, we will consider projects which imply only small changes in the production of $z$. Let the vector $dz$ denote the difference in the total supply of commodities between two projects under evaluation, and let $z \in Z$. $dz$ can be associated with a project, and it is said to be small if

$$(z + dz) \in Z$$

for any two projects. The implication of this assumption is important. It means that the projects under consideration do not affect the vector of states $s$, including relative prices, income distribution etc. significantly.

The evaluation of projects must be made in accordance with an objective function, the social welfare function. The social welfare function is an ordering of states

$$V : s \rightarrow V(s). \tag{11}$$

For a given state, the authorities make certain choices resulting in a composition of produced goods that we may call a *policy.* Since we are primarily interested in the social implication of a given choice, we specify the policy as a function $\Phi$ which associates a unique state $s$ to each production plan $z$ such that (9) and (10) are satisfied,

$$\Phi : s \rightarrow z.$$

Recall that we are in the ideal world. The policy, therefore, inherits all information of relevance to the evaluation of projects in relation to the social welfare function (11). Now, the change in social welfare, $dV$, from a change in production of $dz$, can be written:

$$dV = \frac{\partial V}{\partial s}\frac{\partial \Phi}{\partial z}dz, \tag{12}$$

and the shadow price of this change is defined as

$$\delta = dV/dz = \frac{\partial V}{\partial s}\frac{\partial \Phi}{\partial z} \tag{13}$$

The planner's problem is to find $\delta^* = \max_{\forall \delta} \delta$. It can be shown that if the production set $Z$ is convex, an optimal production plan $z^*$ has the maximum shadow price, i.e.

$$\delta^* z^* = \max_{z \in Z} \delta^* z. \tag{14}$$

$\frac{\partial V}{\partial s}$ is a row vector with $n$ elements, $\frac{\partial V}{\partial s_i}$, and $\frac{\partial \Phi}{\partial z}$ is a matrix with $m$ elements $\frac{\partial \Phi_i}{\partial z_j}$. Now, we may "sort out" the welfare effect on one welfare component, $k$, (e.g. reduction in emissions of greenhouse gases), or the shadow price of this component related to a comparison of two projects as

$$\delta^k = V_k' \frac{\partial \Phi}{\partial z} I \tag{15}$$

where $V_k'$ is a $1 \times n$ vector with $\partial V / \partial s_k$ in its $k$-th column and 0 in the others and $I$ is $n \times 1$ vector with 1 in all its rows. To distinguish between alternatives, we denote by $\delta_n$ the difference in welfare between the current situation and the situation after having invested in alternative $n$.

To the receiving country, the projects should be evaluated according to comparisons of the values of $\delta_n$. However, the decision on what project should eventually be funded through joint implementation will depend on $\delta_n^k$ (the effect of project $n$ on the reduction in greenhouse gases compared to the current situation). Consider two alternative projects, labeled $a$ and $b$. Assume that $a$ yields the social optimum such that $\delta_a > \delta_b$, but that $b$ implies a stronger reduction in the emissions of greenhouse gases, thus $\delta_a^k < \delta_b^k$. If $\delta_a > 0$, $a$ correspond to the *baseline*, mentioned above. The required funding of $b$ to be preferred to $a$ can be written as

$$f_b = \delta_a - \delta_b, \tag{16}$$

which will be denoted as the *incremental cost.* To sort out the potential projects for funding through joint implementation, a comparison of $\delta_n^k$ is required. However, only a full comparison between all costs and benefits of all candidates can provide a fair determination of the amount to be transferred to the receiving country. If the willingness to pay for a marginal reduction of greenhouse gases exceeds $f_b$, the project should be funded.

The contribution to reductions in global emissions of greenhouse gases from a joint implementation project is the difference between the reductions from projects $a$ and $b$, compared to the current level of emissions. Denoting by $\partial\Phi_k/\partial z$ the $k$th row of the matrix $\partial\Phi/\partial z$ this reduction can be written as

$$r_k = \frac{\partial \Phi_k}{\partial z} I, \tag{17}$$

and thus the contribution from joint implementation is

$$dr_b = r_b - r_a \tag{18}$$

Both $dr_b$ and $f_b$ are difficult to assess because of the problems in collecting and putting together adequate information. This is partly a problem in making the right estimates for the costs of the projects, but more problematic is to assess the benefits. As shown, the shadow price of a project depends also on the choice of the welfare function of the receiving country, which indeed is a matter for the receiving country to decide. The benefits from changes in income are in most cases easy to represent, but other effects such as the effects on distributional factors and non-utility information, are certainly more difficult to include in the analysis. The importance of such information is, however, well documented (see, e.g., Sen, 1970, 1979, and 1984), and the problems concerning how to include it are no excuse for leaving it out from the evaluation of projects. One preliminary suggestion might be to present a set of social and environmental indicators displaying different, "non-economic" effects of the projects.

Apart from general problems with social cost-benefit analysis, joint implementation may cause another problem related to the fact that the projects have a potential of being funded. The receiving country therefore has an incentive to bias their true preferences in order to increase the potential of funding. One way to do this is neglect their own benefits from improving environmental factors complementary to the reductions in the emissions greenhouse gases, such as reductions in the emissions of $SO_2$ and $NO_x$. To see this, consider three alternative projects, $a, b$ and $c$ for which

$$a \succ b \succ c,$$

($\succ$ means *preferred to.* ) Assume that $c$ yields the largest reduction in the emissions, which means that there is a potential in funding $c$ through joint implementation. From (16) we know that if the willingness to fund $c$, $p$ is such that

$$p \geq f_c = \delta_a - \delta_c \Rightarrow c \succeq a \tag{19}$$

In some cases, $p$ will be more or less known to the receiving party. Thus, if $p > f_c$, they have incentives to try to increase the potential funding. One way to do this is to "lie" about their preferences by disregarding their own preferences for the effect on emissions. Assume that there exists a project $b$ which is less effective than both $a$ and $c$ with respect to the emissions of greenhouse gases, and that if we disregard all positive effects of reduction in emissions, $b$ will be the most preferred. Then

$$\delta_a - \delta_a^k < \delta_b - \delta_b^k \tag{20}$$

Thus, when the effect on emissions is neglected, we have $b \succ a \succ c$ (the shadow price of $c$ is, of course, affected more than either $a$ or $b$ if the effect on emissions is neglected). For $c$ to be preferred in this case, we must have:

$$p \geq f_c^* = (\delta_b - \delta_c) - (\delta_c^k - \delta_c^k) \tag{21}$$

The receiving party will have incentives to "lie" about their preferences if $f_c^* > f_c$, i.e. if

$$\delta_b - \delta_a > \delta_b^k - \delta_c^k \tag{22}$$

But the reason why $c$ is preferred to the investing party, is that the effect on emissions is highest in $c$, i.e. $\delta_c^k > \delta_a^k > \delta_b^k$. Using (20), we obtain $\delta_b - \delta_a > \delta_b^k - \delta_a^k > \delta_b^k - \delta_c^k$, which is in accordance with (22). In other words, if a project like $b$ exists, the receiving party will always have an incentive to "lie". This conclusion applies for all factors contributing to welfare that are complementary to the emissions of greenhouse gases in the above sense. Thus, there may occur considerable problems when trying to capture the adequate preference ordering in the receiving country.

Despite all the problems in making pre-assessments of benefits and costs of climate measures, one should *not* conclude that joint implementation with necessity will do unjust to one or more of the countries involved. The problems pointed out here are connected to calculations, while the crucial factor for the success of joint implementation is whether or not investing countries are willing to pay the incremental cost and receiving countries are willing to accept the funding that are offered. The above problems arise only to the extent that the price of projects are assessed by calculations. This may depend *inter alia* on the joint implementation regime.

I shall not discuss alternative regimes in detail; deLucia (1992) and Hanish *et al.* (1993) review some of the possibilities. Two extremes may, however, be mentioned to illustrate how important the organization may be to the need for pre-assessments. On the one hand, one may think of a regime with only bilateral agreements. The role of an international institution in charge of the follow-up of the FCCC can be restricted to register agreements, and to accept the reductions emanating from it. The "price" of the project will be a matter for the two countries to negotiate.

On the other hand, the international institution may take a more active part in mediating joint implementation projects. One may think of them as a "bank" to which the investing countries pay in exchange for reductions in their emissions targets and from which the receiving countries are funded in exchange for fulfilment of projects that diverge from their baseline choice. Such an organization requires a considerable reliance on pre-assessments, probably worked out by the institution in charge. The advantage of this kind of organization compared to a system of bilateral agreements is that the information about potential projects around the world will be much better, and that the uncertainty about the effects on emissions can be spread out on all the investing countries instead of letting each investor bear all the burden of uncertainty. In other words, the potential for attaining cost effectiveness is clearly higher when the regime of joint implementation is centralized. One may therefore say that in order to attain cost effectiveness, there is a "trade-off" between reliable pre-assessments and a smooth market for joint implementation projects.

## 4. Trade and Intertemporal Effects

The basic argument for joint implementation leading to Pareto improvements presented in Section 2 was based on reasonings within closed economies. The scepticism mentioned in the introduction will hardly shrink for that reason, being the prototype of a simplified argument. One of the uncertainties is indeed how the relative economic development between rich and poor countries may be affected by joint implementation compared to a situation where the countries with the largest emissions per capita have to restrict their efforts to domestic measures.

To answer this question, we may slightly extend the model presented in Section 2. Consider two countries or groups of countries which both seek to maximize total welfare over a given time horizon. We may, for instance, group potential investing countries and potential receiving countries and associate the first group as being "rich" and the second as being "poor" according to the listing of countries in the FCCC. For simplicity, however, I shall call them "the investing country" and "the receiving country".

Both countries produce consumer goods and capital goods, but they export only one of these. The receiving country exports only consumer goods to the investing country, while the investing country exports only capital goods (in which new technology may be embedded) to the receiving country. Of course, this is quite extreme, but it is assumed to reflect some important trends in the trade between rich and poor countries.

Now, the model from Section 2 can be modified for the two countries as follows:

*The investing country A:*

$$w_0 = \int_0^T w(c_A, b_{BA}, e, t)dt \tag{23}$$

$$x_A = \phi(k_A) \tag{24}$$

$$x_A = c_A + a_{AA} + a_{AB} + i_A + b_{AB} \tag{25}$$

$$\dot{k}_A = i_A \tag{26}$$

$$e = e_A + e_B = g(x_A, a_{AA}) + h(x_B, a_{AB}) \tag{27}$$

$$b_{BA} = pb_{AB} \tag{28}$$

The subscripts refer to the countries and can be read as "from - to". Thus, A's imports from B is denoted $b_{BA}$. Equation (23) is A's welfare function. It distinguishes between domestically produced goods and imported goods. This means that the goods are qualitatively different, with different demand functions. In addition, global emission (of greenhouse gases), $e$, enters the welfare function of the investing country, and $t$ is a time indicator.

Global emission is determined in (27) from production in both the investing and the receiving country. In addition, one may reduce emissions by increasing $a_{ij}$ which denotes the units of output in the investing country used for this purpose. This effort, which we may call abatement cost, may be used to reduce emissions both domestically and in the receiving country through joint implementation.

Equation (24) is the production function. We assume a constant workforce and no technical change, thus domestically produced capital is its only argument. Equation (25) is the national account restriction and (26) describes capital formation. Finally, (28) is the restriction on international trade and the terms of trade is denoted by $p$. This is quite restrictive, since it requires balanced trade at each point of time. Alternatively, one might relax this condition by requiring balance over the whole planning period. The choice here is made to make the results somewhat easier to interpret. It will not make any difference to the analysis of the relative competitiveness between the two countries, which is the focus in this section. More disputable, perhaps, is the assumption that investments in abatement activities does not affect the terms of trade. Recall, however, that $a_{AB}$ is restricted to the idealized incremental cost of a joint implementation project.

*The receiving country B:*

$$v_0 = \int_0^T v(c_B, t)dt \tag{29}$$

$$x_B = \psi(k_B, q_B) \tag{30}$$

$$x_B = c_B + i_B + b_{BA} \tag{31}$$

$$\dot{k}_B = i_B \tag{32}$$

$$\dot{q}_B = b_{AB} \tag{33}$$

In the receiving country, all consumption goods are assumed to be produced at home, but the stock of real capital is divided into domestically produced and imported capital, $k_B$ and $q_B$, respectively. Furthermore, the receiving country will make no effort to abate emissions. Finally, the balance of trade requirement (28) applies also for the receiving country.

Both countries maximize total welfare under the assumption that the terms of trade are exogenously given, i.e. none of them can act as monopolies. Inserting for the allocation of the national product in the equations describing the development of the system, and some manipulations give the following optimality conditions, corresponding to (7) and (8) in Section 2:

*The investing country A:*

$$\lambda_A = w'_{c_A} = \frac{1}{p} w'_{b_{BA}} = w'_e g'_{a_{AA}} = w'_e h'_{a_{AB}} \tag{34}$$

$$-\frac{\dot{\lambda}_A}{\lambda_A} = \phi'_{k_A}(1 + \frac{g'_{x_A}}{g'_{a_{AA}}}) \tag{35}$$

*The receiving country B:*

$$\lambda_B = v'_{c_B} \tag{36}$$

$$-\frac{\dot{\lambda}_B}{\lambda_B} = \psi'_{k_B} = \frac{\psi'_{q_B}}{p} - \frac{\dot{p}}{p} \tag{37}$$

Equations (34) and (36) are similar to the temporal optimum conditions discussed in Section 2, except that the condition for consumption of imported goods in country A is included, and it determines the demand for imports from B. We note that this demand is dependent on the current terms of trade. The intertemporal optimality condition (35) assessing the discount factor in optimum for the investing country is not affected when compared with the solution for a closed economy.

For the receiving country, however, the discounting of imported goods will eventually have to be adjusted to shifts and changes in the rate of change in the terms of trade over time, according to (37). This can be interpreted as an adjustment in the rate of return on imported capital. Thus, if joint implementation somehow affects the terms of trade between the countries, then the optimal composition of imported and domestic capital in the receiving country will also be affected. Of course, this may be of considerable interest if, for instance, introduction of new technology is mainly represented by the imports of capital goods.

Recall that an increase in $p$ is advantageous to the investing country. The higher $p$ is, the more will the investing country receive in exchange for its own products over time. Equation (37) shows, however, that an increase in the terms of trade affects the composition of domestic and imported capital in the receiving country in two ways. The level of $p$ regulates the relative composition of domestic and imported capital, and an increase will lower the import share of capital input. The development of $p$ affects the discount rate directly and shows that increasing terms of trade implies that imported capital is to be discounted at a lower rate than constant terms of trade. Increasing terms of trade thus tends to enforce the receiving country to accelerate investments in imported capital.

The question, then, is how joint implementation might affect the development in the terms of trade. Let us compare two states, with and without joint implementation at some future time $t$. In the following, we concentrate on studying the difference between the two states, in order to find out the possible effect of the terms of trade between the two countries. If $p$ is higher with joint implementation than without, we may interpret this as a directional effect on the development of $p$, between "now" and "future $t$". Therefore, the model would probably also yield a higher $\dot{p}/p$. However, we will assume that the effect of the discounting on imported capital from a higher $\dot{p}/p$ can be ignored.

Figure 1 displays a production technology map for country B in quadrant 2 and an indifference map between home-made consumption goods and imported consumption goods for country A in quadrant 4, and applies for one future $t$. The terms of trade between the two countries is displayed as straight lines in the first quadrant. The figure is just a variant of the Edgeworth box.

Take as the point of departure a situation without joint implementation where we assume that the terms of trade is represented by the $p_0$-line, giving the optimal composition of consumption goods, $(c_0, b_{BA_0})$ in A, and the optimal composition of investments $(i_0, b_{AB_0})$ in B. $(0,0)$ in the second quadrant represents status quo with respect to capital input at a future $t$. Introducing joint implementation means that the shadow price on the use of resources in A, $\lambda_A$ is reduced. In A we must expect that both the level of investments and the level of consumption is increased as a result. We shall not consider the consumption/saving-decision, but assume that the total increase in consumption is $dc_A$, indicated along the $c_A$-axis of the forth quadrant. If the terms of trade is kept constant, the new optimal composition of consumption goods in A would imply higher imports from B. However, then the system is out of equilibrium.

The immediate effect of the increase in imports from B would be a higher price of B's products, and an increase in the production of commodities in B. To manage this increase, total investments in B will have to be increased, say by $di_B$ measured in domestic capital units in B.

To simplify the discussion, we assume that $dc_A$ and $di_B$ is positive in all future periods, and take them as our points of departure. For both countries, we may now assess the optimal compositions of consumption goods and capital goods respectively at different terms of trade. The candidates for optimal compositions are indicated by thick lines for each country. By a transfer of these optimality lines to the first quadrant, we obtain the new terms of trade by the intersection of the two lines. If the $p$-line representing the terms of trade becomes steeper, it is advantageous to the investing country.

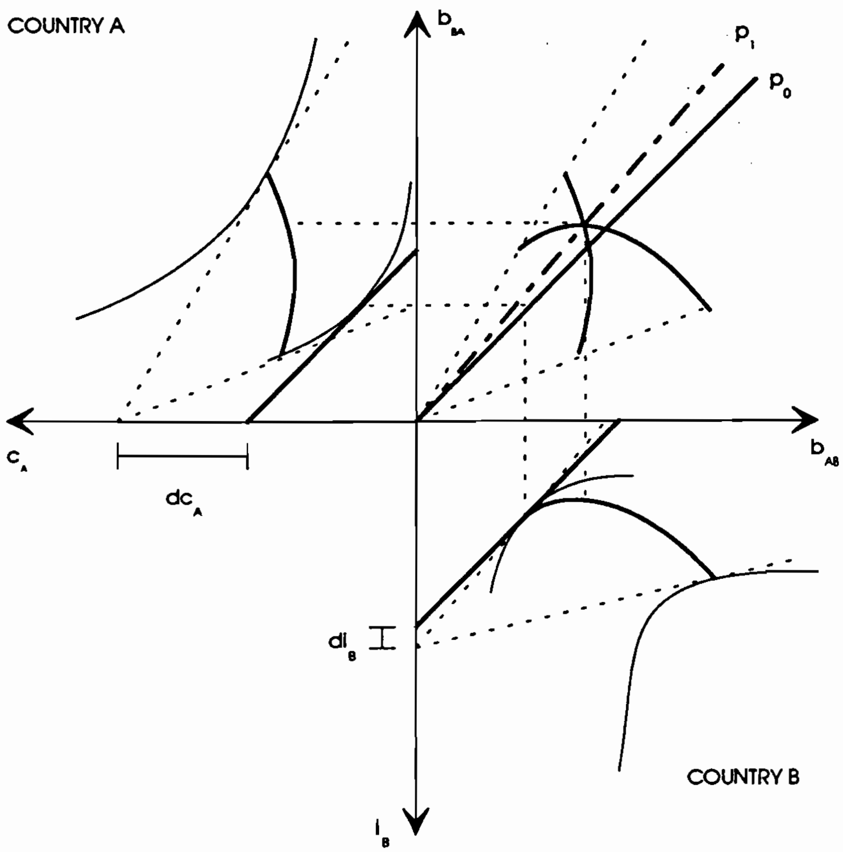


**Figure 1.** Terms of trade with and without joint implementation.

The figure shows that the direction of the change in the terms of trade will depend on the elasticities of substitution between imported and home-made goods in both countries. It is therefore ambiguous which country takes advantage of the introduction of joint implementation with regard to the terms of trade. Generally, "the winner" will be the country with the best ability to substitute between imported and home-made goods. In the example outlined in the model, the flexibility of the production structure in developing countries will then have to "compete" with the flexibility of the consumption pattern in developed countries, which perhaps may be too hard for the developing countries. Thus, if the economic structure in the above model actually gives a reflection of differences between possible investing and receiving countries, one may find it reasonable to expect that receiving countries may loose terrain in terms of trade potential vis á vis the investing countries. As to the assessment of the incremental cost of a joint implementation project, this should imply the use of a higher discount rate for imported capital in joint implementation projects than usually applied.

## 5. Uncertain Environmental Effects of Abatement

Regardless of how the costs and benefits of alternative projects are assessed, the environmental effect attached to each of them will be uncertain, in some cases very uncertain. The investing countries will have to pre-assess this uncertainty anyhow, and evaluate the projects in the light of the presumed risk. One way of doing this is to include a risk premium in the cost function for abatement. In addition to the enhanced "certainty equivalent" cost, the effect of the uncertainty within the scope of the model presented above will be that the desired target level for the investing country will become lower.

For the receiving countries, the uncertainty related to the emissions are irrelevant initially, as they are not supposed to make commitments on emissions of greenhouse gases. For some countries, such as the newly industrialized countries (NIC) and former centrally planned European countries, however, introduction of commitments on emissions of greenhouse gases may not be too far ahead. Targets may occur as a result of own interests, or from pressure from other countries, see e.g. Bohm (1993). At the same time, many of these countries are regarded particularly attractive as receivers of projects. This is partly because of their potential future economic performance, and cooperation in general is regarded by rich countries as investments for the future, although perhaps with a quite uncertain outcome. Another reason is that side-effects of greenhouse gas-abatement such as reductions in other air pollutants may be beneficiary to (rich) neighboring countries in search of joint implementation projects.

To what extent should a receiving country take account of the cost of implementing an anticipated future target? Since they do not know the future target they must regard it as uncertain. In addition, they are uncertain about their own future emissions, which probably will be decisive for when to make commitments.

Here, we restrict ourselves to consider uncertainty only in the emissions and assume that the level of the future target for emissions is given. We recall the model of the receiving country in Section 4, but omit the trade variables and relations as these are unimportant to the present argument, and can therefore also omit the country labels. We are left with the following economic relations:

$$\max_c \int_0^T u(c_t)dt \tag{38}$$

s.t.

$$\dot{k} = \psi(k_t) - c_t \tag{39}$$

We assume that the emissions, $e$, can be expressed by a deterministic term related to the production of goods (and thereby including capital as its only argument), $\xi(k_t)$, and a stochastic term $z$ with $Ez = 0$. Thus, the emission target implies the restriction

$$e_t = \xi(k_t) + z_t \leq \epsilon, \tag{40}$$

where $\epsilon$ is the future (certain) target level and $Ee_t = \xi(k_t)$. The target is not supposed to be binding at $t = 0$, i.e. $e_0 < \epsilon$. Denote by $\pi^s$ the probability for state $s$ to occur, and to simplify (a lot) we assume that its distribution is independent on level of production and emissions. The nation maximizes expected utility which implies that restriction (40) will give rise to one shadow price for each state of the world at each point of time. The Hamiltonian becomes

$$H = u(c_t) + \lambda_t[\psi(k_t) - c] + [\sum_0^\infty \mu_t^s \pi^s(\xi(k_t) + z_t^s) - \epsilon]. \tag{41}$$

$\mu_t^s$ is the shadow price of the emission restriction at $t$ in state $s$. The country may be fortunate and avoid targets even at a "high" level of production, but it may also be unfortunate and need to impose a future target at a "low" level of production. From the first order conditions, we obtain the following social discount rate along the optimal path for this country (see interpretation in Section 2)

$$-\frac{\dot{\lambda}_t}{\lambda_t} = \psi'_{k_t} + \frac{\xi'_{k_t}}{u'_{c_t}} E\mu_t. \tag{42}$$

Equation (42) tells us that the discount rate should be assessed according to the expected shadow price of future targets, and not according to the expected future emissions. The situation for a given future period is illustrated in Figure 2. For simplicity, we have reduced the number of states to

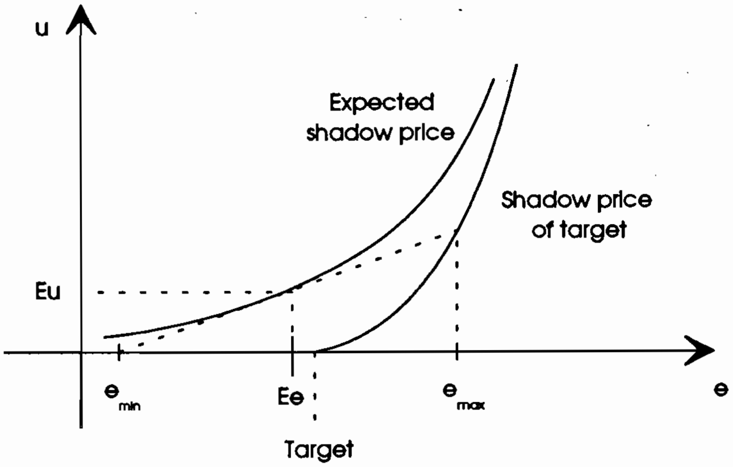


**Figure 2.** Effect of anticipated future target.

two, and assume that each state has the same probability. Thus, expected emissions in this period are found as the median of the emissions in the two states, and thereby lower than the given target, $\epsilon$.

The figure shows that the country may very well account for the future target, even if expected emissions are far below. This is because there may be a chance that emissions will exceed $\epsilon$, and this possibility has a cost. The optimal solution shows that the proper way to account for this possibility is to include the expected shadow price of the target into the social discount factor of the economy.

Introduction of joint implementation has a second effect on the discount rate which is not equally evident from the model. In the present model, eventual abatement activities consist only of reductions in output in order to meet the target $\epsilon$. There are no other opportunities for such activities in the model. Joint implementation means that some other countries "use up" the least cost alternatives for reducing emissions. In the framework of the present model, this implies that when or if $\epsilon$ is reached, a higher amount of produced units will have to be withdrawn in order to satisfy the emission restriction (40). Consequently, the shadow price of this restriction gives a positive shift from the joint implementation project. It is seen from Figure 2 that this also implies a positive shift in the expected shadow price, and thereby on the discount rate of the project in question.

## 6. Concluding Remarks

Evaluation of projects to be considered for joint implementation of the Framework Convention of Climate Change requires, at least to some extent, pre-assessments of costs and benefits. Apart from the well-known problems in making such assessments, an application for joint implementation purposes raises new aspects to be considered. The proper "price" of a joint implementation project will depend on the receiving country's evaluation of effects of the project. Thus, different opinions about how such effects should be evaluated may be a source of conflict between investing and receiving countries when setting the price. This indicates that the problems of including, for instance, non-utility information in the analysis may be more critical when we come to projects to be considered for joint implementation than in other social cost-benefit analyses.

Another issue to be addressed is whether a system of joint implementation itself may have macro-economic effects that should be included when setting the "price". Such effects cannot be represented as cost- or benefit items in a given project, but an analysis of the optimal development of the economy with and without joint implementation shows how such a system may affect the optimal path, including the choice of the discount rate to be used in social cost-benefit assessments.

It is shown here that introduction of joint implementation may change the terms of trade between investing and receiving countries, and that it will be advantageous to the country with the highest economic flexibility. There may be reasons to expect that this flexibility is highest in investing countries. If so, the "price" of joint implementation projects should be increased to account for this loss in the receiving countries.

Finally, some receiving countries may anticipate a future target on their own emissions. This contributes to reductions of the present value of joint implementation projects. As long as there is any chance that the receiving country will have to impose a target on emissions within the scope of time covered by the analysis, one should account for the expected cost of this target. This cost may be substantial even if the target is not expected to be binding. In addition, joint implementation projects may remove low cost abatement opportunities for the receiving country before it needs to impose its own target. The expected cost of a future anticipated target may be even higher.

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# Joint Implementation and Sharing Commitments: A Southern Perspective

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## Abstract

The possibility of joint implementation (JI) is mentioned in the Framework Convention on Climate Change (FCCC). This means that one country can invest in another to reduce $CO_2$ emissions.

There may be GHG-reducing projects in developing countries that are more cost-effective than measures in industrialized countries. However, developing countries may not have the necessary resources to carry out such projects. Should joint implementation with industrialized countries then be permitted to execute such projects under the FCCC? If so, under what conditions and on what terms? Does it only involve benevolent assistance, or is some credit toward the country's carbon reduction obligation desired by each party in such projects? Who bears what proportion of the costs – should the industrialized countries receive credits for GHG emissions saved? What types of projects should be permitted? Even if it is benevolent assistance, commitments expected from the developing countries to complete joint implementation projects should be made amply clear. How can they be defined so that they do not involve long-term deprivation of development alternatives. It is necessary that socioeconomic, scientific, political, and environmental aspects are considered prior to such decisions. This paper elaborates on some of these issues from the point of view of the DCs.

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# 1. Background

After the signing of Framework Convention on Climate Change (FCCC, 1993), at the Earth Summit at Rio, one of the next most important issues on the agenda was "joint implementation" (JI). There are many interpretations of joint implementation, but generally it means that two or more countries reduce carbon emissions jointly. For the industrialized countries (ICs), this provides an opportunity to reduce emissions in other countries, especially former centrally planned countries (referred to as countries in economic transition, CIETs) or developing countries (DCs, also referred to as the South or Group 77+China).

In August 1993, the Intergovernmental Negotiating Committee (INC) met in Geneva to discuss this matter further as mandated by the FCCC. Some of the developed countries wanted to know whether JI with offsets or credits would be permitted before agreeing to a timetable for a commitment to reduce carbon emissions. At the INC meeting, perceptions differed about what JI is, whether credits should be given for emissions reduced in another country's territory, and whether JI with DCs should be permitted only after 2000 when the ICs will have begun to reduce their emissions. Since the final decision has been postponed until the next meeting in February 1994, it is timely to discuss these issues in a wider perspective.

The FCCC gave no precise targets for emissions reductions, referred to as "commitments". This issue remains to be sorted out in the subsequent post-Rio meetings. However, many developed countries would like to know *first* whether JI with offsets will be permitted before agreeing to commitments. Thus, JI and commitments are closely linked and may determine the effectiveness of emissions reductions.

Developing countries have provided environmental space to the industrialized countries at no cost for decades, and will continue to do so for many decades in future, before the regional emissions balance is altered. Annually, this environmental subsidy is estimated to be around US$70 billion.[1]

[1] If the world had a balanced development, everyone would have a carbon emissions entitlement of 1.1 t per year. Due to the skewed income distribution, in 1990 the ICs emitted 75% of emissions, rather than their share of 25%, of the total emissions of 5.6 billion tons. 50% of 5.6 billion tons is 2.8 billion tons of excess emissions, which is the extent of environmental subsidy provided by the DCs to the ICs. It is assumed that while the first billion tons could be reduced at a cost of $15 per ton, the next 2 billion tons would cost much more, since the cost rises exponentially. Assuming, for simplicity, an average cost of $25 per ton for the entire 2.8 billion tons of emissions, the South–North transfer or subsidy is approximately $70 billion equivalent per year.

Therefore, it is reasonable to ask to reverse this and to expect North–South flows in proportion to this subsidy.

Some environmentalists in the industrialized countries oppose joint implementation on the grounds that the ICs must reduce their greenhouse gas emissions at home through their own actions and by changing their own consumption patterns. They should not use other countries to do their work for them. They should not seek to solve the problem by "throwing money at it". Others oppose the idea on the basis that it would prevent new technological development. Resentment is also expressed by the environmentalists in developing countries against the passing on of others' burdens to them in the name of "burden-sharing". They fear "eco-colonialism". Faced with such opposition, JI projects need to be selected with extreme care. However, there is justification for joint implementation, if only to discharge a *portion* of the obligations of the developed or industrialized countries listed in Annex I of the FCCC. As long as JI projects are related to the development priorities of developing countries, there is a long-term advantage to the global environment as well as to the parties involved in such projects. This is so because with additional funds, carbon emissions would be reduced in the developing countries from early on, rather than several decades later through their own efforts.

## 2. Criteria for Joint Implementation

Criteria for JI have to conform to the objectives of the FCCC (Article 2), which deal with

- Stabilization of GHG concentrations.
- Avoiding risk to food production systems.
- Sustainable economic development.

The FCCC objectives do not include cost-effectiveness, although this is mentioned at several other places in the FCCC. However, care should be taken to ensure that developing countries are not saddled with the burden of JI projects, under the guise of cost-effectiveness meant for the industrialized countries. JI projects should be formulated to serve other commitments mentioned in the convention, such as eradication of poverty and sustainable development.

It is not enough that JI projects be not harmful; they should not be unrelated to the priorities of developing countries. Projects that are harmless but unrelated to development priorities divert attention and scarce skills away from priority areas and thus involve high opportunity costs for developing countries. When a project is directly related to their own priorities, it ensures the enthusiastic participation of developing countries and, therefore, also its success.

## 3. Joint Implementation: Economic Interpretation of the Transactions

For an industrialized country, there is a cost involved in discharging its GHG emissions reduction obligations. When talking about JI in developing countries being "cost-effective", it is implied that industrialized countries acquire something that would be "otherwise expensive" in their own country. The cost incurred in a JI project is in lieu of the GHG reduction credit. We call this the cost of carbon credit, and it can take any form: direct foreign investment, or North–South transfer, or any other mechanism. However, as long as an industrialized country wishes to have carbon credits, this is a transaction involving market exchange, a trade. Joint implementation could be viewed as trade in carbon credits or direct foreign investment rewarded in terms of carbon credits. Trade is an instrument from which both parties benefit from their respective comparative advantages.

Proposals to give assistance and keep separate records at home and abroad also come into this category if at any time offsets or concessions are sought for reductions at home against reductions abroad. It is no longer assistance without returns and three issues emerge:

- Do developing countries who participate to make the reductions cost-effective get a fair deal?
- When carbon credits accumulate with industrialized countries through JI projects, they appreciate in value with time, assuming that as time goes on reductions will become more expensive. How does one share these benefits of value appreciation?
- If emissions reductions abroad are substituted for emissions reductions at home, what happens to global accounts of emissions and distributions? This may be the worst option.

These issues are discussed below.

# 4. DCs Need JI Now, and Not in 2000

If developing countries reduce *more* and *earlier*, the benefits would be substantial over the lifetime of energy efficiency programs and equipment. It is possible to stimulate greater carbon reductions with adequate investment and effort. This would bring developing countries to low GHG paths faster and sooner. (The analogy of reducing births to control population comes to mind; faster and earlier birth control could reduce the global population from 15 billion to 8 billion or less in the year 2100).

If this is not done, the gains made by industrialized countries in *reducing carbon emissions will be wiped out at a faster rate by developing countries.* It is fallaciously argued by some that through JI, developing countries will be paid for energy efficiency programs that they would have carried out anyway, and that world GHG levels will not go down. These arguments assume a fixed amount of carbon reduction is possible every year due to energy efficiency programs, not only in terms of quantity but also of time. Analyses for India and other countries have shown that progress in the area of energy conservation is rather slow despite the large potential. Addressing this issue with vigor will yield more benefits to all parties and to the global environment. Waiting until 2000 for permitting JI with DCs will be too late. For example, Thailand expects that their emissions will triple by 2006 (Chirarattananong and Limmeechokchai, 1993), and for India, Parikh and Majumdar (1993) find that by the year 2010 fossil-fuel-related emissions may rise to 533 million tons of carbon equivalent (Mtce) from 168 Mtce in 1990.

# 5. Priorities for JI Projects

The FCCC stresses the need for sustainable development and compatibility with development priorities. Therefore, it is advisable to begin JI cautiously. At first, those areas should be considered where both parties are certain to benefit, that is, "no-regret" projects. In principle, carbon reductions should be won by controlling the sources of emissions or by enhancing carbon sinks.

## 5.1. Projects to reduce carbon emissions through increased efficiency

The best projects currently on the list of priorities of developing countries in the area of energy include "no-regret" options:

1. Reduction of carbon emissions by saving imported oil or electricity through improved and efficient technologies, which are investment- and

import-intensive. All countries use oil and electricity. Therefore, this would be of interest to all developing countries. Even oil-rich countries could export more if they used oil more efficiently.
2. Investment in reducing power supply system losses or modernizing them to make them more efficient.
3. Conservation projects for fossil fuel resources such as coal and gas which are used mainly when they are available domestically.
4. Reduction of methane emissions from gas flaring, leakages from gas pipelines and coal mines, reducing or harvesting methane emissions from sewage and wastewater, improving ruminant digestion to reduce methane.
5. Projects which reduce biomass burning by providing or developing efficient cooking stoves, brick or charcoal kilns; or by providing or developing clean fuels such as biogas; or by providing kerosene.

This list of projects could be enlarged to include less carbon-intensive technologies for transport, construction, industries and agriculture as well. For example, a project could propose assistance for mass transit systems such as railways or suburban transport because private transport – serving as it does, only a chosen few – is not a sustainable solution, given the large populations of developing countries. Carbon reductions from mass transit systems could be large over the long term; and investments in mass transit also would reduce traffic congestion, fuel consumption and air pollution.

## 5.2. Projects to enhance carbon sinks

Joint implementation projects for the enhancement of carbon sinks present considerable difficulties in terms of the calculation of credits. A distinction needs to be made between different schemes such as

- preservation of existing forests,
- rehabilitation of degraded forests,
- afforestation projects,
- conversion of agricultural lands to establish plantations.

The last two involve complex issues of alternative land use. When prices of carbon credits are high, there is the danger that subsistence farmers could be tempted to give up their land for carbon reduction. With his high discount rate, a farmer may trade in his hunger for short-term gain, thus satisfying the hunger of industrialized countries for more fuels and hence carbon. Such a distressing sale would land him in trouble in the long run. However, it will be difficult to avoid this problem and to confine joint implementation projects to wastelands or forests alone, where irrigation, soil quality, and labor may not be easily available.

In general, those investing in forests are looking for a long-term supply of carbon credits. In long-term forestry projects, there are many risks such as forest fires, droughts, and pests. Who bears these risks? Can there be insurance against them? The interests of local communities living in and around forests may be compromised by treating the forests as carbon sinks when these areas play such complex role in their lives.

### 5.3. Synthesis of priority projects

Joint implementation projects to *reduce* emissions from given activities by increasing efficiency should have priority over carbon sink enhancement because:

- there may be a problem in calculating credits for carbon sink projects;
- there are problems of uncertainty and asymmetric information related to carbon sink projects;
- there are no conflicts with development priorities [through the "no-regret" (absence of conflicts with development priorities) nature of the efficiency projects]. The example of the project in Guatemala described below also highlights these difficulties.

Although there is a need to preserve forests, this may best be done by individual countries themselves. Moreover, forests and biodiversity require more suitable international conventions where the complexities of forest ecosystems may be valued appropriately, rather than by treating them merely as carbon sinks. Since the Global Environment Facility (GEF) looks after all of these conventions, these projects could be handled in a professional manner by them.

There is a general impression that investing in forests will lead to a greener world so let us rush to it; in reality it could lead to more conflicts, as will be shown later.

## 6. Principles of Sharing of Savings between Parties

Considering the lack of capacity of developing countries to negotiate fair deals for themselves, compensation should not be based on individual negotiations but on a market-oriented approach. While currently there are many options which could cost as little as $10–25 per ton of carbon, many economists have come up with long-term costs as high as $200–300 per ton (Manne and Richels, 1992). If cheap carbon credits are taken by the industrialized countries through JI projects for long periods of time in the early stages, some developing countries could be deprived of their true worth later. With asymmetric information, the danger of "selling Manhattan for glass beads" is very real. An arrangement in which payments are linked to the global price of carbon may have to be negotiated, as is done in some oil deals. Carbon credits will be fairly priced only when the savings in costs are shared between industrialized countries and developing countries more than equally. Cost sharing could not be on the basis of incremental costs, which deprives developing countries of their fair share of the savings. All savings accrue entirely to the industrialized countries (i.e., consumer's as well as the producer's surplus; this is explained in Figure 1).

Incremental costs are those that are required for the change from conventional to carbon-reducing technologies. These are generally high for the industrialized countries where energy-efficient technologies are already used and labor is expensive. These are plotted against the quantity of carbon reductions "purchased" in developing countries. The figure argues in favor of receiving the equilibrium price which shares the benefits among the carbon reduction supplier and the purchaser. Considering the inadequate capacity of developing countries to negotiate even through market-oriented trade, the FCCC may think of setting a minimum price per ton of carbon saved, so that these countries may receive at least that much. This price could be updated every one or two years. This may limit the projects to only these cost categories, but that may not be such a severe restriction.

Reductions due to *policies*, such as increased energy prices, should accrue to the people of the host countries who follow such policies and suffer the consequences of high-cost energy.

Very often, what may have been calculated or assumed before a project begins does not hold after the project is completed for a number of reasons such as drastic changes in costs or prices of factors of production, acts of nature such as earthquakes, cyclones or other mishaps such as accidents, fires, etc. The risks of failure should be discussed, anticipated, and accounted for in favor of the developing countries because they are merely sharing the burden of reducing carbon and not the other risks. *Such failures could also have occurred in Annex I countries, had the projects been located there.*

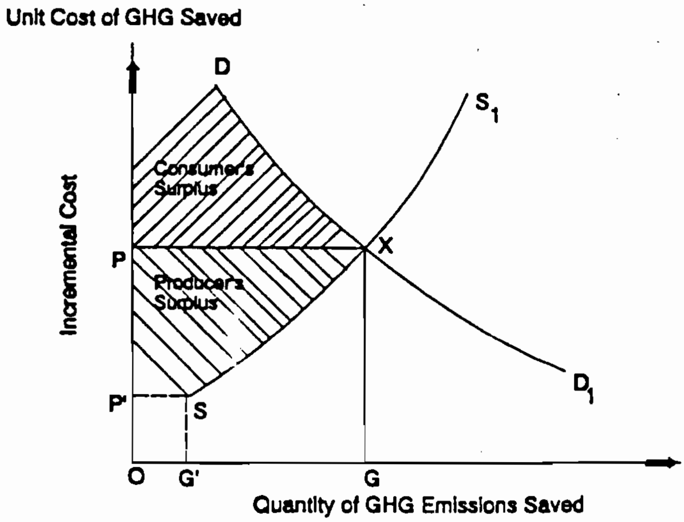


**Figure 1.** Sharing fairly the gains from joint implementation.

A logically clean way to look at joint implementation is to think of it as a market exchange or transaction. In the figure, $SS_1$ is the cost curve of developing countries to supply GHG saving options. The demand curve $DD_1$ shows what the industrialized countries need to pay for GHG emissions. Obviously, the intersection X gives the market clearing price, P, and the quantity traded, G. At X, demand equals supply. An amount OG of emissions would be traded at price OP. The shaded area representing the producer surplus is the gains to developing countries, and the area denoting consumer surplus is gains accruing to industrialized countries. In simple terms, this means that through JI both developing and industrialized countries gain. Industrialized countries pay less than what it would have cost them to reduce as much GHG emissions (consumer surplus), and developing countries gain *more than* what it costs them (producer surplus) to do so. JI should give more than just fuel incremental costs given by the GEF which only gives the price at P′ rather than at X. However, due to this, carbon reductions will also be lower at G′ and will not reach G.

## 7. Distinction between JI Projects and GEF Projects

In the FCCC, the industrialized countries (ICs) agreed to take on two types of obligations. One is to finance the agreed full incremental costs to reduce GHG emissions in developing countries. This will be done through the GEF.

Another obligation is to reduce their own emissions. While the former is to be viewed as partial reparation to developing countries under the "polluter pays" principle, the latter is related to the "polluter should reduce pollution" principle:

- Joint implementation belongs to the second category of obligations, to reduce carbon emissions, and is separate from the obligation to provide the "agreed full incremental costs". Therefore, any investment that is less than what the industrialized countries are likely to incur in their own countries should be acceptable to the ICs.
- The GEF's current approach is restricted to incremental costs only and does not pay adequate attention to sustainable development, which hopefully, North–South transfers through JI may be able to do.
- Many projects may not fit into the incremental costs concept of the GEF, in that there may be no way to fund the basic costs, even if they are low. Such projects could be undertaken by JI.
- Another distinction with respect to GEF projects is in the area of technology. A GEF project may be linked to the technology employed for the basic project (to which it is incremental), and which is quite likely to be selected through global tenders. JI offers an opportunity for industrialized countries to promote their own technologies without going through global tenders. Thus, in addition to receiving carbon reduction credits, an industrialized country could also promote its technology through a JI project. This may not be the best choice for developing countries, however; they may wish to consider several options from a long-term viewpoint before locking themselves into inappropriate or unsuitable technologies.

A related concern that may emerge later is that if energy-efficient equipment comes free or cheap, the domestic manufacturing bases for engineering goods that have been created in developing countries at great effort may be undermined. A better solution would be to upgrade such manufacturing bases through technology transfer or through joint technology development programs.

Thus, joint implementation provides another channel – in addition to the GEF – for reducing GHG emissions in developing countries, and the difference lies in the definition of costs and the selection of technology.

## 8. JI Between Which Parties?

Should the concept of JI only involve industrialized and developing countries, or should the countries in economic transition (CIETs) be included? In some CIETs the per capita emissions are even higher than in some industrialized countries. They have their own share of obligations to reduce their own emissions. While they may be excused from making contributions to the GEF,[2] they should not at the same time deprive developing countries of the funds meant for those whose emissions are low and who have not contributed to the global environmental problem. The economies of the CIETs have remained closed to technological changes that took place elsewhere in the world. In addition to their technological backwardness, their fossil fuel pricing system did not encourage rational utilization of energy resources even with the backward technologies that they had, so that cost-effective solutions were not adopted.[3]

Joint implementation with CIETs should be treated as JI between any two Annex I countries. However, the FCCC indicates a condition that

> ... Parties may ... make a joint communication in fulfilment of their obligations under this Article, provided that such a communication includes information on the fulfilment by each of these Parties of its *individual obligations* under the Convention.

Therefore, the CIETs need to declare their intention to discharge their obligations, and the year from which they wish to start, prior to getting into JI projects. As will be explained in Section 9, the CIETs need to receive a share of the benefits of carbon credits even more than DCs because they have their own obligations to meet, and therefore the value of these credits is higher to them.

JI projects should mainly be undertaken with developing countries whose emissions are low, since they are permitted to *increase* their emissions and have no obligation to reduce them on their own.

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[2]The GEF at present funds projects in these countries and has even defined per capita GDP limits for eligibility for GEF funds as \$4,000 to accommodate them. These eligibility limits should be defined in terms of GHG emissions per capita, rather than GDP per capita, which in any case is the most nebulous variable, especially in the CIETs.

[3]Not surprisingly, the former Soviet Union has been described as the "Saudi Arabia of energy efficiency", i.e., there is a vast potential for energy savings. Even the sale of efficient equipment through normal trade channels will reduce emissions. Can we call such trade JI?

# 9. Global Accountability of Emissions in the Case of JI Credits[4]

If emissions reductions abroad are credited (offset or compensated) against obligations at home without compensation to the DCs, these countries will perceive no stake in either watching what is recorded (given their relatively low negotiating capacities) or in ensuring that projects are successful. Eventually, the credits accumulated by the ICs could be so large that global emissions will increase because the ICs can continue with their present lifestyles while spending only a pittance on emissions reduction exercises. With their relatively high purchasing power, they could cream off cheap emissions credits available all over the world within ICs, DCs, and CIETs. Such a strategy could eventually give the ICs a monopoly in carbon credit holdings, if these credits are not withdrawn after some time. We should keep in mind that opportunities for generating cheap emissions credits is an exhaustible resource.

How much carbon can be considered reduced? Credit for reducing emissions can be given only to the extent of reducing it faster and earlier.

## 9.1. Illustrating the issues with a review and analysis of existing JI projects

Some existing JI projects need to be comprehensively reviewed by experts in both North and South to evaluate their long-term implications from the viewpoints of ICs, DCs, and global environmental objectives. We note that these projects were implemented *prior* to the FCCC. Some of them are acts of goodwill and no credits are claimed. But there are a number of problems associated with them. Some questions are raised below.

Let us take the example of an agroforestry project in Guatemala to offset carbon releases in the USA. A US power plant proposed a scheme (WRI, 1991) in which 40,000 farmers in Guatemala toil for 10 years for our JI project for the sum of \$3.8 million. However, the life time of a power plant is 40 years. It is indicated that the plantations will have to exist for 40 years. In addition, the government of Guatemala is required to pay \$1.2 million. Apparently, this sum of \$5 million is to pay for saplings, land, other inputs and continued care for 52 million trees for 10 years. This works out at a mere 10 cents per tree. Is it possible to plant and nurture a tree for 10 cents? The project seems to expect that Guatemala will be perpetually

[4]Some refer to carbon credit as "assistance"-against-recording. When offsets at home are sought against such "recorded" reductions abroad, it is similar to market exchange.

living in poverty. Does it tie these 40,000 farmers to this project for 40 years? What does Guatemala get for this? What happens to the trees after 40 years? If they are burned, would the $CO_2$ belong to the USA? Would the methane generated due to the decay of leaves and underground matter (roots) after the trees have been cut down belong to the USA? What if Guatemala needs this land for something else during these 40 years? Will it tie down generations for a paltry sum of loans by the rich? What if the new generation wants a shopping complex or any other remunerative activities on this area? If the US company received tax breaks for this purpose, then it did not go through any pains for this project. Rather, it is the Guatemalans who have paid for this project.

The purpose of presenting this case is not to discourage private enterprise from taking initiatives such as this, but to highlight the need for an institutional structure that provides a broad framework and guidelines for joint implementation so that such enthusiasm can be channeled in the right direction.

The above questions reinforce the earlier conclusion that it is naive to use trees as carbon sinks and that it should not be handled by the FCCC.

It is clear that we are dealing with markedly different capacities to negotiate and implement global strategies. Unless a capacity building program is put in place and has made reasonable progress, the DCs could find themselves tied to certain development paths chosen by the ICs. An experimental phase could look into various aspects of JI projects to decide:

- What constitutes a JI project?
- How can responsibilities for carbon reduction, human effort, investment and technology development be shared?
- Do the JI projects conform to the development priorities of developing countries or do they saddle them with new responsibilities to suit the consumption patterns of the rich?

Some of these questions need to be examined for each existing and future JI project before political agreements are reached.

## 9.2. Simplification of JI Schemes

In order to avoid the pitfalls of schemes such as the Guatemala project, a fixed (base not ceiling) amount of compensation could be declared – say \$10 per ton. All schemes cheaper than this could be done first in the ICs by the countries themselves. When projects in the DCs are cheaper than this amount, say \$2 per ton, the remaining amount of \$8 per ton could be used to benefit the community or workers participating in the project, say for schools, hospitals, sanitation schemes, libraries, or other community-oriented projects. Alternatively, this money could simply be distributed among the community or workers. Since carbon will be reduced every year, they should receive that amount every year, thus ensuring the continued success of the project.

Since the ICs have to pay for reducing this carbon, they will refrain from exaggerating their claims and there will be self-imposed verification (unless $10 per ton is underpriced and both parties (DC and IC) collude to exaggerate the claims at the cost of the environment).

### 9.3. Modalities of JI

Modalities of JI should be such that it brings in fresh and additional funds. As clarified earlier, JI is in lieu of another obligation and should not be seen as a substitute for contributions to the GEF, which is also supposed to provide new and additional funds over and above development aid, as mentioned in the FCCC. How is it possible to raise additional funds when the ICs complain about paucity of funds even for the GEF? In order to bring about the required carbon emissions reductions, the ICs may have to levy a carbon tax. Tax breaks could be offered to those private enterprises who carry out JI projects in DCs. Since the purpose of the carbon tax is not to generate revenue to balance budgets but to discourage carbon emissions, IC governments would be free to grant tax rebates for JI projects to private enterprises corresponding to the carbon emissions saved in the DC. First, this tax liability could be reduced by the enterprises by reducing carbon emissions in the IC itself. Second, even this reduced liability could be reduced further through JI projects in DCs. What about individuals who wish to reduce carbon tax on their fuel consumption? Carbon reducing enterprises could be set up that undertake JI projects in DCs. These individuals can contribute to these and receive tax rebates in proportion to the carbon saved by such projects.

## 10. Link between JI and Commitments

The draft paper on joint implementation discussed at the INC in August 1993 introduces three new concepts and principles in a single phrase which need to be discussed before adoption. When the paper talks about "jointly returning to 1990 levels of greenhouse gas emissions", four major issues emerge:

## 10.1. "Grandfathering"

The main difficulty is the goal of reverting to "1990 levels". This introduces the principle of "grandfathering"; that is, those who have had high emissions in the past need only go back to those high levels and this establishes their right to higher emissions. This introduces a major problem that needs to be debated. Furthermore, in the FCCC, differentiated responsibilities are mentioned. These need to be clearly expressed in terms of per capita emissions because even within the Annex I countries, some enjoy different lifestyles than others. They therefore ought to have "differentiated responsibilities", as agreed in the FCCC. Those Annex I countries with high per capita emissions should have greater responsibilities for reduction. This would be the first time the INC would adopt this principle and debate is necessary on this issue. If the principle of reverting to "1990 levels" is accepted, several decades later developing countries will also be asked to revert to the levels of 2010, and so on. This would be unfair to those who have been less profligate in the past. Those who have occupied more environmental space due to higher historic emissions should have greater responsibilities and therefore higher obligations for reduction.

## 10.2. What if 1990 levels are higher?

Another problem with taking 1990 levels as a goal is the underlying assumption that 1990 levels would always be lower than those in 1993, which may not be true. As shown in Table 1, the emissions of Annex I countries are fluctuating and many have been declining steadily since 1980, e.g., France. Therefore, to revert to 1990 levels, 1980 levels, etc., would not address the global environmental problem. For example, in Western Europe, emissions in 1980 were higher than 1988. If one were to decide to "go back" to 1980 emissions should they *increase* their emissions? "1990 levels" is no goal at all. There are some who could do better than "going back to 1990 levels" for the same cost. The goals should be such that they should be encouraged to do so. Thus, the goal of reaching 1990 levels could be economically inefficient and environmentally inadequate (if not absurd).

## 10.3. Emissions reduction commitments in percentage terms

Rather than fixing targets in terms of past emissions levels, it may be more desirable to fix targets in terms of fixed percentage reductions in average per capita emissions for the decade. This way, there would at least be equity among Annex I countries to start with. Those who have emitted more should

**Table 1.** Comparison of emission levels in 1989 and 1980.

| Countries | Total emissions (million tons) | | Per capita emissions (tons) | |
|---|---|---|---|---|
| | 1989 | 1980 | 1989 | 1980 |
| USA | 1328.9 | 1259.3 | 5.37 | 5.53 |
| USSR | 1038.2 | 895.5 | 3.62 | 3.37 |
| Canada | 124.3 | 115.8 | 4.73 | 4.82 |
| Czechoslovakia[a] | 61.8 | 66.1 | 3.95 | 4.32 |
| France[a] | 97.5 | 132.1 | 1.74 | 2.45 |
| Federal Republic of Germany[a] | 175.1 | 208.0 | 2.86 | 3.38 |
| Poland[a] | 120.3 | 125.4 | 3.15 | 3.53 |
| United Kingdom[a] | 155.1 | 160.6 | 2.70 | 2.83 |

[a]Five countries had higher emissions in 1980 than in 1989.
Source: CDIAC, 1991.

work harder according to their "differentiated responsibility". In a fixed percentage reduction scheme, country A with higher emissions would reduce more every year than country B with lower levels. Some may argue that even this scheme would permit some "grandfathering" because it would give country A more time to reach a specific level of emissions per capita per year. However, that much more time may be permitted to restructure their economies. To help them achieve this more difficult goal, offsets may be permitted with developing countries for a limited period. This would be one way to compensate developing countries for their lower emissions in the past and also for some time to come, since GEF contributions will clearly be inadequate to meet the challenge.

Figures for 1993 emission levels are not yet available, but one strongly suspects that the above argument will also hold for the comparison of 1990 and 1993 emission levels.

## 10.4. No offsets for Annex I countries

The word "jointly" in the FCCC could be interpreted as "providing assistance". The FCCC does not recommend offsets against emissions limitations in another country's territory. For example, if the USA and France declare goals to reduce emissions "jointly", the USA could actually increase their emissions by taking advantage of France's past reductions. France, of course, could extract some benefits for permitting such an "arrangement". Therefore, the agreement on joint implementation should clearly state "no offsets will be permitted for emissions limitations for projects in other countries' territories between Annex I countries".

There is an additional difficulty in the case of countries in economic transition (CIETs). In the FCCC, the CIETs are given flexibility to declare the year in which they would begin reducing emissions. The CIETs must be required to specify the year by which they would reduce emissions prior to entering into JI agreements. Without such declarations, there will be a problem in the global accounting of emissions. Their energy inefficiencies are such that even the sale of some equipment through normal trade channels will result in "joint" reductions. Despite the fact that their emissions are high, the CIETs are given the facility not to reduce emissions. This flexibility will be misused if it is used to offset another country's emissions, since, in practice, they also need to reduce their emissions. A more important point is that taking advantage of their past inefficiencies is unethical, especially for those countries who have contributed to the problem. Thus, joint implementation should only mean assistance. No offsets should be permitted for JI among Annex I countries. Permitting offsets among Annex I countries, i.e., with CIETs and IC countries, is letting the "polluters profit".

### 10.5. Permit offsets with developing countries

JI with offsets makes sense only if it is done with developing countries who do not have obligations to reduce their emissions. There is nothing wrong if they profit by small sums because they have already offered environmental subsidies of the order of $70 billion per year to Annex I countries. Therefore, for them to receive token fees in the form of offsets would be justified.

## 11. Concluding Remarks

In summary, joint implementation can benefit both parties, provided that the principles of sharing savings are followed and provided both the main objectives of the convention – *global accounting of emissions reductions and the promotion of sustainable development* – are adhered to. Fair price for JI has to be higher than the full incremental costs given by the GEF where producers surplus does not come to the developing countries.

Since JI projects are responses to the second obligation of reducing emissions by the ICs, one expects more North–South transfers from private enterprises to obtain carbon tax rebates in ICs. These transfers will be in addition to GEF funding, which is also a new and additional source of funding according to the FCCC.

We have discussed two modes of joint implementation. One is the "trade-mode" where a fair price is given against offsets. This is meant for JI between

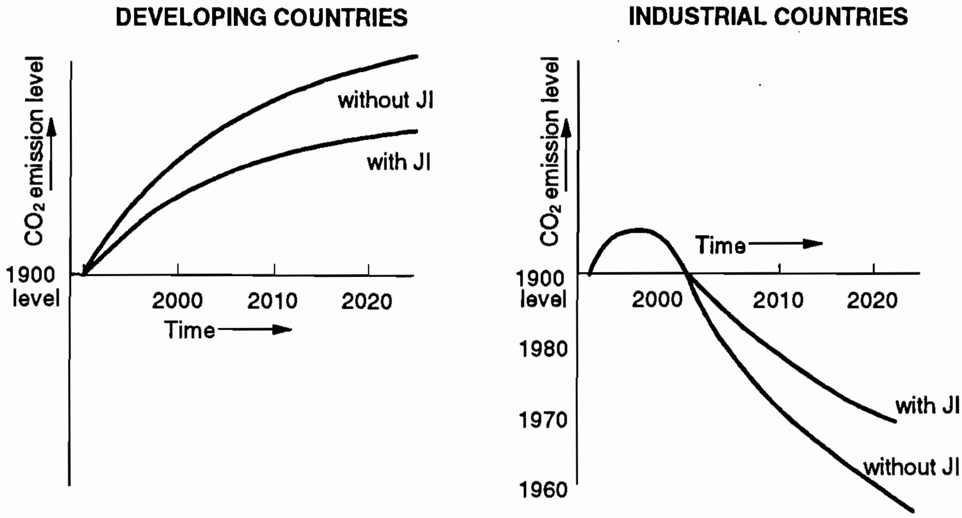


**Figure 2.** "Assistance but no carbon credit": reduced pressure due to joint implementation.

If the developing countries reduce their emissions due to JI, the effect will be to slow down the build-up of carbon in the atmosphere, and there will be less pressure to resort to severe cuts in emissions by the DCs. Therefore, the chief advantage of JI for the ICs is less pressure in future to reduce emissions, if climatic uncertainties turn out to be more severe than we now think. This could be thought of as a risk-aversion measure or insurance. In future, for example, instead of reverting to 1960 levels, it may be sufficient to revert to 1970 levels, if the global balance of $CO_2$ emissions is considered. *Carbon credit is not explicitly given* for every project, but the net result will be reduced pressure.

Annex I and developing countries. The second is the "benevolent assistance mode" where costs are given but no offsets are expected in return. The second mode, explained in Figure 2, is expected between Annex I countries. There could be several combinations of this, but the worst combination would be that developed countries do not pay a fair price and still claim offsets against these credits.

Credits for emissions reduced in the host countries may not be used between Annex I countries to compensate for their own emissions. However, offsets may be permitted for JI is with DCs. This will be a token contribution by the ICs for the $70 billion subsidy the ICs receive for their emissions from the DCs. Even if offsets are not permitted, there are other advantages. The ICs should view JI as an opportunity

- to induce capacity building, and so to raise awareness in DCs and CIETs, enabling them to shift to different development paths that reduce emissions;
- to slow down the increase in emissions by the DCs and CIETs. This will reduce pressure on the ICs and give them breathing space to restructure their economies; and
- to carry out confidence-building exercises necessary for the partnerships that will be required for many decades of collaboration necessary for this endeavor.

JI could pave the way to enormous demand for energy-efficient equipment, and could strengthen cooperation through technology development and technology transfer. It could increase jobs in industrialized countries and reduce the fuel needs of developing countries, while serving global environmental objectives.

Having given the positive aspects, one must also admit that if JI projects are inappropriately defined or conceived, some serious questions could arise later and the DCs may find themselves bound to carry out projects with few benefits and without adequate compensation. This paper has suggested some simple schemes that are (partially) self-verifiable.

An experimental phase for JI projects could be initiated in several areas to reduce emissions in DCs. Projects that bring about systemic changes to reduce fossil fuels could be mutually beneficial. Existing JI projects could also be analyzed to see what lessons can be learned from them. It is as yet unclear how to account for carbon reductions, and a number of alternative schemes need to be analyzed before an understanding can be reached. After this experimental phase, and the completion of reviews, JI could be formalized by the INC. However, the INC may agree to initiate an experimental phase. Decisions concerning JI projects should be taken only after careful considerations of socioeconomic, scientific, political, and environmental aspects.

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# Comparable Assessment of National Greenhouse Gas Abatement Costs: Results of Ten Country Studies

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Risø National Laboratory, Denmark

## Abstract

A methodological framework for national greenhouse gas abatement costing has been developed and tested in ten country studies: Brazil, Denmark, Egypt, France, India, the Netherlands, Senegal, Thailand, Venezuela and Zimbabwe. The main focus of the country studies was on "bottom-up" technical-economic investigations of the reference case and abatement scenarios.

Country teams estimated abatement costs for reduction targets of 12.5–25% from the baseline in the short term (2005 to 2010) and 25–50% in the long term (2020 to 2030). Abatement cost is defined as the incremental cost of GHG reductions, relative to a baseline in which abatement is not an objective. Costs are measured as the direct/financial costs on an energy system and sectoral level. The costs include levelized investment, operation and maintenance, and fuel costs.

Some of the important methodological lessons derived from the process of developing and evaluating the country studies are summarized in the paper. They relate to definition of the baseline, treatment of energy-efficiency improvements, macroeconomic feedbacks, implementation barriers and costs, and joint products.

## 1. Background

The UNEP project on developing a common methodological approach for assessing the costs of limiting greenhouse gas emissions (GHG) was initiated in 1991 in an effort to improve understanding of the subject and to help establish a basis for national studies of the economic issues which would be accepted as consistent and comparable between countries.

The first phase of the project consisted of detailed studies of the underlying issues in estimating abatement costs, including analysis of modeling options and reviews of existing cost estimates, and a small set of preliminary national studies. These country studies established the status of analysis and data in the countries concerned, drew lessons from past experience, and illustrated the practical issues raised in embarking on abatement cost studies in widely diverse countries.

This work was documented in the report of Phase One of the project published in autumn 1992 (UNEP, 1992). The studies highlighted the complexity of the issues, noting that assessing the full economic impact of greenhouse gas abatement is unlike any previous environmental issue because of the central role of GHG-emitting sectors in economic development and the complexity of the markets involved. The issues raised in assessing abatement costs vary greatly according to country, status of development, energy and economic system, and the time scale and degree of abatement considered.

Phase One was able to draw some general conclusions on the likely upper and lower bounds to the abatement costs from a review of the literature. For example, it was recognized that all countries have some options for limiting emissions which cost little or nothing, and that the costs of stabilizing global $CO_2$ emissions over the next 30–50 years are unlikely to exceed 2.5% of global GNP and could be much less. Regarding national-level analysis, the study noted that abatement costs may be inseparable from the policies employed and highlighted the importance of understanding the practical constraints and hidden costs of different policies.

## 2. Development and Testing of the Methodology

On the basis of the first phase of the project, a methodological approach was developed and tested in Phase Two, under which ten country studies were carried out by national teams from Brazil, Denmark, Egypt, France, India, the Netherlands, Senegal, Thailand, Venezuela and Zimbabwe (UNEP, 1994). The central project team led by the UNEP Centre was responsible for formulating the project guidelines and coordinating the country studies. The approach was laid out in a guidelines document (UNEP, 1993). The guidelines were improved in an iterative fashion in conjunction with the national teams, particularly through four project workshops, and through application of the guidelines in their national studies. A parallel aim throughout the project has been to help build capacity for conducting such analyses in developing countries.

The proposed methodological framework for GHG abatement costing in Phase Two comprises three elements:

1. definition of key concepts and terminology
2. a set of common quantitative assumptions (international fuel prices, test discount rates, reduction targets, etc.)
3. an analysis structure (see Figure 1)
   - country review (background and existing studies)
   - definition of a reference scenario
   - identification and ranking of abatement options
   - construction of abatement scenarios
   - macroeconomic assessment
   - subsequent evaluation (political, social, etc.)

The general analytical structure and quantitative assumptions were followed by all the country teams. The main focus of the country studies was on "bottom-up" technical-economic investigations of the reference case and abatement scenarios. Following this approach, most of the national teams were able to construct consistent abatement scenarios for the specified reduction targets of 12.5%, 25% and 50% reduction from baseline scenario emissions. India, Thailand, and Venezuela stopped at a reduction of less than 30% from the baseline in 2030 as the maximum achievable reduction. Note that the reduction targets were defined according to the reference scenario emissions, not from the current emissions.

## 3. Reference and Abatement Scenarios

The results of the Phase Two country studies are summarized below. A national GHG abatement costing study is dependent on the definition and construction of scenarios. The cost of GHG abatement is defined in terms of the difference between a *Reference Scenario* and an *Abatement Scenario.* The term scenario is taken to mean a consistent description of the country in question, particularly its energy system and GHG emissions, over the period of the study, from the present to 2025 or 2030. Thus, a scenario consists of a set of assumptions concerning national economic and demographic development, technical details of energy consumption and supply systems for the country in question and for the international energy economy, to the extent that this affects GHG emissions and abatement costs in the country.

The present project aims to make comparable assessments of abatement costs at certain levels of emission reduction. We have therefore attempted

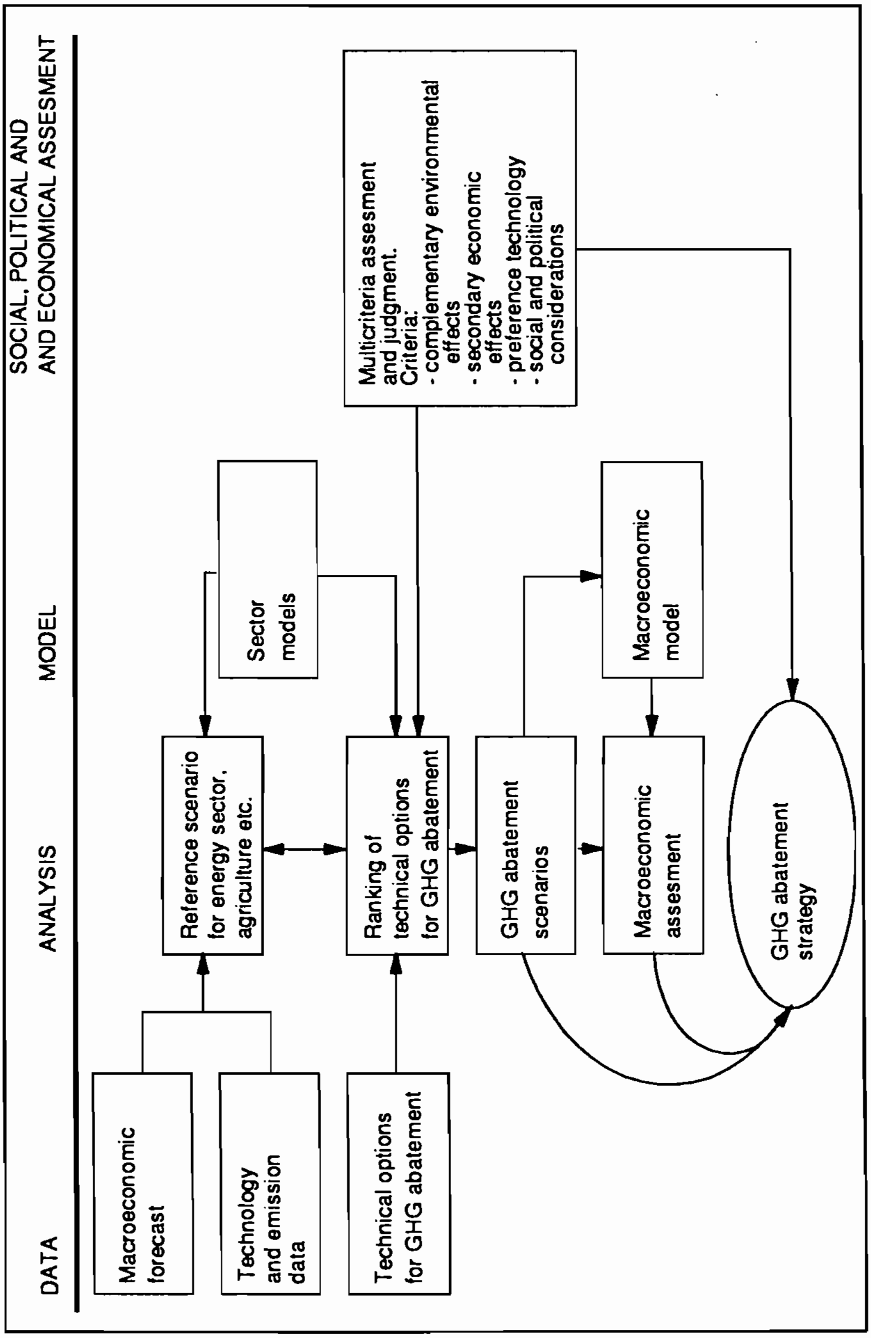


**Figure 1.** Structure of proposed abatement analysis procedure.

to establish a comparable framework for reference and abatement scenario definition. While each country's future scenarios will inevitably be unique, the comparability of studies is enhanced by following a similar approach and a consistent set of assumptions, for example with regard to world fuel prices and overall global economic development.

Because the abatement scenarios are defined in terms of reductions from a baseline scenario, the emission results depend on the definition of the baseline. The results are most sensitive to the degree to which potential low-cost energy-efficiency improvements are captured in the reference scenario, rather than being available as possible emission-reduction measures in the abatement scenarios. As explained below, the abatement cost results are especially sensitive to the definition of the baseline scenario and the energy-efficiency assumptions used.

The trends in $CO_2$ emissions projected in the ten country studies show great variation. Differences between the emission growth rates among countries reflect differences in development levels, assumptions, economic structure, etc. In particular, there is a marked difference in the projected emission trends in the group of developing countries from those in the three industrialized countries. In spite of these differences, the common structure, terminology, and background assumptions in the project make it possible to explain and understand the differences and similarities. As stated above, much of this explanation depends on the details of energy-sector developments in the country studies.

The reference scenarios tend to be influenced heavily by recent developments, consistent with the assumption that cheap energy will last for many years, due in part to the global GHG abatement effort assumed in the guidelines as the context for the national studies. A consequence of these projections is a dramatic increase in energy consumption. The oil consumption of developing countries involved in the present study was 3.5 million barrels per day in 1990, while their demand by 2025 is projected to reach 16.2 millions of barrels per day. This volume represents about 70% of current OPEC production and is large enough, especially if extrapolated to other countries, to impose great pressure on world oil supplies and prices. The consistency of the projected oil prices is thus a matter for some discussion

The reference scenarios for the seven developing countries calculate that the total carbon dioxide emissions from the group will increase from 750 million tons in the base year to about 3500 million tons by the end of the period in 2025–2030. The high abatement scenario reduces $CO_2$ emissions to 2100 million tons. This corresponds to a 40% reduction in $CO_2$ emissions from baseline, but still almost a tripling of emissions compared to 1990 levels.

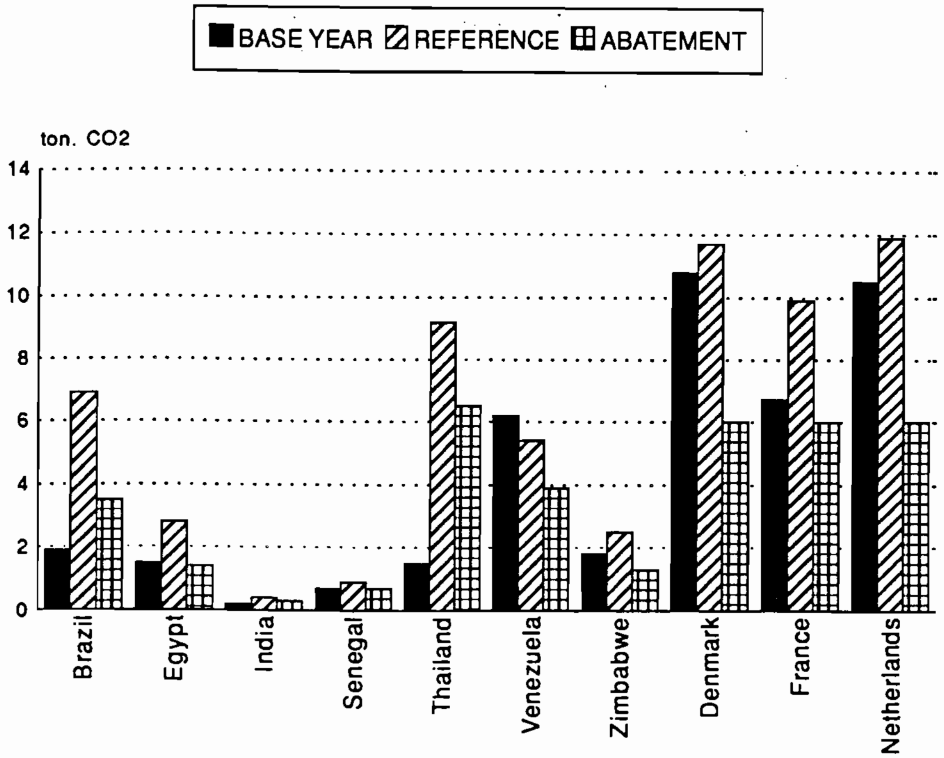


**Figure 2.** Calculated per capita $CO_2$ emissions in the base year (1990) and end year (2025/2030) for reference and abatement scenarios.

The full 50% reduction target was not achieved in the aggregate because some countries did not achieve feasible solutions at the 50% reduction level (India), or because not all abatement options were exhausted (Thailand and Venezuela).

The country studies show substantial differences in terms of the amount of $CO_2$ emissions per capita (Figure 2). For example, the Thailand reference scenario projects a six-fold increase in per capita emissions, while in Senegal and Zimbabwe per capita emissions increase very slowly. Comparison in absolute terms reveals a huge gap among the countries: $CO_2$ emission levels per capita in Thailand are expected to exceed by more than 20-fold those of India and reach the levels of the industrialized countries by 2030.

As noted above, the emission reduction targets were specified in relation to baseline emissions for the two reporting periods. This specification was made to allow the use of uniform reduction targets for developing and industrialized countries. It is important to note that such an emission reduction will have a very different impact on the future emission trends in a developing country with high projected emissions growth, compared to an industrialized country, where emission levels are high at present but not expected to grow as fast in the future. Thus, the long-term emission reduction targets of 25% to 50% still allow a 100- 200% increase in emissions for most of the developing countries. For Brazil, a 50% reduction from baseline still means a three-fold increase of emissions compared to 1990. Industrialized countries such as Denmark and the Netherlands must decrease total emissions in the abatement scenario to reach their targets, although per capita emissions remain high.

## 4. Abatement Costs

Following the project guidelines, country teams estimated short- and long-term abatement costs for reduction targets of 12.5–25% from the baseline in the short term (2005 to 2010) and 25–50% in the long term (2020 to 30). Abatement cost is defined as the incremental cost of GHG reductions, relative to a baseline in which abatement is not an objective. Costs are measured as the direct/financial costs on an energy system and sectoral level. The costs include levelized investment, operation and maintenance, and fuel costs. Thus, the emission reductions and related costs are defined in terms of differences from the reference point, and the incremental cost assessment is therefore closely interrelated with the definition of the baseline.

Cost curves containing marginal abatement costs for several target reductions in a specific year illustrate how the cost varies with the degree of reduction and allow different country studies to be compared. Figures 3 and 4 show marginal abatement costs for most of the participating countries in the short and long term, respectively. The cost curves for developing countries exhibit a number of similarities.

A particular feature is the large potential for negative cost abatement options,[1] amounting to up to 20% reductions from the baseline in 2005/2010 and about 35% in 2020/2030. The curves are also similar in shape: the first part of the cost curve, up to 5 to 10% emission reductions, indicates very low abatement cost, followed by a long interval, up to about 25% reduction

[1] "Negative cost" refers to the incremental cost of meeting the demand for energy services, like transport, lighting, etc., in the abatement scenario, compared to the reference scenario. If the *total* cost of an option or package of options is less than the corresponding cost in the reference scenario, the *incremental* cost is negative. However, implementation and transaction costs are often not included in the direct cost calculations in the scenarios.

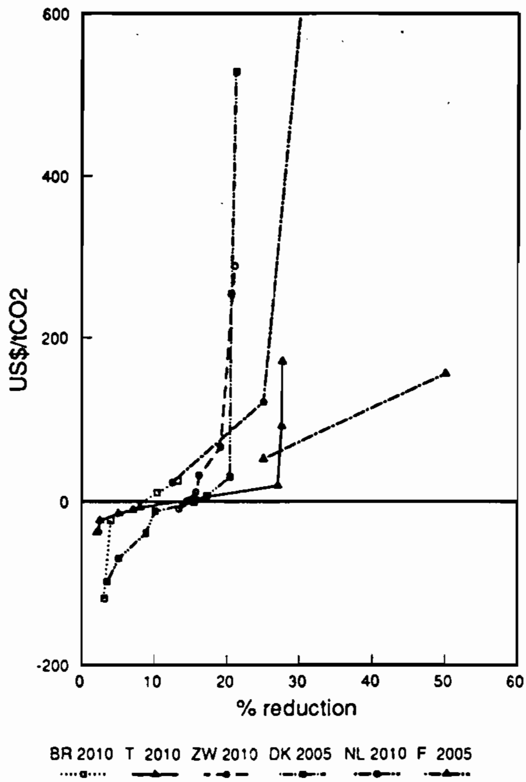


**Figure 3.** Marginal abatement costs for emission reductions in 2005/2010.

in the short term and up to about 40% in the long term, in which marginal abatement cost falls within a narrow range between –\$10 and +\$30 per ton $CO_2$ reduced.

The abatement cost estimates for industrialized countries are more varied. The Danish results are similar to the majority of the developing countries identifying a substantial negative-cost potential, while the Netherlands, and to an even greater extent France, estimate much higher abatement costs. The divergent results can be explained to a certain extent by different assumptions regarding the inclusion of negative "no-regrets" options in the reference case.

The abatement cost curves develop in a similar way as the time horizon for emission reductions is extended. Over time, the cost curves become less steep and move downward in absolute cost. This reflects the fact that, over time, increasing opportunities for capital replacement allow the use of more efficient and less polluting energy technologies in new and replacement

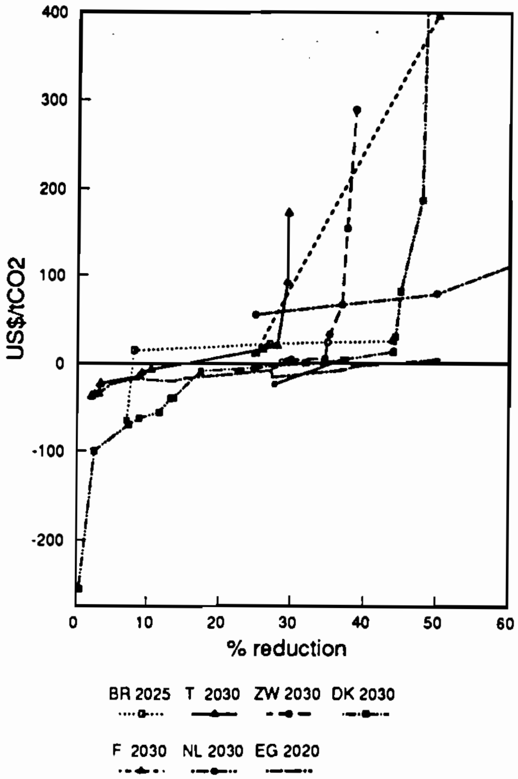


**Figure 4.** Marginal abatement costs for emission reductions in 2020/2030.

applications. Moreover, these technologies tend to be more effective and less expensive than retrofits of existing equipment. One would expect such progress in abatement levels and cost reductions over time to be accentuated if a significant degree of technical progress were assumed to take place in the scenarios. However, most of the measures included in the country studies are based on already fully commercialized technologies, which means that the abatement scenarios are relatively conservative in this regard.

One general similarity between all the studies is that the least expensive part of the cost curve contains energy end-use savings in industry and/or households. For the developing country studies in general, the profitability and possible penetration rates of such energy-saving end-use technologies are closely linked to general macroeconomic development and possible energy price adjustments to world market prices.

This means that some of the least expensive GHG reductions will overlap with more general investments in efficiency improvements that are profitable without taking GHG reductions into consideration. Consequently, a cost-effective GHG reduction policy cannot be carried out without investigating more general efficiency problems in the existing energy system and the economic system as a whole. Removal of general inefficiencies in the economic system must be in the national interest and, at the same time, GHG emission reductions should be implemented on the basis of a baseline that is defined according to an efficient but plausible economic development scenario.

Some investments which can contribute indirectly to GHG abatement through overall economic efficiency gains, must therefore be made in advance of investments directly aimed at emission abatement. In addition, some aspects of the implementation process, even for cost-effective measures such as energy-efficiency improvements, will require investments in information programs, testing facilities, training and outreach, and general capacity building. Although the incremental cost of a given level of resulting GHG abatement may be negative, the necessary implementation costs appear as positive cost barriers because it is difficult to allocate these costs to individual abatement measures and to the stake-holders in the measures. In the country studies, the costs of increasing institutional capacity as well as other implementation and transaction costs were not fully included. If these countries are to carry out the types of abatement measures identified, however, such implementation costs will become important considerations in determining their strategy. Institutional capacity-building and other implementation steps will likely involve costs that must be financed before many of the abatement options, even those with negative costs, can begin to be realized.

## 5. Abatement Technology Options

The general classes of technologies that were considered in the abatement scenarios are listed in Table 1, which shows the general categories of abatement measures that provided significant emission reductions in the abatement scenarios for the different countries.

An important result that can be seen from the table is the wide variety of end-use measures considered in the country studies. The category which was examined most intensively by the countries was industrial energy efficiency, details of which depend on the industrial structures of the countries.

**Table 1.** Abatement options applied in the country studies.

| Abatement option | Br | DK | Eg | F | Ind. | NL[b] | Sen | T | V | ZW |
|---|---|---|---|---|---|---|---|---|---|---|
| *Energy use* | | | | | | | | | | |
| Agricultural fossil fuel savings | | | X | | X | | | | | X |
| Building/domestic energy efficiency | X | X | | X[a] | | X | | X | | |
| Building fuel substitution | | X | X | | X | X | X | | | |
| Industrial cogeneration | | | X | | X | X | | | | |
| Industrial energy efficiency | X | X | X | X[a] | | X | X | | X | X |
| Industrial fuel/feedstock substitution | X | X | X | | X | X | | | | |
| Solar heating | | X | X | | | X | | | | |
| Transport fuel substitution | X | | X | | X | X | | | | |
| Transport modal shifts | | | X | | | | | | | |
| Vehicle energy efficiency | | | X | | | X | | X | X | |
| *Energy supply* | | | | | | | | | | |
| Biomass fuel | X | X | | | | X | | | | X |
| Biomass power | X | X | | | | X | | | | X |
| Hydropower | | | X | | | | | | | X |
| Natural gas | | | | | | X | | | X | |
| Nuclear power | | | | X[a] | | | | X | | |
| Reduced power losses | | | | | | | | | X | |
| Solar power | | | X | | | X | | | | |
| Wind power | | X | X | | | X | | | | |
| Forestry | | X | | X[a] | | | | | | |

[a]Individual technical measures are not listed in the French report.
[b]The Netherlands study includes in addition $CO_2$ removal technologies and the use of hydrogen as an energy carrier.

The residential sector was covered more generally by most of the developing countries, which assessed either fuel substitution or energy-efficiency options for that sector, but not both, although both could be expected to be relevant for all the countries.

Most of the supply-side abatement options were focused on the potential of $CO_2$ reductions in electricity generation. Alternatives for electricity supply vary widely among the different countries, but most emphasis was placed on fuel substitution rather than increased conversion efficiencies. Similarly, reductions in transmission and distribution losses, with the exception of the Venezuela country study, were not a priority area. Direct use of solar or wind power is not a significant factor in most of the abatement scenarios. Large-scale contributions from renewable energy sources to electricity generation were considered only in Denmark, with increased use of wind power, and Egypt, where wind and photovoltaic systems are projected to contribute

19% of the electricity supply in the abatement scenario. Both of these countries already have significant reliance on the same renewable sources in their reference scenarios.

While the range of options considered in the scenarios is an interesting result of the country studies, it is also interesting to consider the options that could be assessed further in the country studies, if more information, time and resources were available. Some of the countries omitted some possible abatement options, particularly for far-reaching emission reductions above 20% reduction in the short term and 35% in the long term. For example, if energy-efficient lighting is cost-effective in Brazil, this result should also apply to Venezuela. Similarly, supply-side options such as reduced transmission losses, biomass-fired cogeneration, and wind power may be applicable to several countries other than the few that considered them in this analysis. Although the economics of energy efficiency improvements and renewable sources are highly site-specific, it is unlikely that they vary so much from country to country as to completely exclude these options from the ranking of options.

Other aspects of the analysis, however, may lean in the optimistic direction. For example, the market penetration for certain energy-efficient technologies appears to be near 100% in the abatement scenarios for Denmark, Egypt, and Zimbabwe. While this kind of assumption may be unrealistic, it may also be balanced by the omission of other abatement options in some of the same studies. All in all, we would conclude that the approach of the country teams is reasonably realistic, and slightly pessimistic with regard to technology assumptions.

The introduction of more efficient end-use energy technologies and low-cost energy supply technologies would probably cause a more gradual increase in marginal abatement costs than in the present analysis. This could lead to the establishment of a more detailed overview of technical possibilities for abatement, or a more accurate estimate of the costs of far-reaching emission reductions targets, such as the 2020/2030 targets specified in the present analysis. Nevertheless, the main conclusion on the consistency of the abatement cost curves is that most of the country studies are reasonably consistent for the specified range of reduction targets. Thus, we can conclude that the cost results are reasonably comparable and that the observed similarities reflect real similarities between the different country situations.

A major discussion point in the development of guidelines was whether a standard set of technology data should be recommended, in order to identify abatement measures and analyze their costs and performance. This was rejected, because a high priority was given to the evaluation of the appropriateness and performance of different technologies in the national context. Instead, this information was developed within each participating country. The results of the country studies, with regard to both the low-cost abatement potential and the omission of additional potential options, suggest the need for more international effort to identify and evaluate energy efficiency and emission abatement options, especially within and between developing countries.

## 6. Methodological Lessons

Some of the important methodological lessons derived from the process of developing and evaluating the country studies are summarized below. They relate to definition of the baseline, treatment of energy-efficiency improvements, macroeconomic feedbacks, implementation barriers and costs, and joint products.

Because the emission reductions and related costs are defined in terms of differences from the reference point, the incremental cost assessment is closely interrelated with the definition of the baseline. There are three different types of baselines that have been considered in the country studies, namely: economically efficient, business as usual, and a realistic compromise between these two extremes. It is important that the baseline cases are linked to realistic macroeconomic development projections, which provide input data to projections of demand for energy services, in order to identify profitable energy efficiency improvements, whether they are included in the baseline or not.

The structural adjustment plans that many developing countries are undertaking will make investments in energy more profitable. A national GHG abatement strategy must consider the investments related to these economic adjustment plans and make explicit assumptions regarding how they are captured in the baseline case. However, it is only possible to make a soft boundary between profitable efficiency improvements included in the baseline case and those available in the abatement case. Inertia, implementation barriers, and capital constraints must be evaluated in order to define a baseline that is a realistic compromise.

All the country studies identified "no-regrets" options and either assumed these to be part of the baseline or added them to the abatement case. The most profitable investments for all countries are decentralized end-use oriented options related to industrial energy consumption or to the household sector. Many such options are more cost-effective than most large investments in power supply systems. The implementation of end-use savings requires a complex effort, with many decision makers being influenced.

Neither macroeconomic models nor technical-economic models are able to predict how a present energy system can move in a direction of a given technical system to fulfill a GHG abatement constraint. Macroeconomic models focus most often on long-term equilibrium points, while technical-economic models project the development from the basis of presently available and implemented technologies.

Interaction between macroeconomic development and the technical systems should ideally be analyzed in an iterative process, where calculations to balance the modeling at the top-down and bottom-up level should include: energy demand forecasts, energy production and demand technologies, and macroeconomic impacts on required investments in the energy sector. The national studies have generally linked the macroeconomic level and the technical-economic level only by initially assuming a specific macroeconomic background for projecting energy demand. No feedback is measured between relative prices and investment requirements. This means that the evaluated abatement options exclude possible effects of economic structural effects. This is a consequence of missing macroeconomic modeling capability in the countries.

Overcoming the implementation barriers to energy-efficiency improvements and other potential "no-regrets" options requires institutional changes and involve transaction costs. Implementation issues were generally not treated explicitly in the country studies. A few countries explicitly excluded implementation costs and barriers in the assessment of the timing and costs of capturing abatement options. Others assumed specific penetration rates, for example for end-use savings, in order to represent barriers and inertia in the systems.

Implementation barriers and costs can primarily be measured on a short-term basis in relation to the implementation of individual technical options. Information campaigns, technological learning, and other comprehensive regulation and incentive efforts could lead to synergistic phenomena which are difficult to capture in a modeling framework. A short-term GHG regulation policy must necessarily include a combination of different regulation, incentive and technological instruments, because many different decision makers need to be influenced, and different barriers must be overcome for the different technical options included in an abatement strategy.

Finally, important joint products, such as reduced local pollution, are likely to be produced synergistically with GHG emission abatement measures. Counting these benefits would tend to reduce the net cost of GHG abatement. While the analysis of joint products was beyond the scope of the present study, this is an important area for future work.

## 7. Conclusions

The UNEP GHG abatement costing project has been a wide-ranging activity involving a large number of teams and producing a considerable amount of information. A methodological framework for national GHG abatement costing was established in the guidelines and has been tested in 10 countries. This has resulted in the estimation of abatement cost curves for reduction targets of 12.5%, 25%, and 50% for GHG reduction in the short term until 2005/2010 and in the long term until 2020/2030 compared to baseline development.

The country teams have carried out detailed investigations of individual technical options and packages of options in order to evaluate the costs and reduction potential of comprehensive abatement strategies. The main focus has been on $CO_2$ emissions from the energy sector, which on average contributes to about 80% of total GHG emissions at present in the participating countries (in terms of global warming potential).

It is not possible to find a simple measure of comparability between different studies, and thus to judge the success of the project in achieving this aim. The measure of success of the guidelines lies more in the transparency and documentation of the studies, and in the degree to which consensus was achieved among such a broad group of researchers and planners, spanning ten countries and differing interests, together with the members of the central project team and advisers.

A final indication of the success of the project is the extent to which the subject of GHG abatement costing has been brought to a higher level of awareness and expertise within the participating teams, both in the developing and industrialized countries. Through the discussions, the formulation and revision of the guidelines, and the execution of the country studies, all parties have become more aware and able to deal with the issues in a manner which can be understood, and hopefully accepted, nationally and internationally.

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# Appendix

## INTERNATIONAL WORKSHOP ON INTEGRATIVE ASSESSMENT OF MITIGATION, IMPACTS AND ADAPTATION TO CLIMATE CHANGE

**13–15 October 1993**

**IIASA, Laxenburg, Austria**

## PROGRAM

### Wednesday, 13 October 1993

8:30 **Registration**
9:00 Welcome, Peter de Jánosi, Director, IIASA
9:10 Workshop Background and Overview, Nebojša Nakićenović

### SESSION I: ECONOMICS AND CLIMATE CHANGE

*Chairperson*: John Houghton    Rapporteur: Jesse Ausubel

*Contributors*: William Nordhaus, William Nierenberg, Jill Jäger, George Golitsyn, Ulrich Schotterer Michael Schlesinger,
9:15 Presentations by Contributors
11:15 General Discussion

### SESSION II: INTEGRATIVE ASSESSMENTS

*Chairperson*: Michael Jefferson    Rapporteur: Stephan Schleicher

*Contributors*: Hadi Dowlatabadi, Jae Edmonds, Robert Mendelsohn, Thomas Teisberg, Joe Alcamo
14:00 Presentations by Contributors
16:00 General Discussion
17:30 Computer Model Demonstration

### Thursday, 14 October 1992

### SESSION III: INTEGRATIVE ASSESSMENTS - Part 2

*Chairperson*: Mohammad Al-Sabban    Rapporteur: Toufiq Siddiqi

*Contributors*: Chris Hope, Yoshiaki Nishimura, Michael Hulme/Sarah Raper, Xia Guang, David Maddison, Martin Parry
9:00 Presentations by Contributors
11:00 General Discussion

### SESSION IV: MITIGATION AND ADAPTATION

*Chairperson*: Katsuo Seiki    Rapporteur: Sokrates Kypreos

*Contributors*: Igor Bashmakov, Ajay Mathur, Joel Swisher, Stewart Boyle, Richard Richels, Charles Kolstad

14:00 Presentations by Contributors
16:15 General Discussion
17:30 Computer Model Demonstration

## Friday, 15 October 1992

### SESSION V: INTERGENERATIONAL ASSESSMENTS

*Chairperson*: Peter Sturm    Rapporteur: John Weyant

Contributors: Jyoti Parikh, Asbjørn Aaheim, Robert Lind, Ferenc Toth, Alan Manne, Thomas Schelling

9:00 Presentations by Contributors
11:00 General Discussion

### SESSION VI: THE ROLE OF TECHNOLOGY

*Chairperson*: Gregg Marland    Rapporteur: Francois Moisan

Contributors: Jesse Ausubel, Michael Grubb, Jean-Charles Hourcade, Chihiro Watanabe

13:30 Presentations by Contributors
14:30 General Discussion

### SESSION VII: CONCLUSION OF THE WORKSHOP

*Chairperson*: William Nordhaus

15:30 Session summaries presented by Rapporteurs
16:30 General Discussion
17:30 Adjournment of Workshop

**Scientific Committee: Nebojša Nakićenović, William Nordhaus, Rich Richels and Ferenc Toth**

## INTERNATIONAL WORKSHOP ON INTEGRATIVE ASSESSMENT OF MITIGATION, IMPACTS AND ADAPTATION TO CLIMATE CHANGE

**13-15 October 1993 IIASA, Laxenburg, Austria**

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