Report

Targets and Indicators of Climatic Change

edited by

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Draft

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FOREWORD

This Report is one of four listed below which are devoted to three specific aspects of the issues involved in developing policies for responding to climatic change. They are presented here as useful supporting material, contributing to the process of ongoing work worldwide, especially that being continued via the Intergovernmental Panel on Climate Change (IPCC).

The work itself has grown out of the results of the two-stage Workshop process held in Villach and Bellagio in late 1987. Following a review of the output from this Process in December 1987, the Advisory Group for Greenhouse Gases (AGGG), recommended that it would be timely to address the three topics presented in these Reports and requested terms of reference, which it subsequently approved at the AGGG Meeting in Toronto, in July 1988.

The work has been carried out as an international collaborative effort by a wide range of specialists from various institutes and agencies working together with SEI personnel and co-ordinated by Dr Jill ;er. I would like to thank all the many participants in the studies, particularly the Chairmen of the Working Groups, the individual Report Editors and the reviewers.

On behalf of all the participants, it is a pleasure to acknowledge the advice and encouragement provided by the AGGG and to thank most warmly the former Beijer Institute, the Environmental Defense Fund, 1 especially the Rockefeller Brothers Fund and the SEI for financial support. Additionally, the W. Alton Jones Foundation of the U.S.A. generously helped to defray publication costs.

Finally, my special thanks go to Jill Jäger for undertaking the very onerous task she has completed so successfully.

Stockholm, October 1990

Gordon T. Goodman
Executive Director, SEI

Responding to Climate Change: Tools for Policy Development.
Jill Jäger, Editor. Stockholm 1990. (Summary Report)

tions for Reducing Greenhouse Gas Emissions.
Diane Fisher, Editor. Stockholm 1990.

Targets and Indicators of Climatic Change.
F.R. Rijsberman and R.J. Swart, Editors. Stockholm 1990.

Usable Knowledge for Managing Global Climatic Change.
William C. Clark, Editor. Stockholm 1990.

PREFACE

In July 1988, the WMO/ICSU/UNEP Advisory Group on Greenhouse Gases (AGGG) established three ad hoc working groups, coordinated by the Stockholm Environment Institute. These working groups are: 1) Analysis of Limitation Strategies; 2) Targets and Indicators of Climate Change; and 3) Performing Assessments of Adaptation and Limitation Strategies. This report presents the work of the second working group.

The group has focused on defining and identifying appropriate indicators and quantitative targets for climatic change. Specifically, the utility and feasibility of incorporating long-term objectives into national and international climate policy have been investigated. The Intergovernmental Panel on Climate Change (IPCC) has concentrated, so far, on short-term qualitative targets and response options, and has examined the extent to which these may presently be politically and economically feasible. Targets defined on the basis of long-term risk management have not been considered yet. In the opinion of the WG2, however, it is now time to define long-term environmental goals as a basis for short-term emission targets. The specific targets proposed here are believed to represent a proper balance between the need to improve our knowledge and the need to act. Others are invited, however, to contribute to the discussion on targets for climate policies, and we hope that our efforts will prove to be a useful contribution.

A coherent set of indicators is needed to determine the rate and extent of climatic change and to provide a yardstick for measuring progress in controlling the greenhouse effect. Indicators are also indispensable to detect instabilities in the climate system. Current estimates are essentially based on simple extrapolations of linear representations of a dynamic system with numerous surprises, introducing even greater risks that should be considered when defining targets.

Although important scientific uncertainties remain, they should not keep us from implementing policies that would help achieve the targets identified here. Rather, the uncertainties should be used as a reason to periodically review and adjust targets.

The authors of this report provided drafts of their contributions. These drafts were discussed at a review workshop in Rotterdam, April 25-27, 1990, in which several additional reviewers participated. The participants in this workshop examined the results, and developed a consensus on the recommended indicators and targets for climatic change. The Executive Summary of the report was written at the workshop. After the workshop the various contributions were revised, and edited for consistence and coherence.

We are grateful to the Stockholm Environment Institute, and the Dutch Ministry of Housing, Physical Planning and the Environment for their financial support. We thank the authors --- Blair T. Bower, Michel G.J. den Elzen, Gerrit W. Heil, Monique Hootsmans, Daniel A. Lashof, Irving M. Mintzer, E.O. Oladipo, Kilaparti Ramakrishna, Frank R. Rijsberman, Jan Rotmans, Wolfgang Sassin, and Rob J. Swart --- and reviewers --- Christoph Brühl, Danny Harvey, David James, Rik Leemans, Annie Roncerel, and Hajo Smit ---, also listed in the back of the

report. The work of Frank Rijsberman and Rob Swart, as editors of this report, battling strict deadlines, is much appreciated. The following persons provided valuable assistance: Monique Hootsmans, with organization, Blair Bower and Gerrit Heil, with editing the draft papers, Jacqueline Reason, with proof-reading and revisions, Udo Montfoort, with graphics and computer support. RESOURCE ANALYSIS of Delft, the Netherlands, organized the review workshop.

Pier Vellinga
Peter H. Gleick

Chairmen
Working Group 2, Targets and Indicators of Climate Change

EXECUTIVE SUMMARY

WORKING GROUP 2

Chairmen: Pier Vellinga and Peter Gleick

TARGETS AND INDICATORS OF CLIMATIC CHANGE[1]

The Problem

The focus of *ad hoc* Working Group 2 is on defining and identifying appropriate indicators and targets of climatic change. At the international workshops held in Villach and Bellagio in 1987, the need for a set of indicators of climatic change was recognized -- indeed, as we move toward the Second World Climate Conference in the fall of 1990, a coherent set of indicators is still lacking (particularly with respect to measuring **rapid** climatic change). Such indicators could provide decisive evidence that climate **is** changing and could provide a yardstick for measuring progress in reducing the greenhouse effect. Levels of "acceptable" emissions are typically determined by the economic, political, and technological feasibilities of achieving them rather than by the nature of the environmental and societal risks that these emissions entail.

Addressing the concern that this approach should be reversed, *ad hoc* Working Group 2 specifically considered how targets for climatic change might be identified. Measures that are cost-effective now, such as many energy-efficiency improvements, and measures that help to solve other problems, should be implemented even if the threat of climate change did not exist. In the longer term, related issues of economic development and population growth must also be addressed. These measures alone, however, may not be enough to avoid significant climatic change. In particular, unpredictable feedbacks and surprises may lead to unexpected reactions of the global climate. Hence, more stringent measures are required to reduce emissions and produce longer-term, more significant effects. In addition, the uncertainties in climate response to human perturbations and in the controllability of climatic change lead to a need for regular checks and possible revisions of initially fixed short-term targets.

Choosing the most appropriate measures for emissions reductions requires having a vision of our eventual goal. We therefore address the following questions: What are the objectives in limiting climatic change? What indicators are most appropriate for measuring progress toward these objectives? What level of greenhouse-gas emissions would keep climatic change within acceptable limits? What kinds of climatic surprises and instabilities might arise? Ultimately, decisions on what targets to choose and how to achieve those targets will incorporate a wide range of economic, social, and political factors. These issues are addressed to a certain extent by Working Groups 1 and 3 and discussed further in this Report.

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[1] The Working Group report was edited by F.R. Rijsberman and R.J. Swart. The chapters of the report were written by B.T. Bower, M.G.J. den Elzen, P. Gleick, G.W. Heil, M. Hootsmans, D. Lashof, I. Mintzer, E.O. Oladipo, K. Ramakrishna, F.R. Rijsberman, J. Rotmans, W. Sassin, and R. Swart.

The results of this study are intended to complement the activities of the Intergovernmental Panel on Climate Change (IPCC). As the work of the IPCC has evolved, the formal structure of IPCC has thus far focused its assessment on near-term (to 2010) qualitative targets and response options, and the extent to which they may presently be viewed as politically and/or economically feasible. In this context, the following report of Working Group 2 provides valuable supplementary information to the international policy discussion by: 1) allowing for a long-term target approach; (2) presenting a framework for the analysis and selection of indicators and targets; (3) identifying **quantitative** long-term targets; and (4) expanding the range of analytical tools under consideration.

Organization of the Report

Section 1 provides an introduction to the nature of the climatic change problem, a framework showing the relationship between targets and climate policies, and a systematic approach to the selection of different possible sets of indicators and targets. In Section 2, possible targets for limiting the rate and magnitude of climatic change are reviewed, including goals for temperature, precipitation, and sea-level rise. Section 3 addresses the possibilities of translating long-term environmental goals into operational targets and evaluates emissions-temperature relationships. Attention is paid to uncertainties and possible feedbacks, modelling tools, global warming potentials, and the relationship between temperature and sea-level rise. Section 4 focuses on the implications of long-term target setting in relation to resource use, population growth, and economic activities, with consideration of the differences among countries and regions. A glossary is included in order to provide a common basis for discussion.

Principal Conclusions and Recommendations

Several climate policy objectives (or goals) are identified in this study. The underlying objective of all climate policies is to limit effects or impacts of climatic change on society to socially acceptable levels, or in general terms, to safeguard the global environment for future generations. Such general objectives, however, are difficult to define clearly and provide no basis for implementation. More specific objectives can be formulated that relate to particular stages in the cause-and-effect chain that starts with emissions caused by human activities and ends with impacts of climatic change on society and natural ecosystems. The Working Group formulated the following hierarchy of broad objectives:

- Limit the impacts on human society and natural ecosystems;
- Limit the rate and magnitude of sea-level rise;
- Limit the rate and magnitude of temperature change;
- Stabilize the ambient concentrations of specific greenhouse gases;
- Stabilize and/or reduce emissions of greenhouse gases and enhance sinks to stabilize the atmospheric concentrations of greenhouse gases; and
- Take measures to reduce greenhouse gas emissions in an equitable manner among the different actors.

Ultimately, the choice of objectives will be a product of the political process of negotiation and will depend on perceptions of the severity of the risks, the feasibility of implementing solutions, economic costs, and societal consequences associated with the various alternatives.

The Working Group recommends the use of the following series of indicators of climatic change, and selected quantitative targets for climate policies, in order to protect the structure and functions of vulnerable ecosystems. There are several potentially promising direct indicators of the effects of climatic change on ecosystems, but these require more research and are not yet operational. Instead, it is recommended that targets be specified for the rates and magnitude of temperature change and sea-level rise that will protect both ecosystems as well as human systems.

INDICATOR SEA-LEVEL RISE

Targets A maximum rate of rise of between **20** and **50 mm per decade.**

A maximum sea-level rise of between **0.2** and **0.5 m** above the 1990 global mean sea level.

The lower rate of rise -- 20 mm per decade -- would permit the vast majority of vulnerable ecosystems, such as natural wetlands and coral reefs to adapt. Beyond this rate of rise, damage to ecosystems will rise rapidly. Limiting sea-level rise to a maximum of 0.5 m would prevent the complete destruction of island nations, but would entail large increases in the societal and ecological damage caused by storms. A sea-level rise of 0.2 m would also entail such damage, but at much lower levels.

INDICATOR MEAN GLOBAL TEMPERATURE

Targets A maximum rate of change in temperature of **0.1 °C per decade**. The rate of temperature change target refers to realized warming.

Two absolute temperature targets for committed warming were identified. These limits entail different levels of risk:

(i) A maximum temperature increase of **1.0** °C above pre-industrial global mean temperature.

(ii) A maximum temperature increase of **2.0** °C above pre-industrial global mean temperature.

These two absolute temperature targets have different implications. It is recognized that temperature changes greater than the lower limit may be unavoidable due to greenhouse gases already emitted. The lower target is set on the basis of our understanding of the vulnerability of ecosystems to historical temperature changes. Temperature increases beyond 1.0 °C may elicit rapid, unpredictable, and non-linear responses that could lead to extensive ecosystem damage.

An absolute temperature limit of 2.0 °C can be viewed as an upper limit beyond which the risks of grave damage to ecosystems, and of non-linear responses, are expected to increase rapidly. The concept of dual temperature limits is elucidated in Figure 2.

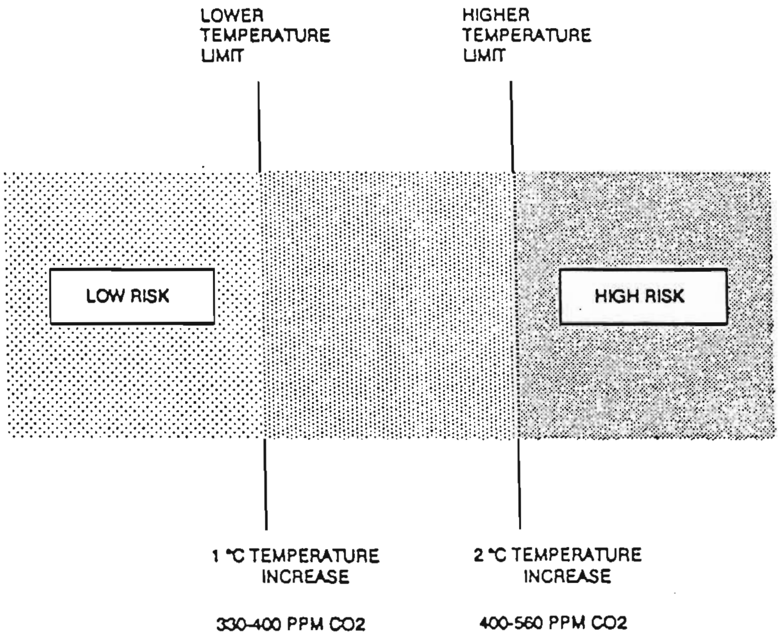
INDICATOR CO_2 CONCENTRATIONS

Targets

Maximum CO_2-equivalent[2] concentrations of **330 to 400 ppm** (for a 4 - 2 °C range of climate sensitivity)[3], to stay within the lower temperature limit, according to our estimates with the IMAGE simulation model; or

Maximum CO_2-equivalent concentrations of **400 to 560 ppm** (for a 4 - 2 °C range of climate sensitivity, respectively) to stay within the higher temperature limit, according to our estimates with the IMAGE simulation model.

Figure 2: **Proposed targets for absolute temperature change and CO_2-equivalent concentrations.**



Temperature targets refer to committed warming expressed in global mean temperatures above pre-industrial levels, and concentration targets refer to stabilized CO_2-equivalent concentrations.

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[2] Greenhouse gases differ in their heat-trapping capabilities. A CO_2-equivalent concentration of 400 ppm refers to a combined warming effect from increases in all greenhouse gases that is equal to increasing the concentration of CO_2 alone to 400 ppm.

[3] Climate sensitivity is the estimated ultimate change in global temperature resulting from a doubling of the concentration of CO_2 (or other greenhouse gases) over pre-industrial levels. A 2 degree level of sensitivity allows for a greater increase in CO_2 than does a 4 degree level, in order to stay within the target temperature limit.

Varying combinations of concentrations of greenhouse gases --- and consequently varying combinations of emissions --- are possible to meet the same temperature targets; only the ranges of **CO_2-equivalent** concentrations are shown in Figure 2.

In order to achieve the above targets, detailed analyses are needed of the relationships between the emissions of greenhouse gases, the concentrations of greenhouse gases in the atmosphere, the effect of greenhouse-gas concentrations on temperature, and the relationship between temperature and sea level. Methods and models for determining these relationships are discussed in detail in Section 3 of the detailed report.

Critical Issues

- Although there are still many uncertainties, we believe that the present generation of assessment models makes the target-setting approach feasible for temperature and sea-level rise targets.

- The indicators and targets we can most accurately measure may not reflect the most severe impacts of climatic change. As our ability improves to measure climatic change and impacts, new targets may be identified.

- Targets must be subject to periodic review in light of feedbacks and nonlinearities that may introduce surprises and unexpected changes. Additional indicators may be identified and additional targets may be set to account for these feedbacks and for improvements in our understanding of climate dynamics.

- Policies to achieve these targets will vary from country to country and region to region, and must be subject to international negotiations and agreements.

- Some degree of climatic change appears to be unavoidable because of past emissions of greenhouse gases. We believe that some adverse impacts to ecosystems and human systems will occur even at the lower targets identified here.

- Other stresses, such as from acid precipitation and the depletion of stratospheric ozone will make it difficult to identify the effects of climatic change.

- A standard format for presenting scenario assumptions should be adopted to facilitate the comparison of results of various studies.

- Important scientific uncertainties remain, for example, about the precise relation between greenhouse-gas concentrations and temperature, and the relative importance of the different gases over time. **These uncertainties must not be used as an excuse to avoid adopting policies that would help achieve the targets identified here.** Rather, the uncertainties should be used as a reason to regularly review and adjust targets.

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GLOSSARY

POLICY-RELATED DEFINITIONS

Criteria: the bases used by decision-makers in selecting a policy/strategy to be adopted. Examples are cost, distribution of costs, legal feasibility, administrative ease, cost effectiveness.

Effects, impacts: the estimated change in state of the biospheric system, of an ecosystem within the biospheric system, of a socioeconomic system or of elements of such a system, at a point in time as a result of an hypothesized or specified scenario, e.g., sea level in 2100 as a result of the discharges of GHGs, the change in yield in corn in Iowa as a result of the discharges under the designated scenario, effects or impacts can also be expressed in terms of rates, e.g., average increase in global mean temperature per year to 2100.

Emissions, discharges: the quantities of gaseous, liquid, solid materials and energy (e.g., heat) discharged into the environmental media from an activity, e.g., agricultural operation, petroleum refinery, power plant, landfill; in the context of climatic change, reference is usually to one or more of the greenhouse gases.

- **Emission reduction**: the reduction in discharges of materials, usually gaseous in the context of climatic change, from activities, as a result of policies.

Energy intensity: a measure of the use of energy by an activity, in terms of amount per some unit, e.g., total energy use per square meter of floor space of retail outlets, energy used in production of a ton of paper napkins of specified characteristics, or energy used per unit of GNP.

- **Carbon intensity** of a fuel, or of a fuel mix: the amount of carbon generated per unit of energy output, e.g., grams per kilowatt hour.

Indicators of climatic change: variables that indicate (express) directly some characteristic of the biospheric system related to climatic change, e.g., mean global temperature, concentration of CO_2, sea level rise, or indirectly relate to climatic change, e.g., emissions of greenhouse gases in a year.

Model: a more or less detailed representation of a system, e.g., global geochemical system, global geobiochemical system, an agricultural operation, a petroleum refinery, a temperate forest ecosystem. An heuristic model is a qualitative representation of how a system works, i.e., describing the interrelationships/flows among components of the system; a computational model is a quantitative representation of a system, such that quantitative estimates can be made of the responses of the system to changes in values of the input variables of the model.

- **General circulation model (GCM)**: a computational model or representation of the earth's climate, consisting of equations that represent the conservation of energy, momentum, and mass, and calculate the distributions of wind, temperature, precipitation, and other indicators of climate as result of emissions from human and natural sources. Typically, GCMs are applied to equilibrium conditions, because of the difficulties in analyzing dynamic conditions.

Objective (goal): a qualitative expression of a desired situation with respect to global climate, e.g., maintain global climate as during mid-twentieth century, or maintain global climate so that existing diversity of species would not be reduced. To be able to develop specific policies, the qualitative objectives or goals must be translated into targets, i.e., specific, quantitative values of indicators.

Policy, specifically climate policy (also sometimes referred to as a strategy): a combination of physical measures, implementation incentives, institutional arrangement, and financial means designed to achieve the emission reductions estimated to be required to achieve some climate target(s), e.g., banning CFCs, requiring energy conservation analyses by all public utilities, imposing regulations with respect to use of energy saving appliances, subsidies to farmers to adopt less energy intensive agricultural operations, designated governmental entities to monitor performance. It should be emphasized that setting a climate target does not comprise a policy. A policy must include not only the physical measures to be adopted but the means of inducing their adoption, the means for ensuring their continued operation after adoption (implementation), and the means for financing measures and administration.

- **Physical measures**: the raw materials, production processes and operations, the characteristics of product and service outputs, which are modified to achieve emission reductions. Physical measures also include changes in behavior patterns, such as shifting from use of automobile transport to bicycle transport, or from downhill skiing to X-country skiing; examples include changes in agricultural production functions from more input-intensive agriculture to less intensive agriculture, adoption of more efficient appliances, shift from bleached paper products to unbleached paper products.

- **Implementation incentives**: the various incentives which are provided for, e.g., residential, commercial, industrial, agricultural, governmental entities, to induce those activities to adopt the physical measures which will result in reduction of emissions. Examples include technical assistance, regulations, charges, subsidies, grants, banning of products or activities.

- **Implementation incentive system**: the combination of a) incentives; b) measures of performance; c) procedures for monitoring performance; and d) sanctions for noncompliance or nonperformance. It is the combination of these four which comprise the implementation incentive system which is necessary to induce action

- **Institutional arrangement**: the specification of the set of governmental entities and sometimes private entities, which have the responsibilities for carrying out the various tasks relating to the implementation incentive system, e.g., who decides on the level of emission reduction by which activities, who decides what financial aids will be given, who will monitor performance, who will provide technical assistance. For example, part of the system would be self-monitoring by an activity of its discharges and reporting to the relevant governmental agency, which in turn must have the means to check the accuracy of the reports from the activity.

Scenario: a set of: (a) values of variables; and (b) assumptions, which affect emissions of greenhouse gases, and thereby affect climate. Variables include population growth, economic output growth, extent of deforestation, factor input prices, social tastes, and climate policies of governments. Both exogenous and endogenous variables are included in specification of a scenario.

Targets for climate policies: quantitative values (levels) of indicators, which policies are designed to achieve, e.g., for CO_2 concentration as an indicator, a target would be not to exceed a concentration of 350 ppm in 2100.

CLIMATE-RELATED DEFINITIONS

Albedo: the fraction of incoming solar radiation reflected back into space.

Climate system: the interactive components of the earth which together determine the earth's climate. These include atmosphere, oceans, land surface, sea ice, snow, glaciers, biosphere.

Equilibrium warming commitment: for a specified year, the equilibrium warming commitment is the eventual increase in temperature that would occur at some point in time in the future if atmospheric concentrations of greenhouse gases were to remain constant at the levels of that year.

- **Realized warming**: the global temperature reached in any given year as a result of emissions of GHGs lags considerably behind the equilibrium temperature to be induced by those emissions, because of the large heat capacity of the oceans. The difference between the realized warming (temperature) and the equilibrium warming (temperature) in any given year is termed the "unrealized warming".

Flux: flow per unit area per unit time; measured in terms of energy, e.g., watts per square meter (W/m^2), or mass, e.g., grams per square meter per day ($g/m^2/day$).

Global carbon budget: the mass balance of carbon for the globe as a result of the aggregate effect of sources and sinks of carbon.

Greenhouse effect: Radiatively active gases in the atmosphere modify the radiation balance of the earth which results in higher global mean temperatures than would have been the case without these gases. Anthropogenic emissions of these gases have increased to such an extent -- relative to pre-industrial levels -- that the resulting concentrations will most probably lead to increased global mean temperatures; this effect is often referred to as "the greenhouse effect".

- **Greenhouse gases (GHGs)**: Gases that contribute to the greenhouse effect, i.e.: H_2O, passively emitted and natural); CO_2 , CH_4, N_2O, anthropogenic and natural; O3, chemically formed in the atmosphere; CFC-11, CFC-12, CFC-113, CFC-114, CFC-115, HCFC-22, anthropogenic.

Radiative forcing (external forcing, forcing, perturbation): a change imposed upon (externally) the climate system which modifies the radiative balance of the climate system, e.g., increased concentrations of GHGs in the atmosphere because of volcanic action and/or human activities. Radiative forcing is often specified as the net change in energy flux at the tropopause, W/m^2.

- **Climate feedbacks**: processes that alter the response of the climate system to radiative forcings, comprised of physical climate feedbacks, e.g., increases in water vapor, changes in cloudiness, decrease in land ice accompanying global warming, and biogeochemical feedbacks, e.g., changes in global biology and chemistry, as in a change in a terrestrial ecosystem. Impact of climate feedbacks is generally measured in terms of effect on climate sensitivity, where positive feedbacks increase climate sensitivity, negative feedbacks decrease climate sensitivity.

- **Climate sensitivity**: the ultimate change in global temperature resulting from a given initial radiative forcing. Climate sensitivity is generally measured as the change in global mean surface air temperature when equilibrium between incoming and outgoing radiation is reestablished following a change in radiative forcing. (Climate sensitivity is defined as the equilibrium warming commitment due to a doubling of the concentration of carbon dioxide from pre-industrial levels.)

- **Biogeochemical sensitivity**: the quantity of greenhouse gas emissions associated with a particular level of radiative forcing. It is determined by the sources and sinks for each greenhouse gas and the instantaneous forcing per molecule in the atmosphere.

- **Transient response**: the time-dependent response of climate to radiative forcing, i.e., the gradual response of climate to changes in radiative forcing, primarily because of the heat capacity of the oceans; results in an imbalance between incoming and outgoing radiation. (Given the continuing emissions of GHGs, with the resulting continuing change in concentrations of GHGs in the earth's atmosphere, the earth's climate will be in a transient mode for the foreseeable future.)

Solar luminosity, solar constant: the total amount of energy emitted by the sun per unit of time. The so-called "solar constant" is the average amount of energy received at the top of the earth's atmosphere at the mean earth-sun distance; this amount changes with changes in solar luminosity.

Time lag: the length of time which transpires between an event and the effect of the event on the system of concern, e.g., length of time between the emission or discharge of a greenhouse gas and the resulting change in global mean temperature.

Troposphere, tropopause, stratosphere: the troposphere is the lower atmosphere, from the ground to an altitude of about 8 kms at the poles, about 12 kms in midlatitudes, and about 16 kms in the tropics. The tropopause is defined as the top of the troposphere; temperature decreases with altitude between the earth's surface and the tropopause; temperature increases with altitude between the tropopause and the top of the stratosphere. The stratosphere extends from the tropopause to about 50 kms above the earth's surface.

1. INTRODUCTION

1.1. INTRODUCTION

B.T. BOWER

GREENHOUSE GASES: WHAT AND FROM WHERE

"Global warming" and "ozone hole" have now, near the beginning of the last decade of the twentieth century, become integral parts of the public vocabulary. In fact, the public has "been subjected to so much in the way of journalistic pyrotechnics surrounding these issues, to such a tide of seemingly contradictory headlines, that no one knows what to believe anymore" (Kanigel, 1990). Yet the Soviet foreign minister seems to have no doubts, as indicated by his statement to the United Nations in August of 1988.

> "Faced with the threat of environmental catastrophe, the dividing lines of the bipolar ideological world are receding. The biosphere recognizes no division into blocs, alliances, or systems. All share the same climatic system and no one is in a position to build his own isolated and independent line of defense. Perhaps for the first time we have seen the stark reality of the threat to our environment---a second front fast approaching and gaining an urgency equal to that of the nuclear and space threat. For the first time we have clearly realized that in the absence of any global control, progress is turning into a global aggression against the very foundations of life on earth. For the first time we have understood clearly what earlier we only guessed: that the traditional view of national security based primarily on military means of defense is now totally obsolete and must be urgently revised." (quoted in Junkin, 1990)

Contrast the foregoing with the response, two decades ago, to the Study of Man's Impact on Climate (1971). That report created scarcely a ripple in public or private waters of the time.

Although there is considerable consensus concerning some aspects of global climatic change, there is by no means complete consensus, with respect to what has happened in the past, what is happening in the present in comparison with the past, what the effects in the future might be. The lack of consensus is reflected, for example, by Rogers and Fiering (1989), Karl et al. (1989), and Michaels (1989).

Consensus does exist on what the greenhouse gases (GHGs) are, see Table 1.1-1. What also is clear is that discharges of GHGs have been increasing, and will continue to increase for the foreseeable future. This is particularly evident with respect to CO_2 discharges from combustion of fossil fuels. Table 1.1-2 shows the estimated discharges of CO_2, from region or country, in 1986. Figure 1.1-1 shows estimated carbon emissions from fossil fuels, 1950-1988, and projections to 2010 under different assumptions.

Table 1.1-1: **Greenhouse Gases and their Characteristics**

concentration	Atmospheric forcing 1980, ppb	Radiative time, °C/ppb	Residence rate of years	Annual increase, %
carbon dioxide	339000	0.000004	2 *	0.4
methane	1650	0.0001	5 - 10	1.0
nitrous oxide	300	0.001	120	0.2 - 0.3
CFC-11	0.18	0.07	65	5.0
CFC-12	0.28	0.08	110	5.0
CFC-13	0.007	0.1	400	NA
ozone	25 - 70	NA	0.1 - 0.3	NA

* Amospheric retention of CO_2 is rather complex. Rather than being destroyed, CO_2 is transferred into other reservoirs, from which it can return to the atmosphere. Estimates that account for ocean uptake result in residence times of 100 - 200 years.

Source: Ramanathan (1985).

Table 1.1-2: Estimated Discharges of CO_2 in 1986

United States	22.6 %	China	10.4 %
Canada	2.0 %	India	2.6 %
Western Europe	15.3 %	Middle East	2.9 %
Japan	4.8 %	Rest of Asia	5.4 %
Soviet Union	19.0 %	Latin America	4.5 %
Eastern Europe	7.6 %	Africa	3.0 %

Source: Natural Resources Defense Council (1989, p. 49).

The foregoing provides a very brief indication of the situation, in terms of the gases and their sources. This brief picture must be considered in the context of some basic "facts of life".

SOME FACTS OF LIFE

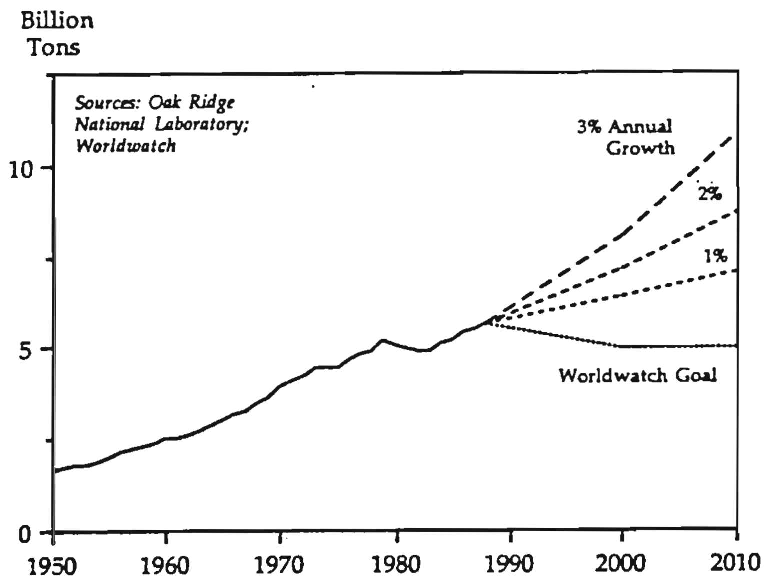
Setting targets and developing climate policies designed to meet those targets must be done with the recognition of some of the factors which will influence generation and discharge of GHGs. A few of these factors are cursorily indicated in the following paragraphs. No attempt is made to indicate relative importance, or to suggest that factors not listed are less important. All of the factors mentioned are relevant to the construction of scenarios, as discussed in Section 1.2.

- **Population and economic growth**---Studies by demographers in various countries, and the data compiled and analyzed by the United Nations, indicate that stabilization of the world's population is not likely to be achieved before the third decade of the 21st century. The estimated level of that stabilized population is about 10 billion, in contrast to the about six billion estimated for the year 2000. Even at relatively low levels of per capita use of materials and energy, to meet the basic needs of that stabilized population will require a five-to-tenfold increase in world economic activity over the next 50 years (Clark, 1989). Even the upper end of this estimate is likely to be conservative, given the increasing proportions of households living below the "poverty level" in many countries and increasing aspirations.

- **Quality of non-renewable resources**---The world's stock of non-renewable resources is finite. For some resources, the ratio of output to material and energy inputs is already decreasing. That is, it is requiring more and more materials and energy to produce one unit of output. For example, even with improvements in technology, on the average each barrel of crude petroleum recovered in the U.S. is requiring more energy than the last. To obtain copper from 0.5% copper ores requires substantially more energy than to obtain copper from 1.0% copper ores, including disposing of mine tailings and the residuals from smelter operations.

- **Side effects of alternatives**---Alternatives proposed to substitute for GHGs may have side effects themselves. These need to be explicitly considered in developing climate policies. For example, the safety of substitutes for CFCs and halons is an issue which is relevant to millions of users and to various aspects of environmental quality (Hembra, 1989). Adequate toxicity testing will not be completed until about the mid-1990s. In addition, some substitutes for uses of CFCs and halons are estimated to require a net energy addition (EIA, 1989).

Figure 1.1-1: Estimated Carbon Emissions from Fossil Fuel Combustion



Source: Worldwatch Institute (1989, p. 70).

- **Improving ambient environmental quality**---In the last two decades, demands for improved ambient environmental quality, as measured by various air quality, water quality, and land quality indicators, have increased in most so-called developed countries. Required removals of undesired materials from liquid waste streams and from gaseous waste streams have become more stringent. Only in the last half decade has the realization dawned that removing more and more materials from waste steams by waste treatment, i.e., end-of-pipe methods, in fact requires material and energy inputs and results in generating **more** materials requiring disposal, e.g., sludge from waste water treatment plants, scrubber slurry from power plant stacks. Energy use to improve ambient environmental quality by these means is a significant contributor to GHG discharges. For example, as much as ten percent of the energy generated in a fossil-fueled power plant will be used to reduce undesired discharges to the environmental media.

IMPLEMENTING CLIMATE POLICIES

Deciding on a target or a set of targets to be achieved by climate policies, based on prevention of estimated undesired effects, is perhaps the simplest task of "managing" global climate. As defined in the Glossary of this report, a climate policy includes not merely the identified physical measures to achieve reduction in discharges of GHGs, but also the means for achieving/implementing the desired reductions. That is, the policy must include the means for inducing the activities to adopt and continue to operate and maintain the **physical measures** required to achieve the desired reductions in discharges, the **institutional arrangement** for imposing incentives and monitoring performance, and the means for financing measures and administration.

The U.S. experience with respect to "water pollution" is instructive. Congress established both a general goal and a specific target in the Water Pollution Control Act Amendments of 1972. The goal was to make every water body "fishable and swimmable" by the mid-1980s (fishable and swimmable for what and for whom was not specified); the target was "zero discharge" to water bodies by 1985. (The latter was clearly an impossible target.) Although water quality in many water bodies had improved by the end of the 1980s, the country was far from having all water bodies "fishable and swimmable". The objective foundered on various problems of implementation.

To illustrate further: Table 1.1-3 shows the various actions to reduce CO_2 emissions in the U.S. proposed by the Natural Resources Defense Council (1989). Note that "State Building Efficiency Standards" is one of the suggested measures. However, establishing standards **per se** does **nothing** to reduce discharges. Discharges will only be reduced if the relevant parties, e.g., contractors and building users, are induced to adopt and implement those standards. What is required is the type of program developed and implemented by the Pacific Northwest Power Council (PNPC) with respect to improving energy efficiency in buildings. PNPC developed, in conjunction with public and private utilities in its area, a set of incentives to induce the adoption of various types of improved energy efficient measures. These incentives included technical assistance, financial assistance, regulations. After 3-4 years, PNPC and its utility cooperators evaluated the program in order to determine what incentives worked, and what had been achieved.

This critical connection between physical measures and implementation systems is what typically is missing in the context of climate policies. Thus, what are listed as "policies" in Table 1.1-4, are merely some indicated physical measures which, if adopted and maintained, would decrease discharges. There is no indication of "how" these physical measures are to be achieved.

Table 1.1-3: Suggested Measures to Reduce CO_2 Discharges in the U.S.A.

Measure	Estimate of % CO_2 reduction (midpoint ranges)
higher federal vehicle fuel efficiency standards	4.4 %
federal actions to improve lighting efficiency	2.5 %
higher federal appliance efficiency standards	2.5 %
federal actions to promote industrial efficiency	2.8 %
state building efficiency standards	2.3 %
actions to promote renewable energy sources	2.8 %
federal conservation reserve forestry program	1.4 %
improved and more intensive management of forest lands	1.9 %
urban tree planting	1.2 %
improved mass transit	.3 %
Total	**22.1 %**

Source: Natural Resources Defense Council (1989, p. 4).

CONCLUDING COMMENT

Three points merit emphasis. One, in appraising the various physical measures which have been proposed for reducing discharges of GHGs---note, physical measures not policies---one notes that almost without exception the measures involve "technological fixes". The proposals are to improve technical means of producing goods and services. There is virtually a complete lack of consideration of modification of components of final demand, i.e., modifying or eliminating products and services. For example, the largest use of CFCs as refrigerants is for mobile air conditioning (EIA, 1989, p. 11). No suggestion is made that perhaps the end use itself could be, and should be, modified.

Another example consists of paper products. The trend over the last two decades in the U.S. is toward higher and higher brightness of paper products, e.g., consumer paper products (towels, napkins, tissues), office papers, even corrugated containers. The levels of brightness sold to the public are unnecessary in relation to the functions to be performed. If the mean brightness [measured by General Electric Brightness, (GEB)] of the 10 million tons of relevant paper products

Table 1.1-4: **Climate Policies, Proposed and Enacted by Various Governments, as of September 1989**

	Policy	Status
The Netherlands	Proposals to freeze or cut CO_2 emissions and increase spending on efficiency	Parliament debating proposals; leaning to 4-year, 8-percent reduction in CO_2 emissions
Norway	Plan to stabilize CO_2 emissions by 2000, then reduce emissions	White paper approved by parliament in June 1989
Sweden	Plan to freeze CO_2 emissions at current levels; tax CO_2 emissions	Parliament approved emissions freeze, 1988; tax planned by 1991
United Kingdom	Considering control of methane leakage, improved energy efficiency	House of Commons Energy Committee recommendations
United States	Comprehensive legislation to cut carbon emissions 20 percent	Several bills pending in Congress
West Germany	Comprehensive policy under discussion	Government commission formulating proposals; report due mid 1990
U.S. States		
California	Comprehensive policy being developed	Government plan to be submitted June 1990
Oregon	Law requiring 20 percent reduction in greenhouse gases by 2005	Enacted July 1989
Vermont	Order to decrease greenhouse gas emissions, reevaluate state energy policy	Proposals announced by state governor September

Source: Worldwatch Institute (1989, p. 50).

produced in 1987 were decreased from GEB 80 to about GEB 25, there would be a saving of about 20 million barrels of fuel oil equivalent in production of these products, used in energy generation, plus a reduction in input raw material required because of the elimination of the 4-5% fiber loss in bleaching, plus a reduction in materials and energy required for sludge disposal.

In fact, many changes in final demand can be justified on the basis simply of improved economic efficiency and conservation of natural resources---renewable and nonrenewable---**regardless** of the extent or degree to which discharge of GHGs would be reduced.

The second point relates to the importance of developing relationships between selected targets and the costs of achieving the targets. Neglecting the differences in estimated results stemming from the application of different models, decision makers are interested in knowing what costs are involved, to whom, to achieve any given target or set of targets. What is needed, particularly in the context of North-South relations, is analysis of the **distribution** of costs associated with any given climate policy.

Three, the central tasks for Working Group 2 are twofold. One is to suggest types of indicators and levels of indicators, i.e., targets, which are relevant for the development and evaluation of alternative climate policies. The development of targets for climate policies, that allow precise and operational translation of more general, qualitative goals and objectives, is a useful --- a necessary, even --- though not sufficient task. This report attempts to provide decision makers with a state of the art review of the most appropriate indicators that are available at the current time, and for which target setting appears to be feasible.

The second task is to indicate to the politicians/decision-makers, the range of uncertainty associated with any estimate of emission reductions necessary to meet a given target, as a result of the limitations of currently available models. Before decisions can be made with respect to the allocation of emission reductions, the magnitude of emission reductions necessary has to be "believable". This is neither an insignificant nor an easy task.

ORGANIZATION OF THE REPORT

Chapter 1 provides an introduction to the nature of the climatic change problem, a framework showing the relationship between targets and climate policies, and a systematic approach to the selection of different possible sets of indicators and targets. In Chapter 2, possible targets for limiting the rate and magnitude of climatic change are reviewed, including goals for temperature, precipitation, and sea-level rise. Chapter 3 addresses the possibilities of translating long-term environmental goals into operational targets and evaluates emissions-temperature relationships. Attention is paid to uncertainties and possible feedbacks, modeling tools, global warming potentials, and the relationship between temperature and sea-level rise. Chapter 4 focuses on the implications of long-term target setting in relation to resource use, population growth, and economic activities, with consideration of the differences among countries and regions. A glossary is included in order to provide a common basis for discussion.

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1.2 SETTING TARGETS FOR CLIMATE POLICIES

F.R. RIJSBERMAN, G.W. HEIL and B.T. BOWER

INTRODUCTION

Policies that aim to: a) limit future climatic change, b) stabilize climate, c) reduce or mitigate the impacts of climatic change, or d) adapt to climatic change, have in common that they all need **indicators of climatic change**, both to indicate the need for action and to evaluate the effects of the policies adopted. In other words, operational objectives of climate policies need to be expressed in quantitative terms (indicators), which can be used to formulate criteria to evaluate alternative policy options and to monitor the implementation and effect of the chosen policies.

Climate policies in which specific values or levels of the indicators have been adopted as "**targets**" follow what has been termed the "**target approach**". The target approach to set climate policy objectives has been discussed in various publications (e.g., UNEP/Beijer, 1989). The clear advantage of the target approach is that - once appropriate targets are universally adopted - progress towards them should be quantifiable and unambiguous. Other authors criticize the target approach because of the difficulty of setting appropriate targets that are generally acceptable (Grubb, 1989).

Where there is no universal agreement over the usefulness of climate policy targets, there is certainly not yet agreement as to what such targets should be. This is caused at least in part by the fact that the climate system, and the system influenced by the climate system, is so complex that it is difficult to obtain a good understanding of the implications of specific targets. That is, it is not a priori clear what the impact of achievement of certain targets will be on: a) the climate system itself, e.g., whether climatic change will be prevented as desired; and b) the socio-economic system, e.g., what the cost will be of adopting targets, and the impacts thereof on the economy.

Decision makers are naturally hesitant to commit themselves to targets when the implications of such committment are unclear. In addition, in setting quantitative targets the conflicts of interests among the various parties become particularly apparent. Countries which rely heavily on coal for their energy supply have a different perspective from those with a system of nuclear or hydro powerplants already in place. Likewise, countries that currently have very high energy use per capita will naturally be more inclined to take the status quo as a starting point - and target increases or decreases - than countries that feel they have to catch up first with respect to energy use.

The conflicts of interest among countries cannot be solved through expert advice; these will have to be resolved at the negotiating table. The contribution of expert groups such as the AGGG can be twofold. First, the experts can attempt to increase the understanding of the climate system in order to decrease the uncertainty about the implications of the targets once they are adopted, both in terms of the effect of attaining the targets on the climate system, and in terms of costs to society of the measures required. Second, analysts can provide information on policies open to decision makers attempting to resolve conflicts of interest.

The first contribution of experts concerns - in part - the scientific aspects of climatic change, in addition to information on the cost(-effectiveness) of specific measures that could be taken. The second possible contribution involves a systematic exploration of - in principle - all feasible policy options open to the decision makers, including their cost and consequences. This requires multi-disciplinary, management-oriented analysis with explicit attention to, for instance: a) the objectives of the decision makers involved in the development of climate policies; and b) the problems related to implementation of policy options. A preliminary conclusion concerning the work of the Working Group is that its mandate appears to be focusing on the second kind of contribution, whereas the actual organization of the work (through individual contributions of specialists) is more related to the first type of contribution.

The objective of Section 1.2 is to lay out a coherent and consistent framework for analysis of targets for climate policies. An additonal objective of Section 1.2 is to carry out a first-cut exploration of the targets (i.e., values or levels of the indicators of climatic change) which decision makers can use to express their objectives for climate policies. Specific target values for individual indicators are then investigated in more detail in subsequent sections.

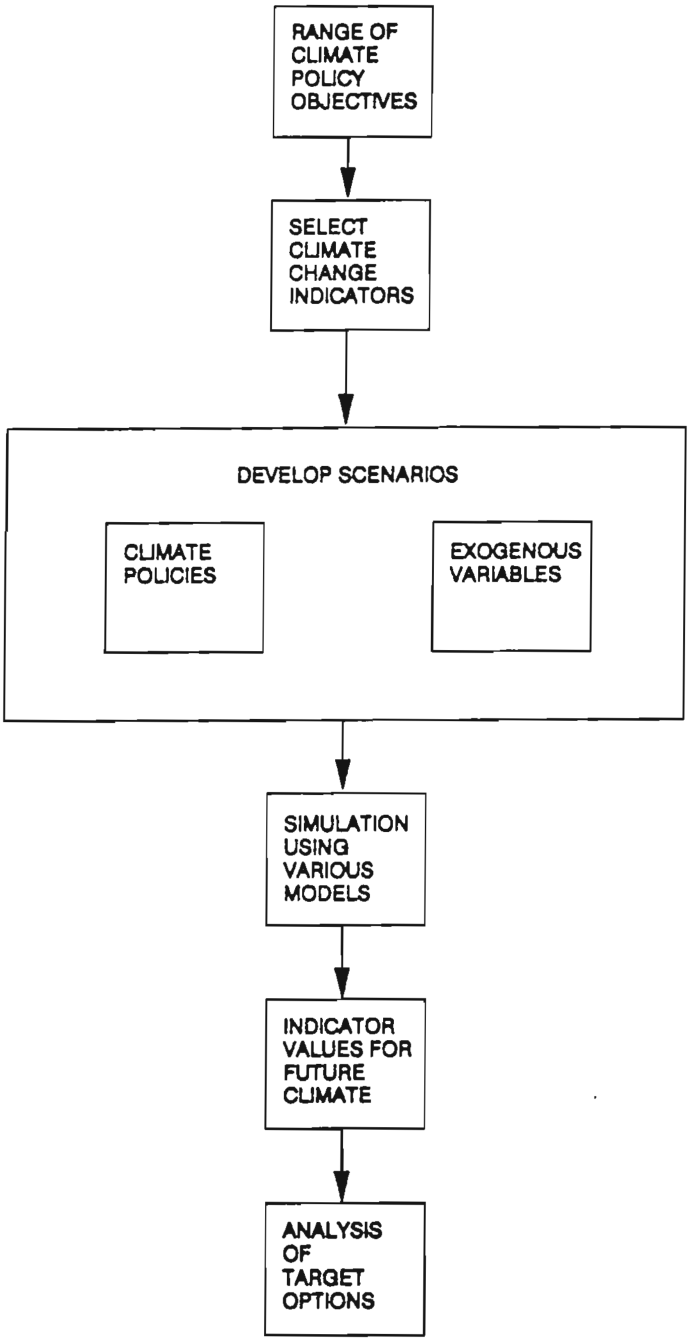
APPROACH

An analysis of targets for climate policies can be carried out by the following steps, as also illustrated in Figure 1.2-1.

- o **Analysis of objectives and associated indicators.** A review of climate policy objectives that are currently being considered in various international fora, and the indicators in which these objectives can be expressed. The main source of the objectives analyzed here are the statements and declarations resulting from the Toronto, Noordwijk, Tokyo, Cairo, and the Hague international gatherings, in conjunction with intergovernmental memoranda of understanding and statements made in various United Nations bodies.

- o **Development of scenarios.** Future climate is influenced by: a) climate policies; and b) changes in the biosphere and in the human system outside the sphere of climate policies. An analysis of future climate should, in theory, take into account all possible factors in both groups of influences. In practice, assumptions are made about the most important factors in both groups. A specific set of assumptions is referred to as a scenario. A baseline scenario is needed, also referred to as a "business as usual" scenario, to evaluate the impact of specific climate policies. Because scenarios are formulated by different research and policy groups, it is necessary to agree on a common format to allow comparison of results. A set of scenarios needs to be defined to cover the full range of alternative climate policies.

Figure 1.2-1: Analysis of Targets for Climate Policies



- **Simulation of the effects on future climate.** Studies of climate policies use a suite of climate and climate impact models as the basis for an analysis of the relation between the implementation of proposed climate policies and the (simulated/ forecasted) resulting ranges of indicator values for each of the scenarios that result from the previous step. The models on which the current studies are based are very complex computer models, but they are still radical simplifications of reality. An important drawback of the climate models currently available is that they are not able to account properly for the various, particularly biogeochemical, feedbacks, or to simulate changes in the structure of the system. All changes are modeled as gradual shifts, whereas in reality there may well be instabilities, jumps, and changes in structure. As a result there is a very considerable uncertainty associated with the model results.

  A schematic overview of a typical modelling framework used for the simulation of the effect of climate policies on future climate, and on the impacts of climatic change, is presented in Figure 1.2-2. In this figure the assumptions and data that are used to drive the models, and the model outputs which are used as inputs for the next model, are shown together with the main models used. The term "model", as defined in the glossary, is used here in the general sense of "representation of a system"; not necessarily mathematical (numerical) model.

- **Analysis of results and development of targets.** The ranges in indicator values resulting from the analysis outlined in the previous step can be used for an analysis of possible targets for climate policies. Advantages and drawbacks of the various target options can be outlined, and scientists can give their recommendations concerning targets that are appropriate from a scientific perspective. This is as far as this report goes. The final selection of targets remains, however, a political decision.

  The process outlined above is reflected in the remainder of this report.

The goals, or objectives, of climate policies express the desired situation with respect to future climate, usually in general, qualitative terms. Operational targets are then required to translate these goals in operational, quantitative terms, for which policies can be developed.

The analysis of targets for climate policies is but one step in the development and implementation of climate policies, which is illustrated in Figure 1.2-3. Following the setting of targets, climate policies need to be developed and tested that would achieve those targets. It is important to note that setting targets, without specification of the "on-the-ground" measures of how to get there, does not have any effect at all. Climate policies need to consist of a complete set of physical measures, implementation incentive systems, institutional arrangements and financing arrangements for policies (definitions of these terms are given in the glossary). Following adoption of a specific climate policy, monitoring will have to be carried out of the climate system, of the activities that generate emissions and of the impacts of climatic change. Monitoring the indicators in which the targets of the climate policies were expressed will allow an evaluation of the effectiveness of the policies, and may lead to a revision of targets and policies.

Figure 1.2-2: Overview of Modelling Framework for the Simulation of Climate Policy Impacts

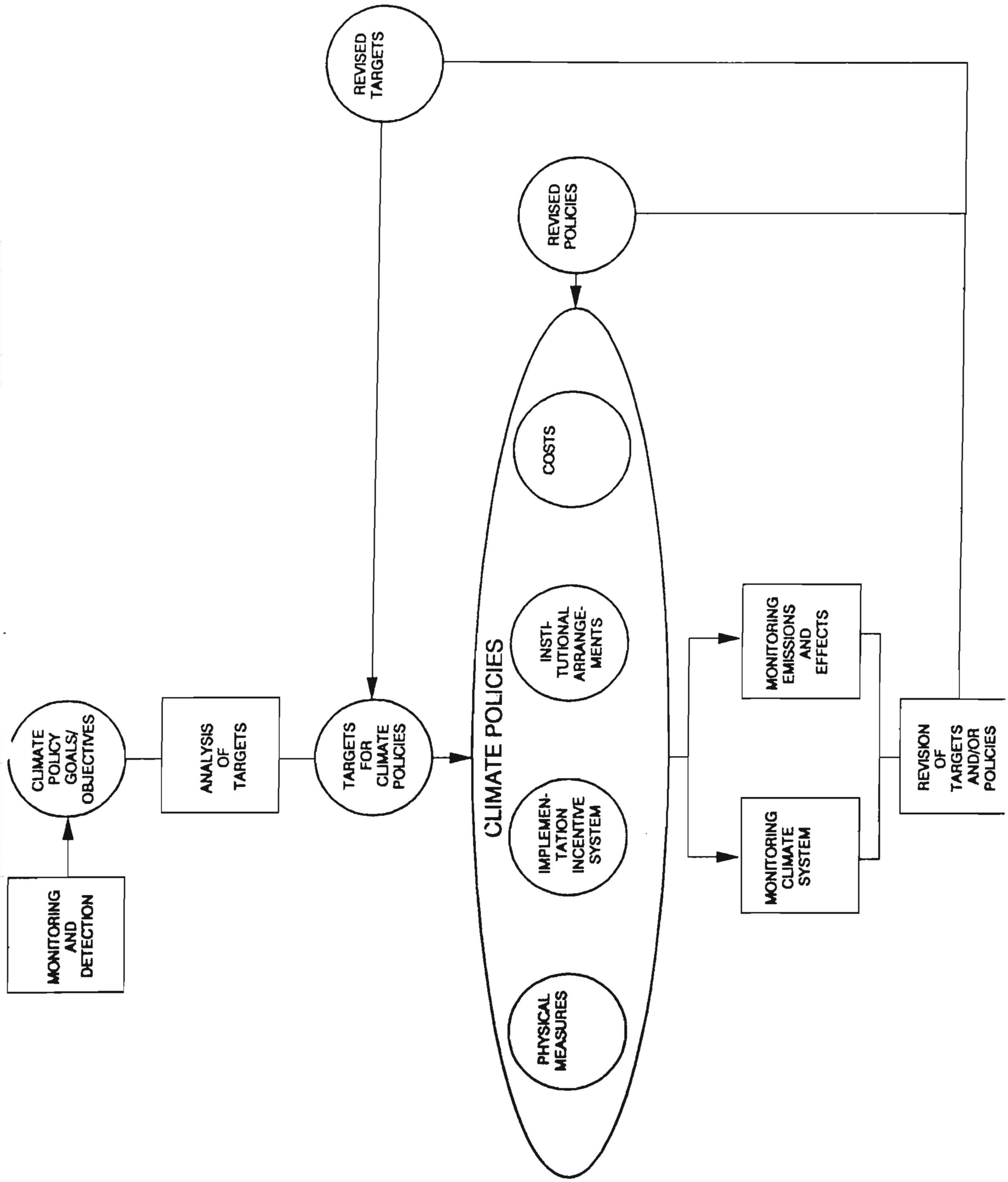
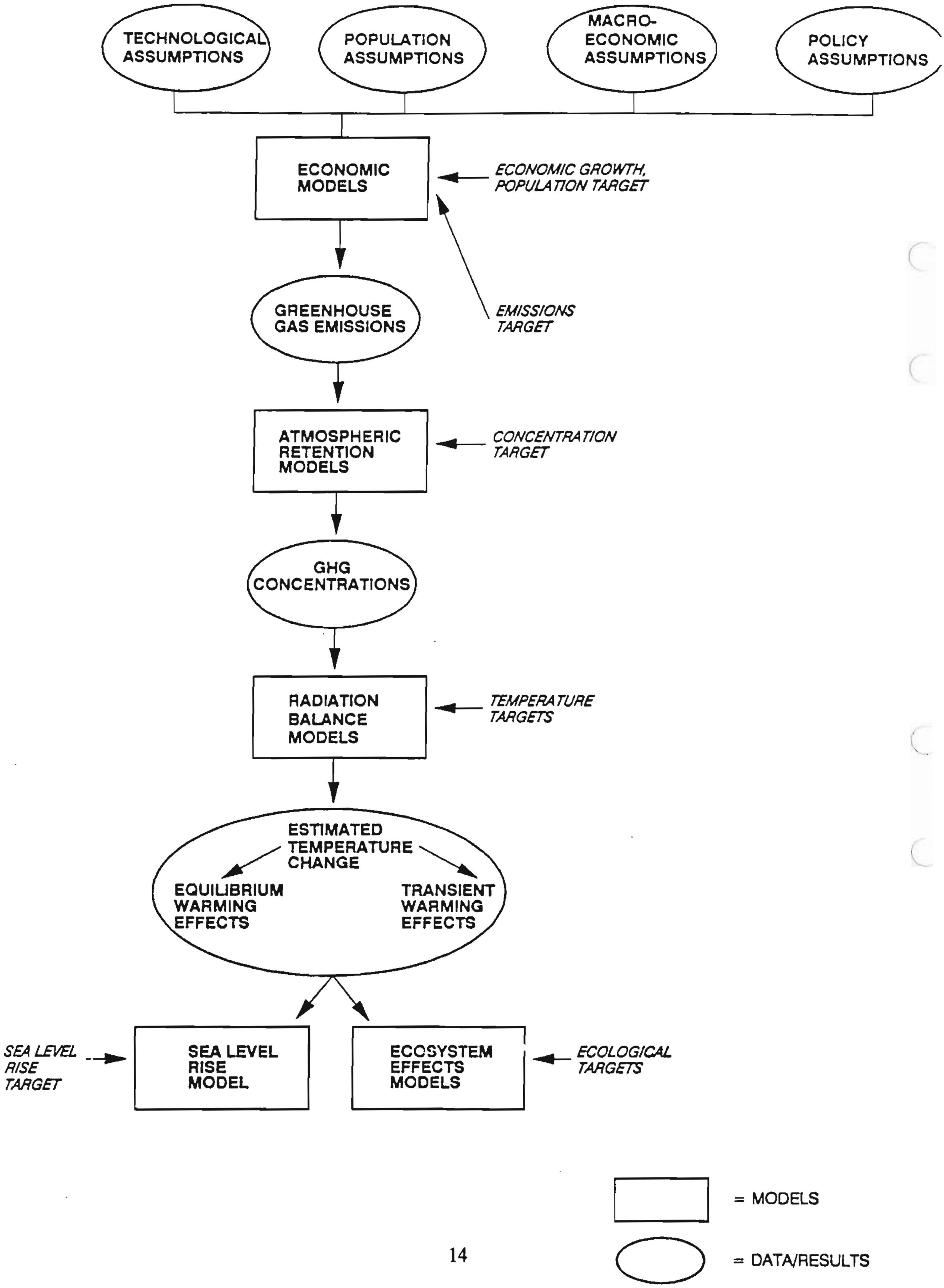


Figure 1.2-3: Development and Implementation of Climate Policies



CLIMATE POLICY OBJECTIVES AND ASSOCIATED INDICATORS

Climate Policy Objectives

As politicians and ordinary citizens have recently become aware that man's activities may be changing the global climate at such a rate that both the biosphere and the socio-economic system may be significantly affected, various climate policies have been put forward and dicussed in a multitude of national and international fora. These climate policies have different objectives, ranging from preventing or limiting future climatic change to adapting to climatic change and its impacts. Furthermore, there are differences in the level of specificity of stated climate policy objectives ranging from general expressions at the level of "safeguarding the environment" to quantified targets in terms of reduction of emissions of specific gases, to quantified targets in terms of maximum increase in global temperature.

Analysis of the statements and declarations of a series of international meetings devoted to climatic change (Toronto, the Hague, Cairo, Noordwijk, Tokyo) and statements issued by international bodies such as the United Nations General Assembly, the European Community Council and the Group of 77, shows that the climate policy objectives discussed in these fora can be categorized in various ways. The following hierarchy of broad objectives is proposed, and the statements that refer to these objectives are mentioned.

1. Limit the impacts on human society and natural ecosystems.

This is the ultimate objective, put in general terms, the preservation of the quality of the global environment for future generations. The UN General Assembly Resolution (United Nations, 1989), the Declaration of The Hague (1989), and the Noordwijk Declaration on Climate Change (1989) all contain language of this kind. It is important to note that, even though this objective is qualitative, the focus is on the final results -- to prevent damage and preserve the quality of the environment -- rather than on causes such as greenhouse gas emissions. Without specification of indicators and targets, however, this type of objective remains non-operational.

2. Limit the rate and magnitude of sea-level rise.

One impact of climatic change which affects both human systems as well as ecosystems is a rise in sea level. Objectives, specifically in terms of limiting the rise in sea level, have been formulated in scientific meetings but have not been found in the more political statements referred to above.

3. Limit the rate and magnitude of temperature change.

Given that the most talked about indicator of climatic change is the change in global mean surface temperature, one would expect objectives in terms of limiting this change to a certain rate or magnitude. Even though this appears to be the objective favored by scientists, such as at the Villach conference, (Jäger, 1988), it has not been found directly in the policy statements analyzed.

4. **Stabilize the ambient concentrations of specific greenhouse gases.**

If all processes involved in the relation between concentrations and resulting global mean temperature were perfectly known, specification of concentrations would be equivalent to specifying temperature. As it is, specification of concentrations objectives eliminates one source of uncertainty. The Noordwijk Declaration includes stabilization of concentrations of greenhouse gases as one of the objectives for climate policies.

5. **Stabilize and/or reduce the emission of greenhouse gases, and enhance sinks, to stabilize the atmospheric concentrations of greenhouse gases.**

When it is considered undesirable or infeasible to formulate an objective in quantitative terms directly relating to the quality of the future environment, a substitute can be to target emissions. Although more easily verifiable, the drawback is that limited emissions do not, by themselves, guarantee the preservation of the environment. To stabilize emissions at current levels, or reduce future emission growth rates may well be insufficient to prevent damage. The Toronto Conference Statement (Environment Canada, 1988), the Noordwijk Declaration on Climate Change (1989) and the European Community Council Resolution (1989) contain specific targets for emission reduction.

6. **Take measures to reduce greenhouse gas emissions in an equitable manner among the different actors and increase CO_2 sinks.**

In a situation in which it is considered imprudent to fix a specific target for reduced emissions of greenhouse gases, the next best thing is to recommend or prescribe certain measures, or, the use of "best technology". This option is also chosen with respect to other environmental regulations. Best technology implies that "we do the best we can" without being held to achieve a specified emission reduction. Recommendations to promote research and development of new technologies, and to use environmentally friendly alternatives (without setting specific targets) fall into this category. The European Community Council Resolution (1989), the recommendations of the Tokyo Conference on the Global Environment and Human Response (1989), the Cairo Compact (UNEP, 1989), and the Environmental Statement of the Group of 77, for instance, contain examples of this kind of objective.

Indicators of Climatic Change

Indicators are necessary, first, to **detect** climatic change. Indicators can relate to climatic change either directly (climate parameters) or indirectly through measuring and monitoring the impacts of changes in the climate system, preferably in quantitative terms. Given the current debate about climatic change a set of generally accepted indicators for which data are - or will be - available is needed to determine unambiguously the rate and extent of climatic change.

Second, indicators of climatic change are essential tools to be able to set alternative targets for climate policies. The same indicators are then subsequently used to monitor and evaluate the implementation and impacts of climate policies.

A discussion of the advantages and disadvantages of the various possible climatic change indicators is given by Swart and de Boois (1989), even though they use the term "targets" for what are called "indicators" in this report. Their list of climatic change indicators is shown in Table 1.2-1. Swart and de Boois evaluate climate indicators in relation to the following criteria:

a) **Relationship with adverse effects:** there must be sufficient evidence that intolerable negative effects will occur if the changes exceed the targets.

b) **Relationship with causes:** the dependence of the indicator on the emission of greenhouse gases must be sufficiently certain and quantifiable.

c) **Positive parameter:** the target should be positive rather than an avoidance of climatic change impacts.

d) **Flexibility:** experience with other environmental problems shows the need for a target that allows for policy changes.

e) **Detectibility:** it would be useful if the degree of success of climate policies could be detected.

f) **Historical support:** it should be possible to establish a value for the target based on historical rates of change, or tolerance levels.

g) **Global significance:** although both causes and effects are essentially regional, climatic change is a global phenomenon and therefore the selected targets should have global implications.

What appears to be missing from this list is a criterion to evaluate explicitly the usefulness of the indicator to reflect (progress toward) policy objectives. That is to say, if decision makers tend to word their objectives for climate policies in terms of "safeguarding the global environment for future generations", then it would be useful to have indicators which can be used to set an operational target for such an objective, and subsequently monitor progress.

Swart and de Boois conclude that it is unlikely that one indicator will satisfy all requirements, and that therefore sets of indicators should be used. For each of these indicators targets can be set. They suggest the following set of indicators:

o **Rate of global mean temperature change** as a central indicator, because of its direct links with both causes and effects, supplemented by an absolute limit on temperature change.

o **Rates of change in sea level** as secondary indicator, especially valuable for the planning of adaptation strategies.

o **Greenhouse gas concentrations** as monitoring instruments.

o **Emission levels** as the basis for national climate policies.

Comparison of the types of objectives listed earlier with the indicators outlined above, gives rise to the following remarks.

Table 1.2-1: **Overview of Climatic Change Indicators**

INDICATORS	CRITERIA a	b	c	d	e	f	g
social/economic effects	++	?	-	-	?	?	++
ecological effects	++	?	-	-	?	?	++
sea-level rise, absolute	++	+	++	++	+	?	++
sea-level rise, rate of change	++	+	++	++	+	+	++
regional sea-level rise	++	+	++	++	++	+	-
warming commitment, absolute	++	+	++	++	-	?	++
warming commitment, rate	++	+	++	++	-	+	++
actual warming, absolute	++	+	++	++	-	?	++
actual warming, rate of change	++	+	++	++	+	+	++
regional temperatures	++	+	++	++	++	?	-
concentration, absolute	+	++	++	++	++	+	++
concentration, rate of change	+	++	++	++	++	+	++
regional concentrations	-	+	++	++	++	?	-
global emissions	+	+	++	++	+	?	++
cumulative emissions	+	++	++	+	+	?	++
regional emissions	+	++	++	+	+	?	-

a= related to effects b= related to causes c= positive parameter
d= flexible parameter e= detectible parameter; f= historical support
g= global significance ++ =very much += yes
?= uncertain; -= no.

Source: Swart and de Boois (1989).

There are no concrete indicators of "the impacts on human society and natural ecosystems" of climatic change (objective 1) in the above list. There are suggestions for potentially useful ecosystem indicators (see section 2.3 of this report), but operational indicators are not yet available. That implies that concrete targets cannot yet be set directly for the first type of objective.

Instead of having direct indicators of impacts on ecosystems, however, there are several indicators available that can be related to impacts on ecosystems, notably sea-level rise, and temperature change. It is possible to set targets to limit the rate and magnitude of sea-level rise and temperature change in order to protect natural ecosystems. This is the approach followed in this report.

It is also possible to find indicators, obviously, to stabilize the ambient concentrations of specific greenhouse gases. The advantage of an objective expressed in concentrations of greenhouse gases is that it is more easily verifiable, and eliminates the uncertainty introduced in the translation of changes in concentrations to changes in temperature. Targets for concentrations could then be set to attain the desired targets for sea-level rise and temperature. It must be noted, however, that the latter targets can be attained through an infinite number of combinations of concentrations of the various greenhouse gases. That is to say, increased concentrations of carbon dioxide, for example, can be compensated by reduced concentrations of the CFCs.

That different combinations of concentrations, and therefore emissions, of greenhouse gases can have a similar effect implies that it is less useful to express objectives in terms of emissions of a particular greenhouse gas. Similarly, recommendations of specific measures or technologies may be helpful, but because of the lack of a direct link with either the causes or the effects of climatic change, these are less suitable as indicators of climatic change or targets for climate policies.

SCENARIOS

Scenarios are needed to summarize the many assumptions about uncertain influences on future climate from both: a) climate policies; and b) changes in the socio-economic and biospheric systems outside the sphere of climate policies. The word scenario is used in various ways in the climatic change context, but any scenario that specifies greenhouse gas emissions, greenhouse gas concentrations or changes in temperature is -- explicitly or implicitly -- based on a number of assumptions for a host of variables.

Some of the most important of these variables, here termed driving variables, are often left implicit. This is true, for instance, of the rates of population growth, economic development, or deforestation. Other variables such as technical change, are implicit in the assumptions for, for instance, emission coefficients.

A complete specification of a scenario essentially covers the complete cause-effect chain that leads to climatic change, starting with basic economic variables, and ending with climate parameters such as climate sensitivity. Different scenarios are developed by different groups of people for various studies, and it would be valuable to compare their results. If a standard format were adopted to describe the various scenario assumptions, a comparison of results would be much easier. An attempt to give an overview of all variables that should be included in a complete specification of a scenario is given in Table 1.2-2.

There are two problems with scenarios that leave a number of these assumptions implicit, and only specify greenhouse gas concentrations and/or temperature changes. First, it is difficult to compare different scenarios if the underlying assumptions are not specified. Apparent differences may not be caused by climate policy related variables but by underlying (exogenous) variables. To properly evaluate alternative climate policies and their impacts among each other, all asssumptions for exogenous variables should be the same.

Second, if scenarios only specify the second part of the cause-effect chain, for example, starting with emissions, then it will be very difficult to evaluate whether implementation of such scenarios is feasible, or even what must be done to implement such scenarios. Scenarios should, as much as possible, be explicit about measures to be taken for implementation. This concerns physical measures, implementation incentives, institutional arrangements and financing of the policies.

If the complete cause-effect chain, from climate policy measures to temperature change - or even socio-economic effects of climatic change further down the line - were well-known and deterministic, then specification of the input or driving variables would amount to the same thing as specification of a specific

Table 1.2-2: Climatic Change Scenario Variables

Driving variables (manipulated variables): - economic growth - population growth - deforestation
Implicit variables (e.g., implicit in emission coefficients): - technological change (e.g., energy efficiency) - social preferences - factor prices (e.g., energy) - climate sensitivity.
Government actions: - energy related subsidies - environmental regulations - energy efficiency requirements - purchasing specifications - reforestation - CFC phaseout - international transfers
Resulting variables: - greenhouse gas emissions - greenhouse gas concentrations - temperature change - sea-level rise

temperature increase over a certain period. Since there are significant uncertainties in the chain, and there are infinite combinations of driving variables to reach a similar temperature result, it is necessary to specify complete scenarios.

Various approaches to the development of scenarios can be found in the literature, based either on simulation of the impacts of climate policies, or on the target setting approach, as demonstrated by the following examples:

a) EPA's scenarios (Lashof and Tirpak, 1989) use the current state of the socio-economic system as a starting point, make explicit assumptions about exogenous changes (GNP growth, technology changes, energy price changes, etc.) and climate policy measures (CFC phaseout, energy efficiency gains, energy emission fee, etc.) and subsequently attempt to find the resulting emissions, greenhouse gas concentrations and temperature increases.

b) IPCC's scenarios (see section 3.4) start with assumptions for greenhouse gas concentration targets, characterized by the year in which the greenhouse effect for all trace gases combined reaches the level equivalent to that which would occur from a doubling of global mean CO_2 concentration compared with pre-industrial levels, i.e., 2030, 2060 and 2090. Subsequently, two additional scenarios have been developed that reduce emissions to maintain equivalent CO_2 concentrations at levels well below doubling along two different time paths. The initial assumption about concentration implies assumptions about the underlying driving variables and associated emissions, and these are deduced by reasoning back along the cause-effect chain.

c) Krause's (1989) scenario is based on an assumption for a maximum rate of global mean temperature change target **and** an absolute limit on temperature change target, and subsequently traces back along the cause-effect chain what global equivalent carbon emission budget, associated measures, etc., should be to reach these targets.

Most other published scenarios are variations on the above examples. In theory, if all scenarios specified the complete cause-effect chain, the starting point for the scenario would be immaterial, and one could compare the results for an analysis of the implications of various alternative climate policies, in order to select targets for climate policies. This is what was attempted by the authors of this section. In doing so, however, it became clear that because not all scenarios explicitly state all underlying assumptions, partly caused by the fact that the various scenarios have been developed for different purposes, one should be very careful in the comparison of these results.

Scenarios, in the climatic change context, are commonly defined as a combination of exogenous (such as economic or population growth) and endogenous (climate policy) variables. A rigorous policy analysis needs to separate the effect due to changes in endogenous variables --- the policies one wants to compare --- from those caused by changes in exogenous variables. If this is not possible --- as appears to be the case for the scenarios currently available --- it is essentially not possible to compare the results of different studies.

The lack of a generally accepted base case --- or baseline --- scenario is a serious limitation. A baseline scenario, or a set of several baseline scenarios to reflect uncertainty in the development of exogenous variables such as the EPA Rapidly Changing World and Slowly Changing World (Lashof and Tirpak, 1989), would provide a common basis to compare the impacts of alternative climate policies. It may be a practical solution to use the IPCC 2030 scenario as a base case scenario.

SURVEY OF INDICATORS AND TARGETS

In the following, potential indicators and targets are outlined to provide a general overview of the options. The discussion follows the order of the hierarchy of broad objectives presented above. Chapter 2 subsequently presents a detailed discussion of the most important of these indicators and the recommended target levels associated with each of them.

a) Ecosystem change and shifts in vegetation zones

The expected poleward shift in climate zones will cause a shift in vegetation belts to higher latitudes and altitudes than in the present situation. Present model calculations predict shifts in range limits for tree species in the order of magnitude of 100 km per °C. Vegetation responses to climatic change in the past, however, indicate that tree species, such as beech or hemlock, were able to migrate at average rates of 20-25 km per century (Davis, 1989). Maximum migration rates may be higher. Possibilities for future migration will, however, be significantly limited, not only because of natural barriers such as mountains and rivers, but also because of man-made barriers such as roads, cultivated areas and destruction of suitable habitats (de Boois, 1989; Davis, 1989).

Biological diversity would be an useful parameter to quantify ecosystems and to detect climatic change. A difficulty with respect to decrease in biological diversity would be to isolate impacts of climatic change from those of other factors such as acid rain. More research and monitoring is needed to define indicator species and/or indicator ecosystems.

b) Agriculture and food supply

Agricultural practices will be seriously affected by climatic change. Together with a poleward shift of the regional climate zones, agricultural cultivation areas will shift polewards. As a result of sea-level rise, particularly fertile areas in deltas and estuaries are likely to be lost to the ocean as a result of floods and erosion, and hence be lost as farmland. In addition, seawater will penetrate further into the estuaries of major rivers, thereby reducing arable land in these regions.

It is very difficult to estimate the impact of climatic change on agriculture. In general terms, it can be hypothesized, however, that the highly managed nature of most agricultural systems will make them more flexible to adapt to climatic change than natural ecosystems. This would imply that targets developed for agricultural systems would probably be less restrictive than those developed to protect natural ecosystems.

c) Sea-level rise

As a result of rising temperatures it is expected that global mean sea level will rise substantially. During the last century global average sea level has risen **0.1 - 0.15 m.** Ocean and glacial studies suggest that this rise is consistent with model simulations based on a warming of **0.4 °C** over the past century (Titus, 1986). Recent estimates (Oerlemans, 1989a) predict a total sea-level rise of 0.65 m by the year 2100 under the Villach II scenario.

Because of their high climate sensitivity mountain glaciers and ice sheets would appear to be very suitable as indicators of climatic change. However, at present the observed warming cannot yet be attributed to man-induced greenhouse warming with definite statistical significance (Oerlemans, 1989b). The impact on the Antarctic ice sheet is especially uncertain, because the size of the ice sheet can either increase through increased snowfall or decrease by melting and enhanced calving and contribute to the global sea-level rise with as much as 2 meters or more (Titus, 1986; Oerlemans, 1989a).

Targets for sea-level rise can be based on either, or both, the impacts of sea-level rise on vulnerable natural ecosystems such as coastal wetlands or coral reefs, or the impacts on human systems, varying from small island nations to some of the world's largest cities situated on the coast.

d) Ocean currents and regional climatic change

The ocean considerably modifies atmospheric behavior, because it can store vast amounts of heat and because half of the global temperature compensation between the tropics and high latitudes is achieved by ocean currents. In addition, changes in ocean currents have a major impact on regional climatic variability.

Predictions of regional changes in climate would be particularly relevant, but are made with much more uncertainty than predictions of global change. This is due to the fact that the models available still have major shortcomings (particularly the incompleteness, or absence, of various feedback mechanisms such as ice/albedo feedback, feedback from large scale dynamic processes, clouds and radiation, temperature/water vapor feedback, and biogeochemical feedbacks).

e) Precipitation and water supply

At present, it appears to be very difficult to quantify projections of future changes in regional precipitation. GCMs can only give rough approximations, indicating increases in average annual runoff of up to 60% in latitudes between 40 and 60 degrees for a doubling in CO_2 concentrations (Williams, 1989). Although it is expected that mean global rainfall is likely to increase, there will be wide regional variations with many areas becoming drier. The amount of rainfall in the tropics may increase by 5-20%. Changes in rainfall volumes are closely related to poleward shifts of the major climate zones. Temperature and precipitation changes would seriously affect the length of the growth period of natural vegetation and crops (Brouwer, 1989).

f) Temperature

At present global mean surface temperature values are commonly used to describe climatic change. Results of most climate simulation models (GCMs) forecast a mean temperature rise due to doubling of CO_2 concentrations ranging from **1.5 to 8.0 °C** depending on how they treat the various feedback mechanisms (CDAC, 1983; Dickinson, 1986; Lashof, 1989).

Krause *et al.*, (1989) introduce the concepts of 'unprecedentedness and climatic throwback' to deduce targets for temperature change. Analyzing past rates of changes, they distinguish the following thresholds:

I) A **1 - 1.5 °C** global average warming would represent a climate not experienced since the Holocene period at the beginning of agricultural civilization (6000 years BP);

II) A **2 - 2.5 °C** warming can be compared with the climate during the Eem-Sangamon interglacial period (125,000 years BP) with hunter-gatherer societies, and sea levels raised up to 5 - 7 m;

III) A **3 - 4 °C** warming would represent the situation during the Pliocene period (3-5 million years BP), while human beings appeared on earth only 2 million years ago;

IV) A **5 °C or more** warming would mean a climate not experienced for tens of millions of years, when there were no ice sheets or glaciers on the entire earth.

g) <u>GHG concentrations</u>

For a comparison of future atmospheric concentrations of greenhouse gases under different scenarios, knowledge of concentration levels in the past can be helpful to assess possible impacts. According to Lorius *et al.*, (1989) CO_2 concentration levels during the Würm glacial period were around **190-200 ppm** and during the interglacial periods around **260-280 ppm.** The pre-industrial level of CO_2 (1850) was approximately **275-290 ppm.**

Most scenarios use the following for 1985 concentrations:

CO_2	345 ppm
CH_4	1.675 ppb
N_2O	300 ppb
CFC-11	225 ppt
CFC-12	364 ppt

Krause *et al.* (1989) suggest a maximum allowable **CO_2 equivalent concentration** in the next century of **430-450 ppm,** provided that concentrations decline again thereafter. This CO_2 equivalent limit indicates a CO_2 concentration limit of **380-400 ppm,** with other trace gases limited to a **50-70 ppm** CO_2 equivalent.

h) <u>Emissions</u>

Krause *et al.*, (1989) suggest an upper limit for cumulative fossil carbon releases between 1985 and 2100 of about **300 btC.** This implies an atmospheric concentration of CO_2 of **400 ppm.** There are an infinite number of combinations of greenhouse-gas concentrations that would achieve the same effect. For instance, if CFC emissions were banned completely the reductions in CO_2 emissions could be less substantial.

CONCLUSIONS AND DISCUSSION

In this section a framework for analysis of targets for climate policies has been presented. The framework is intended to provide a structure for the remainder of the report in the sense that it shows how the various sections fit in the process of setting targets. It has also been indicated how the setting of targets for climate policies fits in the larger process of development and implementation of climate policies.

The framework referred to above was subsequently used to explore the main components of the analysis of targets for climate policies as they have been put forward in the current climate debate. This concerns particularly: objectives for climate policies, indicators of climatic change, and scenarios of exogenous and endogenous developments influencing future climate. Models used to simulate the effects on future climate are discussed in detail in subsequent sections of this report.

Analysis of objectives for climate policies put forward in international political fora shows that a hierarchy of broad objectives can be distinguished, for which one can look at the available indicators and targets for climate policies.

Analysis of the indicators proposed by Swart and de Boois in an earlier report dealing with indicators of climatic change (UNEP/Beijer, 1989) in conjunction with the above mentioned hierarchy of objectives leads to the following observations.

Direct indicators for the ultimate objective, to limit the impact of climatic change on human society and natural ecosystems, are not yet available. It is possible, however, to identify indicators and set targets to limit the rate and magnitude of sea-level rise and temperature specifically in order to protect natural ecosystems. Greenhouse concentrations and/or emissions are less useful as global targets for climate policies because different combinations of emissions --- and concentrations --- can have a similar effect on future climate. Emissions of specific greenhouse gases can, however, be useful to shape and monitor national climate policies in the short term.

Scenarios are necessary to analyze how the implementation of the alternative policies would affect future climate. Such scenarios are based on a host of assumptions for both endogenous (climate policy) variables and exogenous variables. To be able to compare the results of different studies which have analyzed different scenarios -- which is necessary to compare alternative climate policies, and to explore targets -- it should be clear what the underlying assumptions are. A format has been proposed to explicitly account for the most important scenario variables in Table 1.2-2.

A limited analysis of a number of relevant scenarios and their reported effect on future climate (specifically realized warming) suggests that there may be important differences in the underlying assumptions for the scenarios which essentially prevents the comparison of their results. In this context it is argued that there is a need for a generally accepted and properly documented base case, or baseline, scenario. It may be that the IPCC 2030 scenario is a practical basis for this.

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1.3 SENSITIVITY VERSUS STABILITY APPROACH

W. SASSIN

INTRODUCTION

Global climate has gone through a cycle of glacial and interglacial periods. Ice cores provide simultaneous information on temperatures and atmospheric composition back to the last but one glacial period (Barnola et al., 1987). The present level of atmospheric CO_2 is about 350 ppm and exceeds the pre-industrial value of about 280 ppm significantly. The present concentration of CO_2 also exceeds the maximum level of 300 ppm reached in the previous interglacial period 130,000 years BP, as shown in Figure 1.3-1.

This is an alarming finding. If the correlation, between atmospheric carbon dioxide concentration and mean global surface temperature derived from such ice core measurements were to hold, under present conditions our global average temperature should already be about 6 °C above the present average temperature (Goreau, 1989).

The prospects for the coming decades are even worse. Harvey (1989a) has projected future concentrations of CO_2 for alternative scenarios with various values of demographic and economic parameters. These CO_2 projections include increased transfer rates of CO_2 from the atmosphere into the ocean. The increased buffer capacity is derived by using coupled atmosphere-ocean models (Harvey, 1989b). Harvey's projections lead to estimated CO_2 concentrations between 360-430 ppm by the year 2050, as shown in Figure 1.3-2.

The present situation does not enable an assessment of the full implications of the climatic challenge. The large discrepancy between the identified climatic change of 0.7 to 0.8 °C since the mid-19th century and the long-run correlation between CO_2 and global mean temperature may be reduced by including detailed secondary and tertiary feedback processes between climatic subsystems. The following questions are important to the scientific debate:

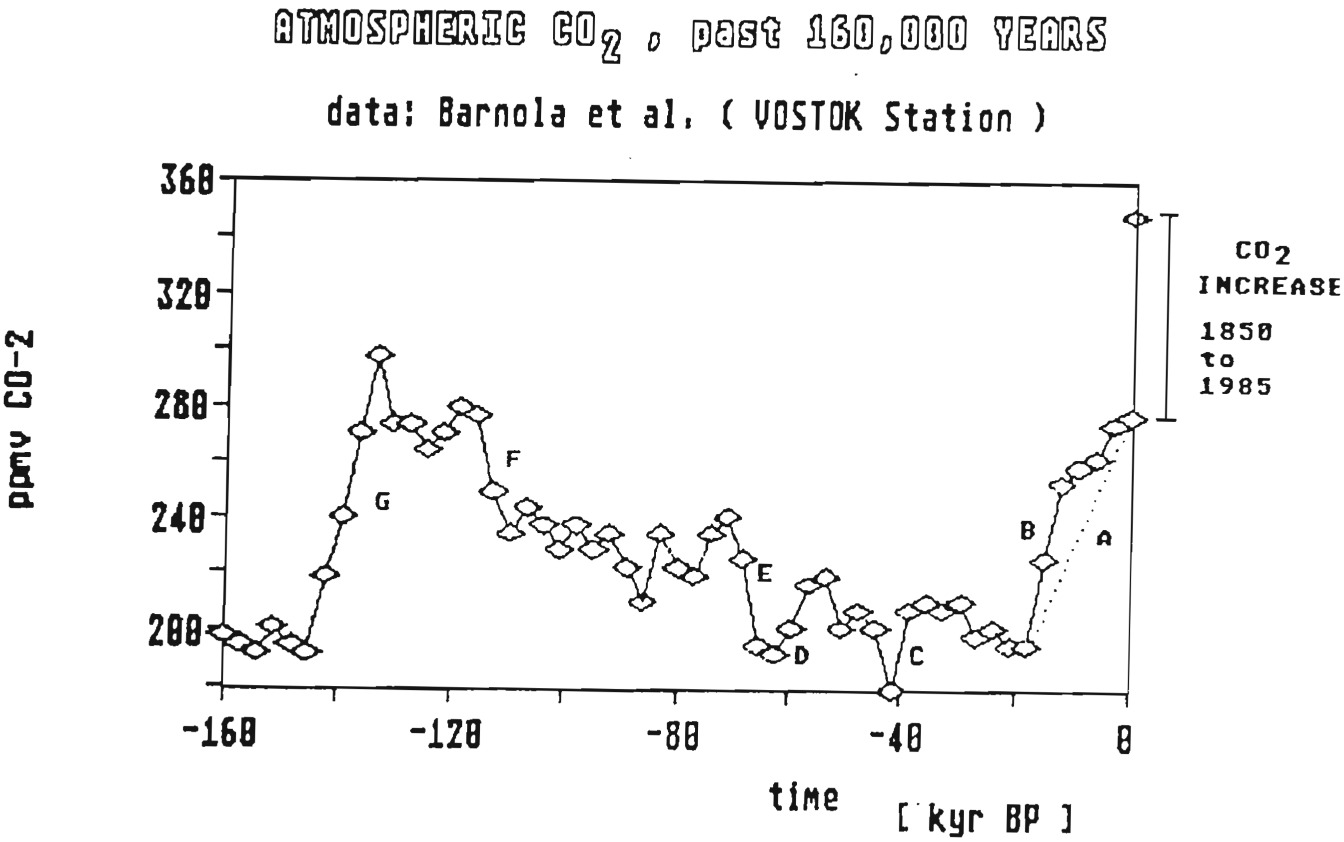
- How important are time lags in the feedbacks between atmospheric concentrations of GHGs and other climate subsystems?

- Have short-term compensatory effects suppressed the climatic impact of the actual buildup of atmospheric concentration of GHGs since the beginning of the industrial revolution?

- Is the radiative forcing effect of GHGs the decisive controlling mechanism of the observed correlation between global mean temperature and CO_2 concentration?

The design of a realistic response strategy has to start with an evaluation of the uncertainties arising from the limited scientific understanding of the climatic processes in relation to the various ecological levels that form the biosphere. Such an evaluation invokes social and political considerations.

Figure 1.3-1: Changes in CO_2 Concentrations in the Past 160,000 Years (after Barnola, 1987)



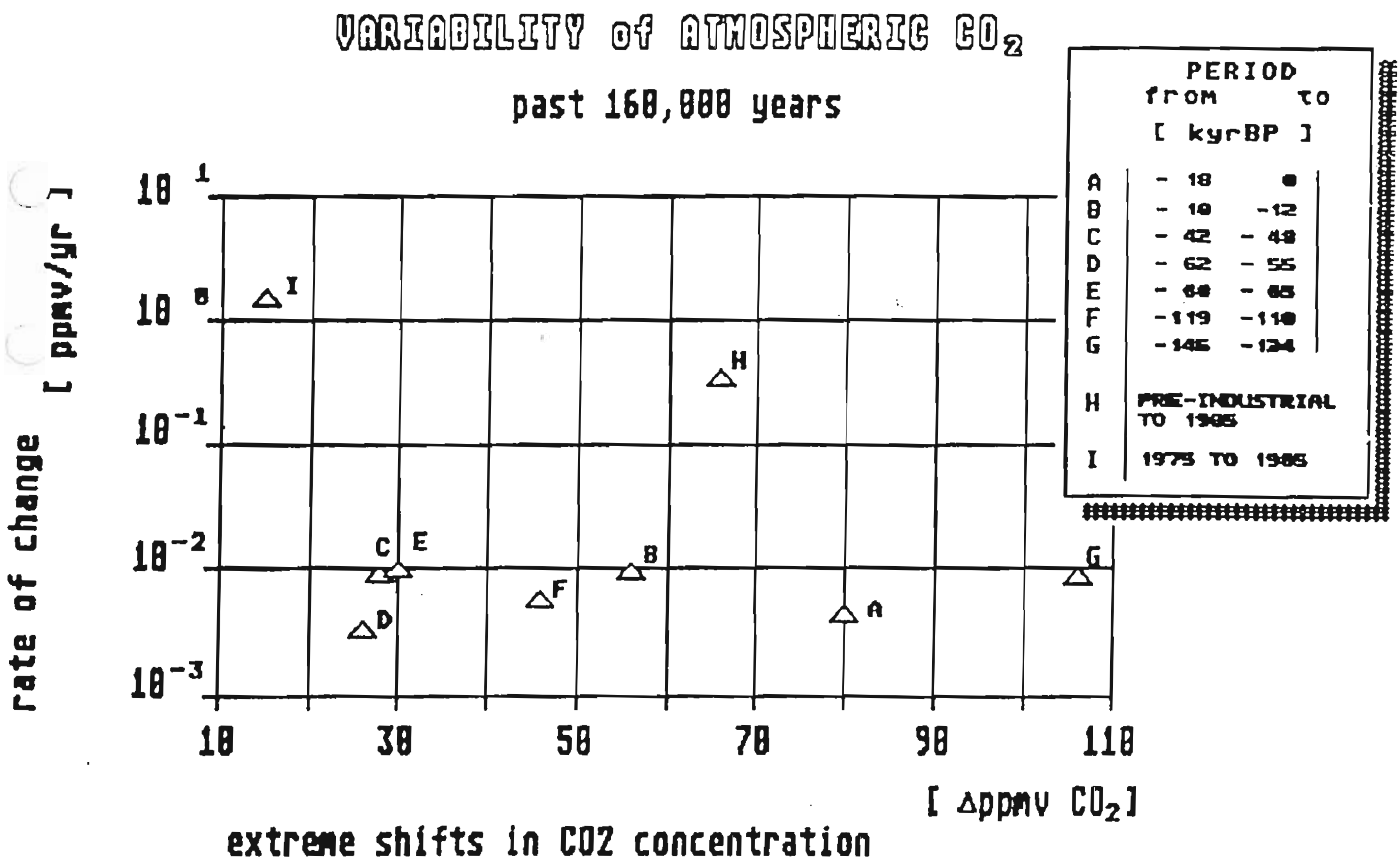
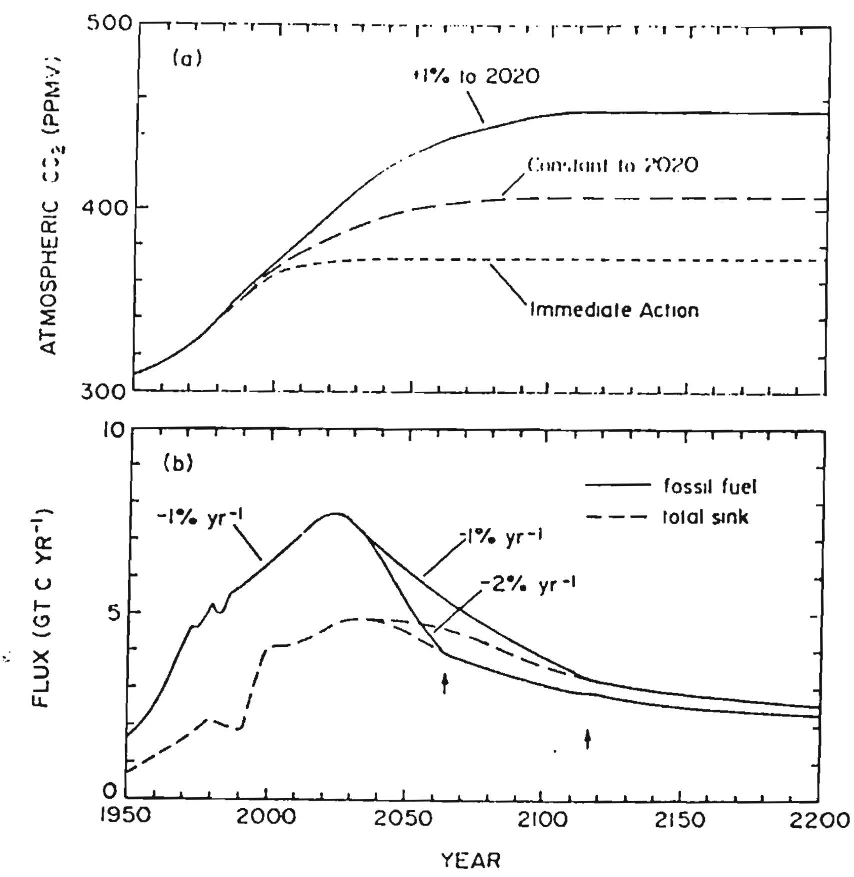


Figure 1.3-2: **Atmospheric CO_2 Concentrations 1950-2200 for Selected Emission Scenarios (Harvey, 1989)**



COMPLEMENTARY APPROACHES TO THE CLIMATIC CHALLENGE

The choice of indicators for climatic change is a prerequisite for deriving operational targets and for the design and later implementation of realistic strategies (policies). This choice depends on the evaluation of the state of scientific knowledge and the possible consequences that can evolve from changes in climatic and ecological conditions. In essence, such a choice is part of a risk assessment with a dimension exceeding historical, social and political experience.

Against this background it is useful to summarize briefly the partly competing, partly complementary approaches and views about the nature of climatic change, in the ongoing efforts to form a *political situation* capable of supporting an international climate convention and protocols to control future interactions between global civilization and climate.

Two approaches are briefly described. They differ with respect to the inherent stability of the present climatic and ecological state. On this basis different indicators and different targets for limiting anthropogenic interference with climate and ecology are then derived.

THE SENSITIVITY APPROACH

The models available try to capture the sequence of effects caused by the emission of greenhouse gases. They are driven by demographic and economic projections supported by statistics, and result in quantified estimates of climatic changes. In a further step such climatic changes are related to modified features of the natural environment, e.g., changes in sea level, regional temperature and precipitation patterns. Finally, these changed environmental characteristics are translated into standardized indicators of the civilizational system, such as economic costs.

Figure 1.3-3 gives a graphical representation of the cause-consequence loop that is characteristic of the analytical efforts organized by the Villach workshops and the preparatory work of the Toronto Conference, *The Changing Atmosphere*. It is also characteristic of the IPCC process of analysis.

The uncertainty of the derived values of indicators is put in perspective by a sensitivity analysis. Upper and lower scenarios yield the bounds on projected impacts.

Limitations of the Sensitivity Approach

Global Circulation Models, Coupled Ocean-Atmosphere-Circulation Models, and further improvements that permit the quantitative incorporation of feedbacks of the carbon cycle, have established a reasonable insight into the hierarchy of interactions that governs the feedback loop of Figure 1.3-3. Nevertheless, this approach is limited. Its limitations in providing a reliable forecast, over a time horizon of a few decades, in terms of consequences emerging from GHG emissions, stem from the following:

- GCMs and 3D Ocean Models are based on a set of initial conditions derived from actual observations. Their internal parameters are tuned to fit longer time series of observed sequences of atmospheric and oceanic processes. The observed sequences were taken in a period in which no significant instability in the dominant energy transport patterns occurred.

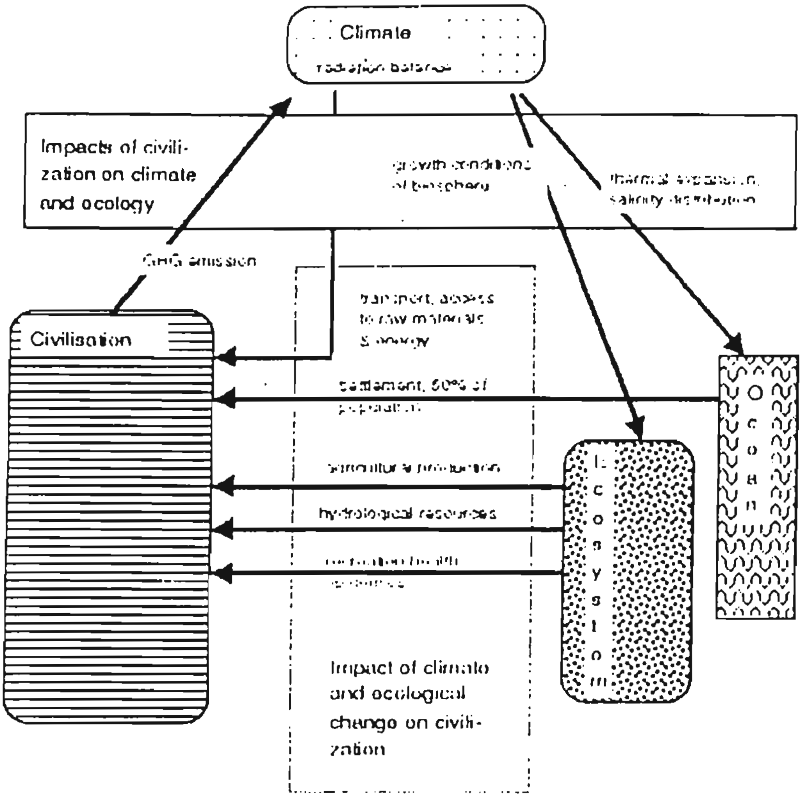
- The carbon cycle is characterized by very large amounts of absolute transfers among different reservoirs. Net transfer rates are small in comparison. Drifts in the characteristics of large carbon reservoirs are not known accurately enough to exclude or to predict, e.g., crucial modifications of the net exchange rates of carbon among the biosphere, the ocean, and the atmosphere.

- Atmospheric chemistry and its possible non-linear influence on residence times of GHGs cannot be projected into the future.

- Synergetic effects from present and future land use practices, significant perturbations of the nutrient cycles, and the consequences of general pollution together with climatic stress on the carbon cycle are not incorporated.

In summary: the art of climate modeling provides a fairly comprehensive analysis of the likely response of a limited perturbation stemming from the

Figure 1.3-3: The Greenhouse Effect: A Simplified Cause-Consequence Loop



emissions of GHGs. It cannot provide accurate estimates on which level of perturbation of the model result will deviate substantially from the response of the real system.

Climate modeling implicitly assumes an inherent stability of the climate phenomenon. The primary question however, whether or not anthropogenic perturbations endanger the stability of the present climate regime has to be answered independently.

THE STABILITY APPROACH

A stability-oriented approach cannot be reduced to one dominant cause-consequence loop, as in the case of the sensitivity approach. Large buffer capacities for energy and chemicals, such as the ocean, sediments or global biota, always include the possibility of irregular and large releases of gradually accumulated amounts of stored quantities of GHGs. The status of a minor subsystem can, at least in principle, contribute to an amplification of otherwise unimportant fluctuations. Independent perturbations of climatic subsystems seem to be responsible for paleoclimatic anomalies. Securing climatic stability would, in this approach, mean controlling the status of each subsystem independently.

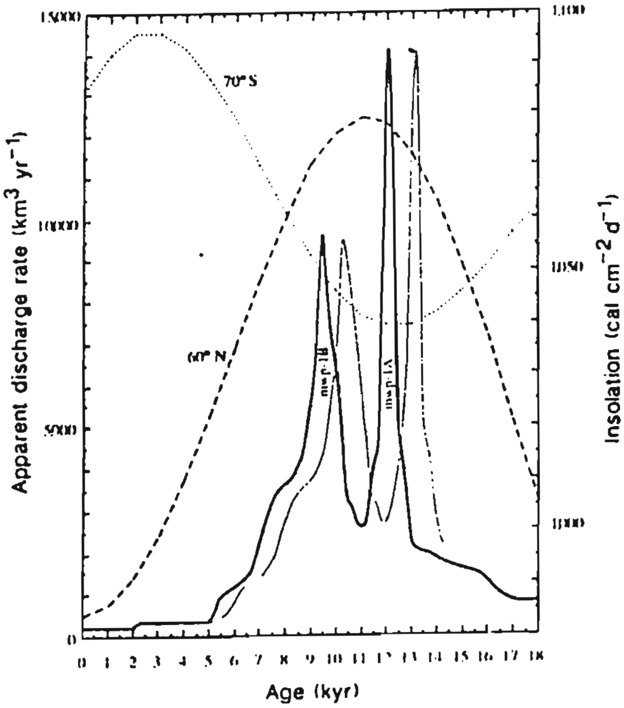
In contrast to the dominant role of industrial GHG emissions in Figure 1.3-3, at least three additional emission sources need to be considered: 1) the release of GHGs from the biosphere (including soils) and the oceans; 2) the release of heat or the blocking of polar heat transport as a consequence of changed ocean circulation; and 3) changes in the chemical decompositions of radiatively active trace gases in the atmosphere. Each group of these processes is partly influenced by human civilization.

CLIMATE ANOMALIES AND FEEDBACK PROCESSES

Recently published data show details of abrupt climate fluctuations that happened towards the end of the warming-up period following the last glacial period (Fairbanks, 1989). Figure 1.3-4 shows two extremely sharp pulses of glacial melting water superimposed on broader melting events. The rate of sea-level rise increased by an order of magnitude above the high average rate for the transitional period from the last glacial to the present interglacial. The abrupt return to near glacial climate conditions in between the two melting pulses is known as the Younger Dryas Event. It is attributed to a blocking of North Atlantic deep water formation caused by the buildup of low salinity surface layers which in turn reduced the transport of heat by ocean surface currents towards the arctic.

The melting pulses suggest that two warm episodes, interspersed by a return to early holocene temperatures, are a more appropriate sequence than the dominant characterization of the Younger Dryas as an episode of return to glacial conditions. Substantial changes in regional temperature and precipitation patterns could be identified for North and Central Africa in the period between 12,000 BP and 10,000 BP (Street-Perrot and Harrison, 1984).

Figure 1.3-4: **Climate Instabilities: Younger Dryas Event (after Fairbanks, 1989)**



The details of the events around the Younger Dryas Cold Period suggest that there must have been at least two very fast climatic heating episodes, giving rise to the melting water pulses identified by Fairbanks. The Younger Dryas cold event did not just halt an otherwise high level of melting of glacial ice volumes. It is not yet known which processes actually led to these enormous climatic changes on a world scale.

The existence of these heating and cooling anomalies is sufficient however, to reconsider all possibilities that might lead to self-supporting feedback processes at present. Such processes can obviously induce fluctuations of several °C within time frames of several decades and thus away from a previously "stable" climate.

At least two such processes have been identified recently:

a) McDonald (1989) has analyzed various feedback mechanisms to explain quantitatively the climatic changes between glacial and interglacial periods. He concludes that **clathrates** *must have played a major role in regulating the composition and climate-controlling radiative properties of the atmosphere during the ice-ages.* In particular, there should be a fast contribution to warming and a slow contribution to cooling, because of the asymmetric process of cooling and heating of deeper layers of sediments. At present, some 11,000 GtC are stored in a clathrate stability zone of 500 m thickness. McDonald's estimates suggest that annual releases of 0.2 to 0.4 GtC in the form CH_4, or in radiative equivalent terms of 5 to 10 Gtc of CO_2, appear possible as a consequence of decompression of sediment layers in areas of retreating ice shields or by sudden permeation of sealing horizons in permafrost areas.

b) The second process involves unusually fast releases of CO_2 from land biota, because climate strongly influences biological activity, such as photosynthesis. Climatic changes can stimulate organisms to emit or incorporate GHGs, thereby amplifying or reducing the primary effect. Shifts in climatic belts, if they are slow enough, create opportunities for species to move into areas that no longer sustain species of the initial vegetation types. Consequently, the climate-biosphere coupling was not considered to be crucial in the sense of supporting climate anomalies. However, within the range of realistic climate scenarios, strong positive feedbacks from the biosphere are possible. Solomon and Leemans (1989) conclude, for a scenario with effective CO_2 doubling by 2050, that up to 40% of the northern boreal forests could quickly disappear. This would then lead to an additional release of approximately 5 GtC over a period of 50 years.

Independent of induced fast climatic changes, significant further releases of CO_2 could result from the so far unrecognized increase in the CO_2 concentration itself, that occurred in the past 50 years. An elevated CO_2 level should directly interfere with competitive processes between organisms. Klopries and Beckmann (1989) point out that genetic adaptation to a worldwide change in CO_2 concentration is not retarded or compensated by remaining ecosystems. Due to orders of magnitude differences in reproductive cycles of macro and micro organisms, a significant decrease in the resistance of higher organisms against diseases could evolve (Klopries and Beckmann, 1989) within a few decades. This **biogenetic** effect would not be prevented by time lags in the physical subset of ocean-atmosphere interactions. It might possibly turn out to be the most stringent constraint for the anthropogenic buildup of atmospheric CO_2. In this respect, the sharp reversal from fixation of carbon by land biota to a net release since 1970 is a crucial finding (Houghton, 1989).

CLIMATIC TARGETS

Both the sensitivity approach and the stability approach require indicators that characterize the specific feedback loops. These loops are represented in a simplified form in Figures 1.3-3 and 1.3-4.

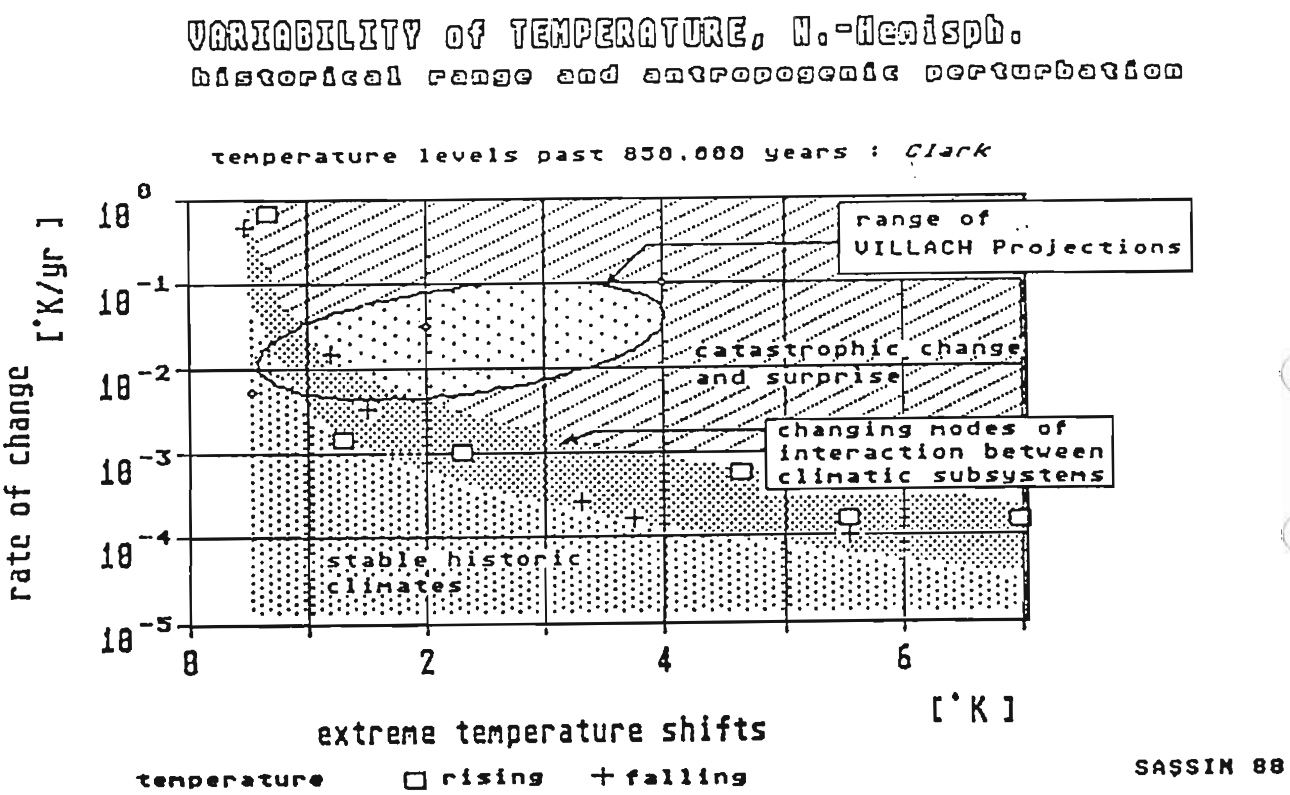
The primary interactions of the greenhouse effect form a straightforward, cause-consequence loop. The sensitivity (Figure 1.3-3) approach assumes that this loop is open, i.e., GHG emissions are determined only by the internal driving forces of the human system. Given this implicit assumption, the sensitivity approach correctly focuses on global and zonal average temperature changes as appropriate indicators. Although precipitation changes are decisive for type and severity of impacts on civilization, by definition they have no influence on direct anthropogenic GHG emissions.

The basic greenhouse feedback loop is also present in the representation of the stability approach, outlined in Figure 1.3-4. The definition of targets for climatic change therefore coincides for both approaches. However, with respect to the stability concern, additional targets are needed in order to respond to the paleoclimatic evidence of possible fast and severe fluctuations of the global climate system.

During the Villach/Bellagio workshops, it was argued that natural ecosystems will not adapt effectively to rapid climatic change, i.e., with rates of temperature change higher than 0.1 °C per decade. In the absence of accurate regional forecasts of future temperature distributions over the surface of the globe, it is necessary that future temperature changes on the global scale should not exceed values experienced in the past during *normal climatic changes* (Sassin et al., 1988). *Normal* implies that extreme anomalies, such as the Younger Dryas event, are excluded from the sample from which *normal climate variability* is derived.

Figure 1.3-5 shows the variability of global temperatures for the past 120,000 years. The maximum rate of change of temperature in the northern hemisphere is given as a function of the temperature differential that was bridged by major climate fluctuations. Large absolute changes are characterized by low mean rates of change; small absolute changes can occur rather abruptly. Below the grey band the number of data points is relatively high. Average climate variability therefore is well below the grey boundary. It can be assumed that the biosphere can cope with changes below the upper shaded area. Scenarios, such as those developed in Villach in 1987, are within the range outlined by the ellipse in the figure.

Figure 1.3-5: Normative Targets for an Upper Limit of Variability of Global Temperature



The grey line provides a rational climate target. This target is composed of a combination of a maximum rate of global temperature change and of a corresponding maximum absolute temperature increase. The indication of stability limits for large unmanaged ecosystems, e.g., of the boreal forests of about 0.1 °C per decade, then leads to an upper limit of < 1 °C for the maximum temperature increase. The global climate system already operates in the upper part of the grey boundary. Further temperature increases above the present level would lead to a temperature range that has not been experienced by current systems.

The **stability approach** requires additional indicators. These can be grouped according to the potential positive feedback loops summarized in Figure 1.3-5. These indicators relate to changes in the interactions between natural subsystems. For this reason such indicators have to be specified on a regional and on a functional basis. Several variables can be suggested as indicators for specific feedbacks, i.e., atmospheric CO_2 concentrations as an indicator for the biogenic CO_2 effect, the net heat influx through the effects of GHGs for oceanic circulation, regional temperature increases for clathrates and wet soil decomposition, and ecosystem limitations such as absorption and respiration rates for deforestation and intense agriculture.

Specification of quantitative target levels is not yet feasible, however, with the exception of the CO_2 concentration. There is a broad lack of knowledge about the degree of coupling between the various feedback loops. It is urgent to close this gap. Additional targets will only tighten, and not relieve, the pressure on limiting or managing human interference with natural systems.

The rate and the level of CO_2 buildup in the atmosphere has been extraordinary. The CO_2 data from ice cores, as in Figure 1.3-1, give accurate evidence that CO_2 levels have changed only gradually along with global temperatures. Natural chemical variability has been changed by orders of magnitude through the anthropogenic increase of atmospheric CO_2 over the past century. If a worldwide forest die-back were to result partly from a biogenetic effect, a dramatic and fast reduction of present levels of CO_2 would have to be formulated as a target for stability. This would shift the present concern from limiting further emissions to the broader response objective of stabilizing the global biosphere.

GENERAL CONCLUSIONS

Indicators of climatic change and the selection of climate policies should be based on realistic measures that can be implemented.

Two types of strategies can be distinguished:

- *passive* strategies, focussing on a limitation of human interference with climatic subsystems; and

- *active* strategies, trying to maintain interactions among crucial climatic subsystems within a well defined band of energy and mass transfers.

Indicators suitable for both strategies are primarily concentrations of greenhouse gases in the atmosphere.

Targets for passive strategies have to be fixed on the basis of a very high risk aversion. For example, CO_2 concentrations should be reduced as quickly as possible to levels that appear tolerable, as derived from long-term temperature-CO_2 correlations and temperature variations characteristic for the historic rates of change.

For active strategies, regional temperature changes, ecological, and geochemical indicators are needed in order to identify changes in the net fluxes of carbon and heat.

Targets for active strategies would have to focus on rates of change of GHG transfers from yet to be identified reservoirs. Changes in oceanic uptake would have to be measured as well as changes in biological fixation and respiration rates of all terrestrial ecosystems. Catalytic effects in different parts of the atmosphere would be considered as well. Anthropogenic emissions of GHGs could be tolerated up to the point of declining rates of exchange, once these can be demonstrated. The emissions have to be reduced and counter-active measures implemented once such exchange rates move away from their identified mean values.

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2. RATES AND LIMITS OF CLIMATIC CHANGE: DISCUSSION OF POSSIBLE TARGETS

2.1 RATES AND LIMITS OF TEMPERTURE, PRECIPITATION, AND SEA-LEVEL CHANGES

P.H. GLEICK and W. SASSIN

INTRODUCTION

Future rates of temperature and precipitation change and sea-level rise associated with global climatic changes are expected to greatly exceed recent historical rates of change. This section explores the range of estimates of past temperature, precipitation, and sea-level rise determined from historical records and paleoclimatic reconstructions and compares them with estimates of future changes. The effect of future high rates of sea-level rise on coastal developments and natural ecosystems is examined and allowable or desirable target rates are derived. A maximum rate of increase in sea level of between 20 and 100 mm/decade appears to be an appropriate target based on ecological and societal considerations. Similarly, a rate of rise of 0.1 C appears to be consistent with recent climate history. For an analysis of the effect on natural ecosystems of different rates of temperature change, and of associated targets, see Section 2.2.

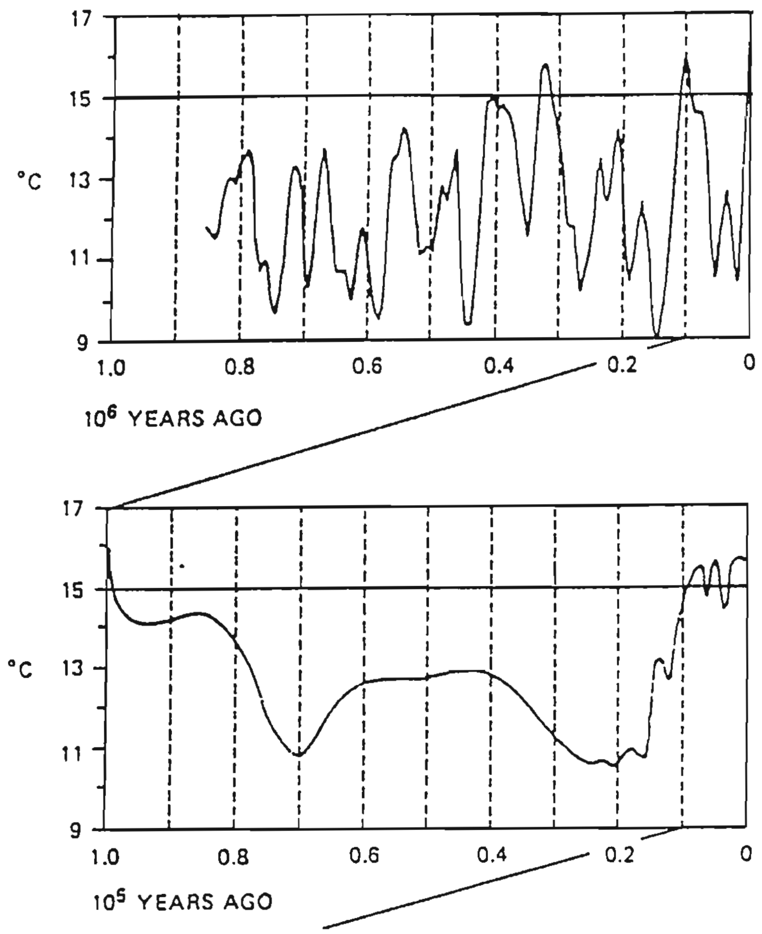
Present concern about sea-level rise stems from two problems: (1) the likely future rise due to global climatic changes; and (2) the extensive and vulnerable human developments and natural ecosystems. Rapid climatic changes pose special threats to both human activities and ecosystems. Rates of adaptation of many ecosystems are slow compared to the estimated rate of future climatic changes, and human developments are often built to last several decades, during which time unprecedented climatic change is expected to occur. Slowing the rate of change can give society time to prepare and plan appropriate responses.

PAST CHANGES IN TEMPERATURE, PRECIPITATION, AND SEA LEVEL

Average global and regional temperature and precipitation fluctuate greatly over time scales of hundreds to thousands to millions of years. At longer time scales, the most important causes of such changes are variations in orbital parameters, solar output, altered ocean circulation, melting and growth of ice sheets, and the concentration of greenhouse gases in the atmosphere. At shorter time scales (decades or centuries), relative sea-level changes are caused by ground subsidence due to pumping of groundwater or oil, by shifts in wind patterns, or by changes in sedimentation rates from rivers. Shorter-term temperature and precipitation patterns are affected by shifts in winds, ocean surface water temperatures, and a variety of human factors.

In the last decade, paleoclimatic research has produced a rather comprehensive and **quantitative** picture of global evolution of climate, in terms of mean temperature, as shown in Figures 2.1-1 and 2.1-2. While this section is not

Figure 2.1-1: Mean Temperatures of the Northern Hemisphere over the past 850,000 Years



An approximate temperatur tory of the Northern Hemisphere for the 850,000 years. The panels are at the sa vertical scale. The top panel shows the p million years, the second panel amplifies t past 100,000 years.

Source: Clark (1982).

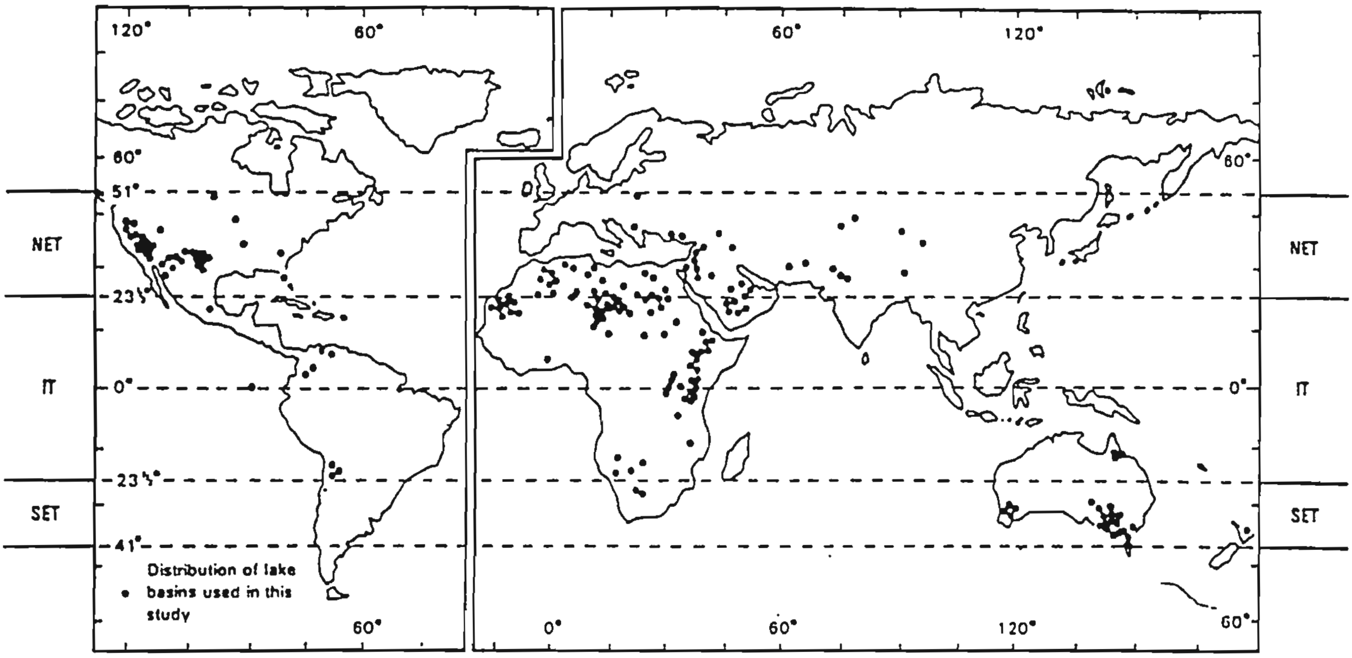
the place for a detailed review and discussion of such long-term variations in climate, it is important to understand the differences between natural rates of climatic change and the changes expected due to the greenhouse effect. For more detail about paleoclimatic changes, the reader should refer to the extensive literature (including, for example, Oeschger, et al. 1984; Dansgaard et al. 1984; Berger et al. 1989; and MacCracken and Budyko, 1990).

While these changes are of academic interest, they are less important for public policy than are past changes that occurred on a shorter time scale or that are due to the forcings that are expected in the next century -- particularly changes in the composition of the atmosphere. As a result, this section focuses on these more relevant fluctuations.

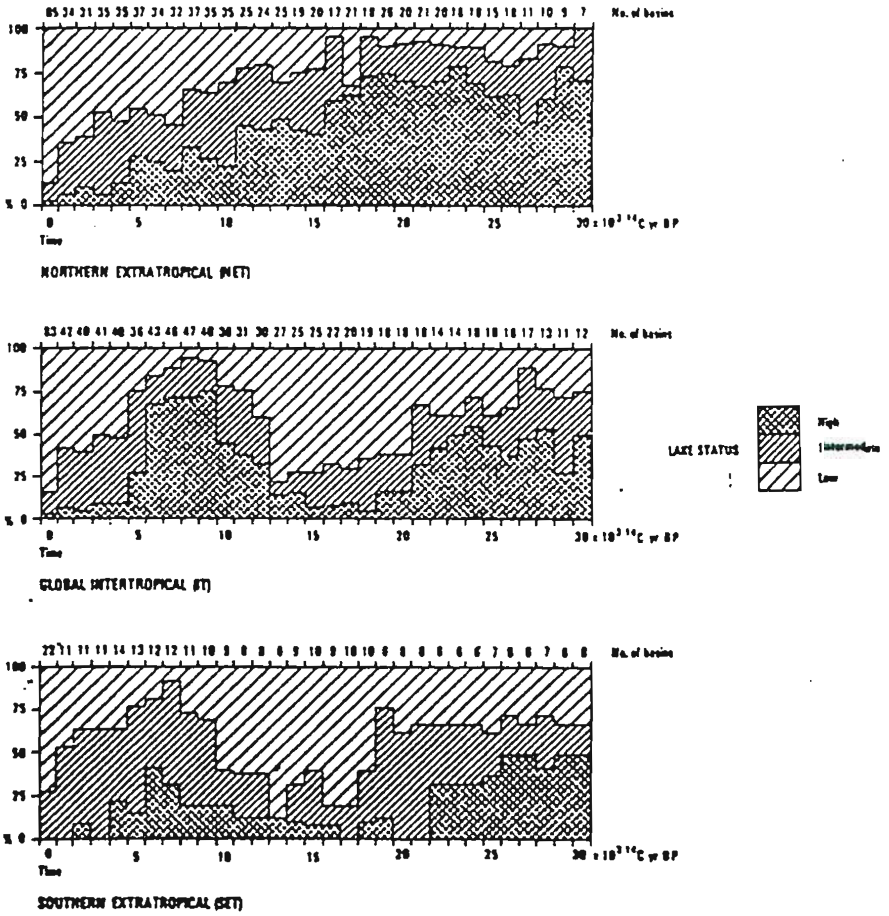
Methods for Determining Past Changes

Various methods have been developed to determine past changes in sea level. While each method has advantages and limitations, there are a number of independent signals that significant sea-level fluctuations have taken place over

Figure 2.1-2: Temporal Variations in Lake Status in Innertropical, Northern and Southern Extratropical Belt



The distribution of lake basins



Source: Street-Perrot and Harrison (1984).

geologic time. These include glaciologic and morphologic evidence, deep-sea planktonic microfossils, coral and mollusc $\delta^{18}O$ records, coral terraces, and evidence for meltwater effects.

For sea level, the magnitude of eustatic change[1] cannot be measured directly. As a result, geologists are forced to use a variety of methods to try to distinguish absolute sea-level fluctuations from relative changes that include changes in land surface levels. Tectonic models that make assumptions about rates of compaction, sediment fill, and tectonic movement are used to try to separate out earth crustal activities. Water volume - crustal response models can be used to determine the general magnitude of crustal flexibility due to changes in water volume. Oxygen isotope analyses, particularly the $\delta^{18}O$ signal, can be used to estimate the magnitude and rate of change in sea level. These oxygen isotope analyses are useful for determining ocean volume and ice age and content, but it is hard to separate out the ocean volume effects from other effects.

One of the more innovative approaches to estimating the volume of the ocean is to determine changes in speed of the rotation of the earth since the Babylonians began keeping records around 500 B.C. (Morrison, 1985).

Magnitude and Rate of Past Temperature and Precipitation Changes

Evidence indicates that there have been extensive periods in which the global mean temperatures were considerably different -- both warmer and colder -- than today's. Extreme temperature variations can be observed far back in the record. For example, geologic data indicate that the late Cretaceous could have been as much as 10 °C warmer than today. The mid-Pliocene (of 2 to 3 million years BP) was about 3 °C to 4 °C warmer than today. Because of the importance of non-greenhouse gas forcing factors, however, these earlier periods are of limited value for setting policy today.

More relevant are recent climatic periods. The past 160,000 years have seen both warm (interglacial) and cold (glacial) periods, as shown in Figure 2.1-1. During the coldest streches of the last glacial periods, global mean temperatures dropped to between 9 °C and 11 °C, while they exceeded 16 °C during interglacial periods. (Today's global mean temperature is approximately 15 °C.) At the peak of the most marked interglacial period, 125,000 years BP, mean temperature was slightly higher than it is today. The most recent glacial period, which peaked around 18,000 years BP and ended about 13,000 years BP, was 4 °C to 5 °C colder than today. Most recently, global temperatures dropped about 1 °C from present levels during the "Little Ice Age", between 1400 and 1850.

These periods, extending back several thousand years, are the only examples of climatic change that might offer some insights for analyzing the effects of climatic change on ecosystems and society and for identifying appropriate targets and indicators. Gribbin and Lamb (1979) review four periods, including the post-glacial warm period, the cooling around 2500 BP, the secondary warm period

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1 Eustacy is defined as global sea level with respect to a fixed point, such as the center of the earth. "Relative" sea-level changes include movements of land surfaces, to give an apparent change greater than or less than the absolute, eustatic change.

around 800 BP, and the "Little Ice Age". Similarly, Soviet paleoclimatologists are using climate reconstructions from three past warm periods as analogs for evaluating future climate impacts (see MacCracken and Budyko, 1990, for a summary). For the two most recent analogs, global mean temperatures were about 1 °C higher than at present (during the Holocene of 6,000-8,000 years BP), and between 2 °C and 3 °C higher (during the Eemian interglacial of 125,000 years BP). These reconstructions also provide information on changes in precipitation patterns that suggest that regional changes even greater than the global means occurred during these periods. There has been considerable dispute over the ability of these paleoclimatic methods to provide insights into future climate impacts, however, and caution should be applied in using the results.

Abrupt changes in regional climate are also evident. During the last ice age in some regions, for example, changes of temperatures of between 3 °C and 5 °C apparently occurred over periods of about 100 years (Deutsche Bundestag, 1989). Such dramatic regional changes are associated with abrupt changes in ocean circulation patterns and winds. The slow, but sustained, temperature increase of about 5 °C from the last interglacial period to the present warm period, and the corresponding variations in rainfall and evaporation patterns, also led to drastic variations of lake levels as shown in Figure 2.1-2. It must be noted that such abrupt changes were accompanied by severe ecosystem disruptions, including species extinctions.

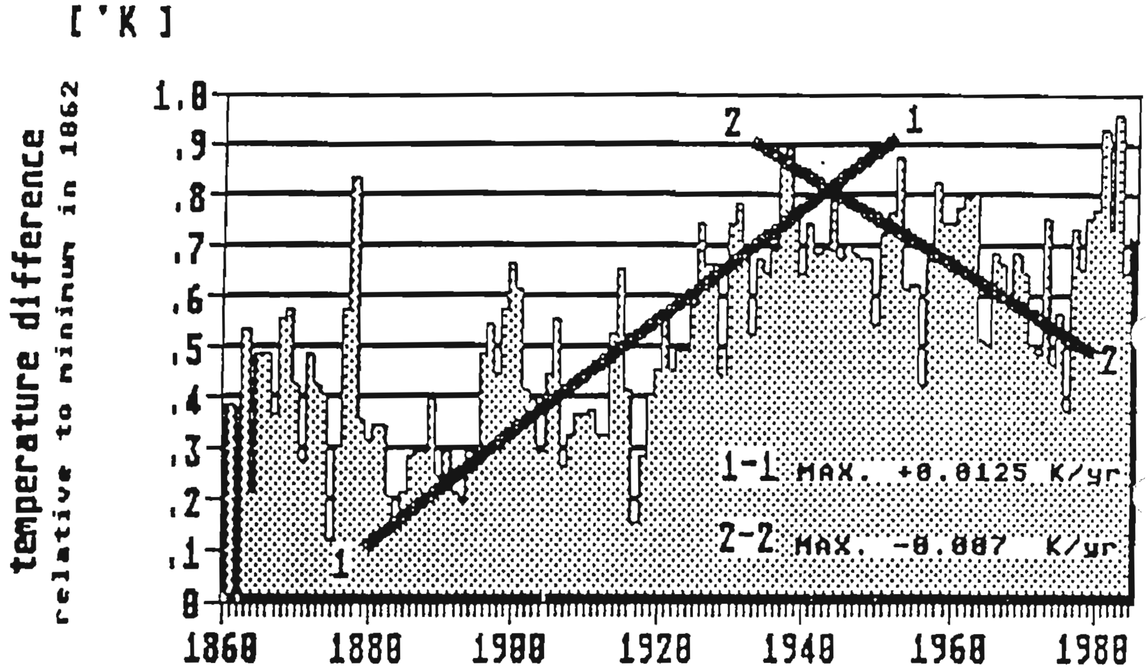
Economic and societal experience with climatic variation spans much shorter time intervals -- typically periods of decades to centuries. Most instrumental records for temperature and precipitation span only 130 to 140 years, as shown in Figures 2.1-3 and 2.1-4, and many of these data are not reliable during the early part of the record. Analyzing these data suggest that the rate of temperature change over the last century has been a maximum of approximately 0.1 °C per decade. Changes in precipitation patterns and rates are much greater than those for temperature, given the natural variability of precipitation. Nevertheless, even these changes have been relatively minor compared to the much larger, long-term changes evident in the geologic record.

Modern industrial civilization has thus emerged in a period of relatively stable climatic conditions. The prevailing distribution of settlements, land and sea communication lines, and the exploitation of natural resources, has evolved only within the last century, with large recent increases in population and total use of materials. During this period of about 100 years, global mean temperatures are estimated to have risen by about 0.6 °C ± 0.2 °C. This increase includes a small increase (about 0.1 °C to 0.2 °C) that is associated with urban heat islands, but correcting for this still leaves a distinct upward trend in temperature (for a good review see Deutscher Bundestag, 1989).

Magnitude and Rate of Past Sea-level Changes

Evidence from the above methods for analyzing past sea levels suggest that there was a sea-level maximum of about 250 meters above present levels during the mid-Cretaceous period of about 100 million years ago, and several sea-level minima of perhaps 100 to 160 meters below today's levels, since the later part of the Cenozoic period of perhaps 11 million years ago (Cloetingh, 1988; Wilgus et

Figure 2.1-3: **Global Fluctuations of Annual Mean Temperature, Northern Hemisphere, Between 1861 and 1985**



Source: Jones et al. (1986).

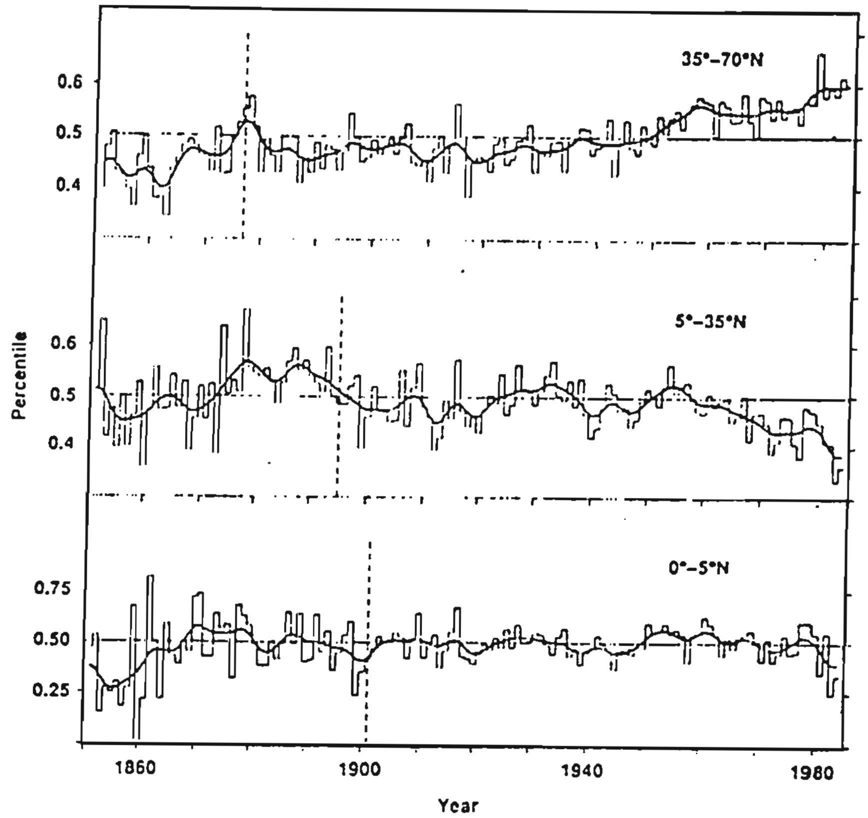
al., 1988). In between these times, numerous increases and decreases in sea level are evident in the geologic record.

The greatest changes in sea level during geologically recent times is the estimated lowering of sea levels to 80 to 160 meters below present levels during the late Wisconsin glacial maximum of 18,000 years ago (Williams, 1984 and 1988).

Using estimates of changes in the rotation of the earth, scientists have inferred an increase in sea level of perhaps 3 meters over the last 2500 years. This change in sea level is supported by archeologic and geologic evidence (De Pratter and Howard, 1981).

While we now understand that very large changes in sea level have occurred over millions of years, far more relevant to the problem of future sea-level rise is the **rate** at which such changes can occur. The many different causes of past sea-level change occur at many different rates. Table 2.1-1 shows rates of sea-level changes due to a variety of processes. Past rates of change of sea level are of considerable interest today because of the widespread development in coastal zones and the possibility of rapid changes. The strong likelihood of future global warming due to increasing atmospheric concentrations of carbon dioxide and other heat-trapping gases could enhance the melting of glaciers and continental ice sheets and cause thermal expansion of the upper layers of the ocean. If such changes occur at rates exceeding the ability of human or natural systems to respond, large negative effects will result.

Figure 2.1-4: Index of Northern Hemisphere Precipitation over Land since 1860



Source: Bradley et al. (1987).

Studies from fossil records suggest that changes in mid-ocean ridge systems have the potential to cause significant (>100 m) changes in sea level, but at a rate that rarely exceeds 10 mm/1000 years. This source of change is not likely to have any impact in the next few centuries.

Pitman and Golovchenko (1983) pointed out that glacially-induced fluctuation in sea level is the only known mechanism that can cause changes in sea-level at rates in excess of 10 mm per 1000 years and with magnitudes in excess of 100m.

We know from detailed $\delta^{18}O$ studies of deep-sea cores that many 50 to 100 meter sea-level changes occurred with frequencies of less than 100,000 years throughout the last 25 million years (the Neogene). The character of the $\delta^{18}O$ signal in many parts of this time period suggests that the rates of sea-level rise and fall are not necessarily equal. Using late Pleistocene $\delta^{18}O$ records, Broecker and Van Donk (1970) defined the rapid transition from glacial lowstand to interglacial highstands as "terminations". The rapidity of these changes approaches 10 to 15 meters per 1000 years (increases of 10 to 15 mm/yr). The terminations are periods of rapid climatic, oceanographic, and biotic events (Berger and Labeyrie, 1986). In sharp contrast, the subsequent return to full glacially induced lowered sea levels may take an order of magnitude longer (decreases of 1 to 1.5 m/1000 years or 1 to 1.5 mm/yr). This asymmetry during the last 3 million years (the late

Pleistocene) suggests that ice sheets decay more rapidly than they accrete on 100,000 years or less time scales (Williams, 1988).

Most relevant to global warming is the rate of change during past periods that may be similar to the expected changes over the next century. Compiling the rates of eustatic sea-level rise during the recent Holocene warming, during which global average temperatures increased about 1°C, shows that sea levels rose 75 m over an 8,000 year period, or about 1 m/century (10 mm/yr) (Tooley, 1978).

The most rapid and highest magnitude of eustatic rise in the latest Pleistocene began at about 14,000 years and ended in the Holocene at about 7,000 years (Mix and Ruddiman, 1985). During this extreme period, sea level rose over 7 m in about 200 years -- over 30 mm/yr (Tooley, 1978). This extreme rate of increase is attributed to the sudden breakup of the Laurentide Ice Sheet over Hudson Bay.

During the last 6,000 years, the rate of sea-level rise has dropped to negligible amounts and eustasy has remained almost constant during this time. Today, sea level is high relative to its position during the past 50,000 years.

Estimates of rates of change in sea level over the last century range from 1 to 3 mm/yr, with most recent and detailed evaluations centering on an increase of 1 to 1.2 mm/yr (Gornitz and Lebedeff, 1987).

There is now some evidence that the rate of sea-level rise is increasing. In the last 50 years, the rate of global sea-level rise has increased by 0.6 mm/yr -- nearly double the previous rate (Gornitz and Lebedeff, 1987). It is tempting to ask whether this recent increase is an indication of global warming, and some analysts have correlated global sea-level rise with global temperature. In one such study, the correlation coefficient between the two variables for the last 100 years is 0.8 when five-year running means are used (Gornitz et al., 1982), and the authors ascribe much of the observed rise to thermal expansion and glacial melting. Unfortunately, other factors such as readjustments of the crust to melting of Pleistocene ice sheets and anthropogenic modifications to the hydrologic cycle may also be playing a role and separating out the most important factors at this point is very difficult.

ADAPTATION OF NATURAL ECOSYSTEMS TO SEA-LEVEL RISE

This section discusses two sensitive ecosystems threatened by sea-level rise and their ability to adapt to rising ocean levels. A similar discussion for temperature and precipitation can be found in Section 2.2.

Marshes and Coastal Wetlands

Some of the richest natural ecosystems are the extensive marshes and wetlands along coasts. These areas provide nutrients for major fisheries, filtering for artificial pollutants, and habitat for waterfowl. Extensive development around the world over the last century has destroyed many of the original wetlands, leaving a smaller and smaller area to provide these natural services. Sea-level rise

Table 2.1-1: Causes and Rates of Past Sea-level Rise

Process	Maximum Rate (mm/yr)
Changes in Ocean Water Volume	10
Changes in Ocean Basin Volume	1 - 10
Sea-floor Spreading, Lithosphere changes	0.01
Sediment accumulation	0.02 - 3
Tectonic uplift/subsidence	1 - 3

Source: Gornitz and Lebedeff (1987).

threatens the remaining marshes with inundation and destruction, unless the rate of rise is sufficiently slow to permit natural adaptation through sedimentation and plant growth.

Few good data are available on sedimentation rates within marshes or on mudflats, and much of these data are site specific. Estimates of the normal marsh accretion rate in bay ecosystems range from 1 to 8 mm per year when sufficient inflow of sediments from rivers is available (Martindale, 1987; Josselyn and Callaway, 1988), though in some types of rich subtidal waters subject to large sediment inflow from rivers, rates as high as 70 mm/yr have been observed (Nolan and Fuller, 1986). In coastal and deltaic areas with extensive marshes and sediment inflow, more typical accretion rates of 10 mm/yr are observed; in areas of moderate wetland extent, 5 mm/yr is typical, while under 2 mm/yr is average in areas with little wetland extent (Armentano et al., 1988). Figure 2.1-5 shows the average rate of marsh sedimentation as 5 mm/yr.

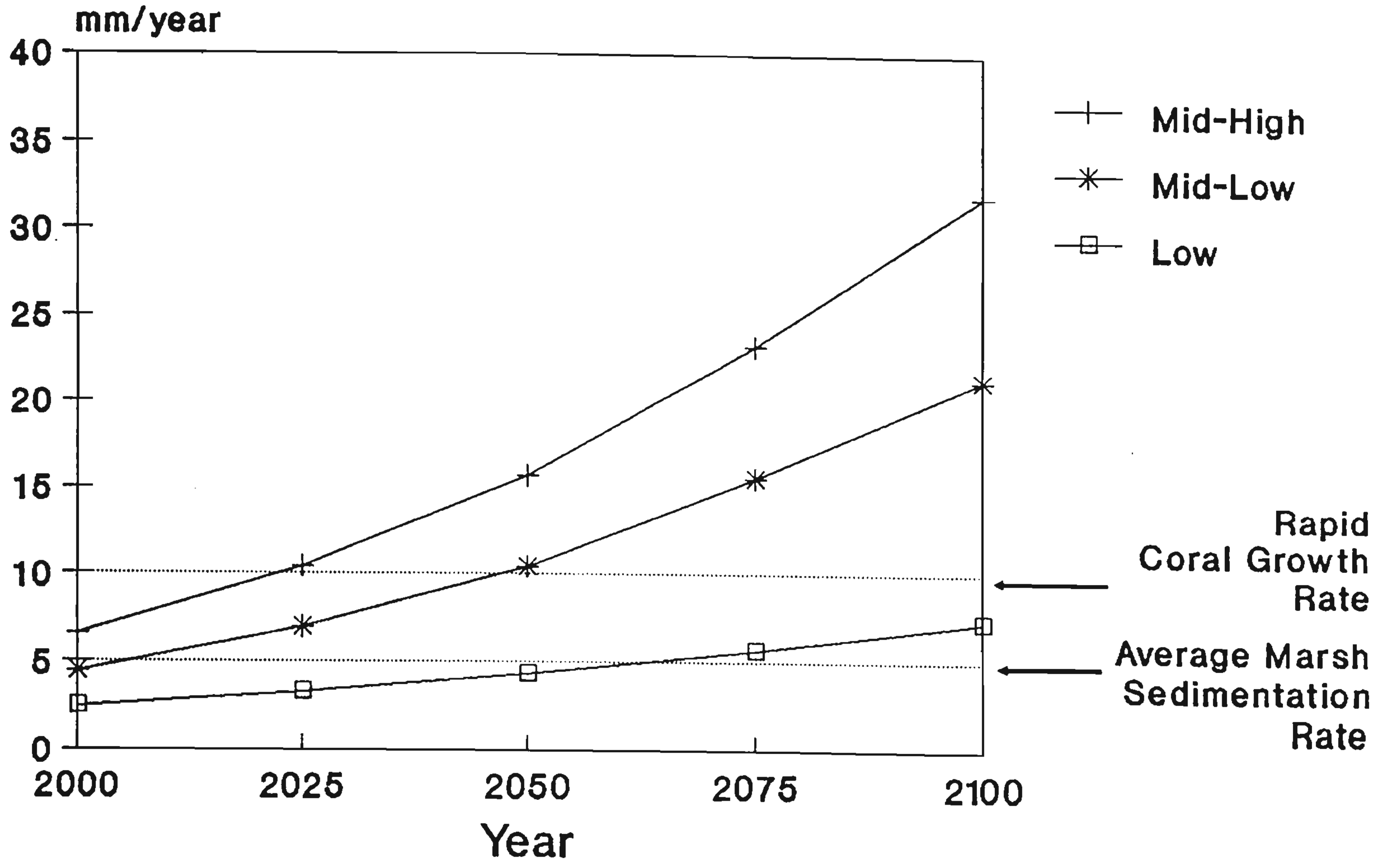
There is also the possibility that artificial activities can help marshes and wetlands adapt at rates higher than their natural ability. These include augmenting the natural rates of sedimentation, restoring natural wetlands through planting of materials and raising surfaces, and building protective barriers. While many such projects have been attempted, they are expensive and not always successful for many reasons (U.S. EPA, 1989). We conclude from these assessments that relying on artifical means to protect the worlds remaining wetlands is unlikely to be successful.

Coral Reef Formation

Coral reef growth is directly linked to sea level, and a rise in sea level has the potential to threaten reef productivity and extent. The rate of growth of coral reefs could be used to set an absolute maximum limit on the rate of sea-level rise.

Both geologic and historical data offer insights into the ability of coral reefs to grow under conditions of rising sea level. The history of carbonate reef deposition during the rise in sea level that occurred during the Holocene

Rate of Future Sea-Level Rise
(millimeters per year average)



U.S. EPA sea-level rise scenarios

Figure 2.1-5: Rate of Future Sea-level Rise (mm per year average) illustrates the effects of changing sea level on carbonate productivity. The vertical growth of corals is a function of total mass balance limited by the relative rise of sea level. The maximum growth rates observed in the geologic record of 12 to 15 mm/yr have outpaced the fastest sea-level rise (with the exceptions of the few extreme events described above) in the early Holocene at 8 mm/yr. Even so, a large number of reefs and platforms grow at slower rates than the maximum and these did not keep pace with the rising sea during the early Holocene and were drowned (e.g. Campeche Bank) or retreated along their seaward margins (e.g. Bahama Banks, Caribbean platforms) (Schlager, 1981; Sarg, 1988).

The long-term accumulation rates of ancient carbonate platforms or banks are much less then Holocene rates. Ancient rates (200-400 millions years B.P.) range from 0.013 mm/yr to 0.37 mm/yr (Sarg, 1988). More recent Holocene growth rates range from 0.5 to 1.1 mm/yr for oolite sands and tidal deposits during the late Holocene rise to over 10 mm/yr for some reefs. The Holocene rates are not anomalously high, however, when one considers that they are calculated over a much shorter time span (less than 10,000 years), and they do not include burial compaction or various other factors that come into effect over millions of years.

More recent observations support suggestions that coral reefs can accrete materials at between 1 and 15 mm/yr, depending on local conditions and coral species (Vreugdenhil and Wind, 1987). The highest growth rates are from short-term vertical accretion data, with the best overall estimate of the sustained maximum rate of reef growth being approximately 10 mm/yr (Buddemeier and Smith, 1988). This value is shown in Figure 2.1-5.

Under conditions of rapidly rising oceans, those species of coral reefs that are capable of increasing their growth rates will keep up with sea-level rise until the rate of rise exceeds maximum coral growth rates. Rapidly growing corals will thus become more abundant and slowly growing corals will quickly be inundated. Eventually, even rapidly growing corals will become submerged. Inundated reefs in areas of heavy seas will be progressively damaged by destructive wave action (Buddemeier and Smith, 1988).

Far more information is needed on reef types, growth rates, wave exposure, and morphology of corals before accurate regional predictions can be made of effects of sea-level rise on different reef communities. While a maximum rate of rise of about 10 mm/yr would be acceptable for some coral communities, even this rate of rise would result in the inundation and destruction of some corals.

EXPECTED FUTURE RATES OF CHANGE

The impact of climatic change on temperature and precipitation patterns and on sea level has been pronounced in the past, and it is expected to be the dominant force for change in the next century. For sea level, higher global temperatures will increase the melting of land ice, alter the balance of high-latitude precipitation, and cause thermal expansion of the upper layers of the ocean. Table 2.1-2 shows the possible contributions of present ice volumes to sea level. Section 3.2 discusses the possible scenarios of changes in temperature. The remainder of this section focuses on sea-level rise.

Table 2.1-2: Contributions of Snow and Ice to Sea-level Rise

	Area (10^6 km^2)	Ice Volume (10^6 km^3)	Sea-Level Equivalent (m)
Land Ice			
East Antarctica	9.86	25.92	64.8
West Antarctica	2.34	3.40	8.5
Greenland	1.7	3.0	7.6
Mountain Glaciers	0.54	0.12	0.3
Permafrost	24.9	0.03-0.7	0.6

Notes

(Titus, 1987)

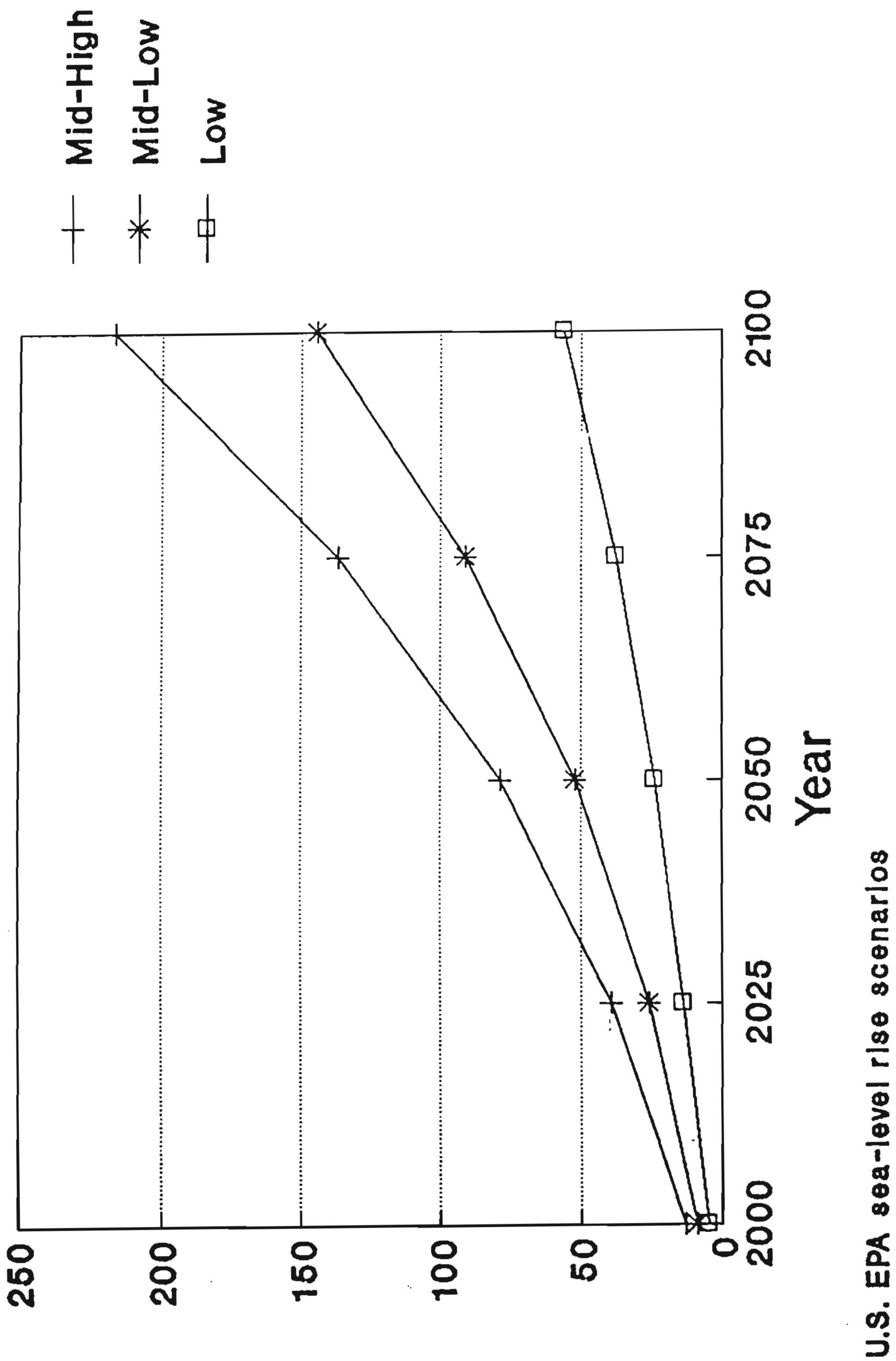
Approximately 400,000 cubic kilometers of ice is equivalent to 1 meter global sea level.

Heat trapped by greenhouse gases raises the temperature of the atmosphere and oceans, which in turn affects sea level. If the oceans absorb the increased heat slowly, higher air temperatures will more rapidly melt land ice. If the oceans rapidly absorb the excess heat, sea level will rise more rapidly due to thermal expansion. At present we cannot accurately determine how the oceans will react, even for well-defined rates of greenhouse gas emissions, and we cannot therefore accurately predict future climate or sea level (Thomas, 1986). Nevertheless, we can estimate plausible rates of rise by evaluating a wide range of climate scenarios. Figures 2.1-5 and 2.1-6 show recent estimates of the magnitude and rate of future sea-level rise.

Recent studies indicate that global sea level has risen by between 100 and 300 mm in the last 100 years--a rate of between 1 and 3 mm/yr (Barnett, 1983; Woodworth, 1987). This increase is attributed to thermal expansion of a warming ocean (Gornitz et al., 1982), melting of ice (Etkins and Epstein, 1982; Meier, 1984), and coastal subsidence (Pirazolli, 1986). The current consensus is that this increase can be explained by both melting of land ice and thermal expansion (Thomas, 1986; Wind, 1987).

The increase in the rate of sea-level rise will be very slow for the first few decades, contributing to policy confusion over the proper response to take. This increase will probably not be unambiguously detected until 2020 or later (Thomas, 1986). The rate of rise will increase progressively, however, leading to more rapidly rising sea level toward the middle of the 21st century. While this gives us time to develop appropriate policy responses, it also may permit policy makers to

Figure 2.1-6: **Scenarios of Future Sea-level Rise (cm above 1980 level)**



become complacent about the problem, which could lead to extensive and expensive development in coastal regions that should be protected or left undeveloped.

There is a wide range in estimates (shown in Figures 2.1-5 and 2.1-6, and in Table 2.1-3) of future sea-level changes because of extensive uncertainties over the physical behavior and dynamics of oceans. This paper is not the place to resolve the uncertainties in these projections. The uncertainties involved in this study and the other assumptions made are explicitly set out in the methodology section, but it is our belief that the uncertainties about human actions and conditions over the next decade far exceed the uncertainties about future sea level.

SETTING TARGETS FOR SEA-LEVEL RISE

With one exception, no satisfactory measure exists of an absolute limit on sea-level rise, since the level of human development varies tremendously along vulnerable coasts, and the amount of damage that society is willing to accept is unquantified. A one-meter rise that is unacceptable in one location may be acceptable in another location. The policy and economic ramifications of these differences are critical.

The one exception is in the case of island nations, or unusual island ecosystems that would be completely destroyed by a certain amount of sea-level rise. For example, it is likely that the Maldives in the Indian Ocean would be devastated by a sea-level rise of only one meter. An absolute limit below this level would therefore be required if saving the Maldives from destruction were a societal goal. Determining the precise level for such a limit is difficult, however, given that storm damages will start to increase dramatically with much smaller increases in sea level. For example, in San Francisco Bay, along the west coast of the United States, a sea-level rise of only 150 mm makes a storm that occurs every ten years as damaging as the classic once-in-100-year storm is today (Gleick and Maurer, 1990). Thus even slight increases will be accompanied by large damages.

A more reasonable target to choose is a limit on the **rate** of sea-level rise. These rates should be related to the ability of natural ecosystems to adapt, since in most cases human developments can be modified and upgraded faster than Among the critical natural ecosystems are coastal wetlands, freshwater estuaries, aquifers, and bays, and coral reef atolls.

If the preservation of coastal wetlands is the determining factor, sea-level rise should be limited to the rate at which such wetlands can accrete materials and evolve. If the preservation of coral islands is the goal, coral growth rates become the determining factor. When a significant difference is observable in such rates, the minimum rate of rise should be adopted.

One complication in using the rate of sea-level rise as a target is the delay, or lag, associated with the oceans. A given rise in temperature can be linked to a given rise in sea level (with many uncertainties) at some period in the future. Actual sea-level rise at this time will be less than the committed sea-level rise, due to lags in ocean response.

Table 2.1-3: Scenarios of Future Sea-level Rise: Magnitude and Rate

Level of rise (mm above 1980 levels)

Scenario	2000	2025	2050	2075	2100
Conservative	50	130	240	380	560
Mid-Low	90	260	520	910	1440
Mid-High	130	390	790	1370	2170
High	170	550	1170	2130	3450

Rate of rise (mm/year)

Scenario	1980-2000	2000-2025	2025-2050	2050-2075	2075-2100
Conservative	2	3	4	6	7
Mid-Low	4	7	10	16	21
Mid-High	7	10	16	23	32
High	9	15	25	38	53

(All data rounded to integers.)

CONCLUSIONS

The rate of sea-level rise over the next century is likely to accelerate rapidly and exceed rates of rise experienced over the last several thousand years. Under these conditions, adverse effects on natural ecosystems such as coastal marshes and coral reef islands would be widely observable by 2050, and would be noticeable in vulnerable ecosystems by the year 2000, even under the low sea-level rise scenario of Table 2.1-3. Non-linearities and sudden events such as storm surges and a change in storm frequency and intensity could lead to damages even earlier. Similarly, change in temperature and precipitation patterns far greater than those experienced in the last 10,000 to 100,000 years seem likely unless strong actions are taken soon.

Rates of change in temperature, precipitation, and sea level over geologic time have often exceeded the rates expected over the next century from global warming. These large excursions, however, were often accompanied by dramatic changes in ecosystems and by large species extinctions, and they occurred when no human infrastructures existed.

The adaptive abilities of natural ecosystems can be used to define targets of maximum rates of rise. For coral reef islands and coastal marshes, the maximum rate of accretion of materials is 10 to 15 mm/yr. At this rate, however, many reefs and marshes that accrete materials at slower rates will be inundated and destroyed. Average rates of accretion for marshes are lower--between 2 and 5 mm/yr, and between 5 and 10 mm/yr for coral reefs. Even at these lower rates, some ecosystem losses are to be expected.

This information leads to a recommended target for the rate of sea-level rise of between 20 and 50 mm per decade, and a target for absolute sea-level rise of between 0.2 and 0.5 above the 1990 global mean sea level.

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2.2. RATES AND LIMITS OF ECOSYSTEM CHANGE

G.W. HEIL and M. HOOTSMANS

INTRODUCTION

An ecosystem can be defined as a community of populations of plants, animals, and fungi, that live together in an environment, as a functional system of complementary relationships, including the transfer and circulation of energy and matter, e.g., a redwood forest (cf., Whittaker, 1975). Climate parameters, such as temperature and precipitation, influence the growth of individual species. Ultimately, however, changes in climate parameters will affect ecosystems through competition and exclusion of species.

Climate exerts dominant control on the distribution of the major vegetation types of the world (Walter, 1985; Woodward, 1987). Vegetation is of paramount importance, because the basis of all biospheric functions is primary production, i.e., the creation of organic matter by photosynthesis of plants incorporating sunlight energy (Lieth & Whittaker, 1975). The different vegetation types around the world are not uniform in their species composition, and can be classified in zones or biomes, such as tropical rainforest, desert, tundra, depending on the different systems, e.g., Holdridge (1967); Whittaker (1975); or Walter (1985).

Increased energy use has led to significantly increased CO_2 levels in the atmosphere since the industrial revolution (Jäger, 1986). When atmospheric CO_2 concentration increases, this may simply lead to a kind of fertilization, because CO_2 is one of the main sources for photosynthesis and growth. It is generally believed, however, that as a result of increasing concentrations of CO_2 and other so-called greenhouse gases, such as methane, ozone, chlorofluorocarbons and nitrogen oxides, a global climatic change will occur which is faster and greater than happened in the past (Warrick et al., 1986). Trend analyses show that global mean surface temperature will increase between 1 and 5 °C during the next 100 years (Jäger, 1988), assuming no changes in underlying factors.

Results of climate scenarios for doubled CO_2 levels derived from different models, such as three-dimensional General Circulation Models (GCMs), are not identical, probably because of the lack of particular feedback mechanisms, such as hydrological processes (Jäger, 1988). GCMs are continuously updated by incorporating and refining various processes influencing climate, such as wind pressure and ocean currents. There is a certain consensus among results of GCMs that there will be a larger temperature increase during the winter in the higher latitudes and a smaller increase during the summer compared to lower latitudes (Schlesinger and Mitchell, 1987). This implies that the growing season of plants will increase as a result of climatic change. It should be mentioned, however, that there are also indications that a return to cold situations may occur locally (Broecker, 1987; Koster, 1989).

The following sections discuss how ecosystems may respond to climatic change, and the aim of targets for climatic change.

EFFECTS OF CLIMATIC CHANGE ON ECOSYSTEMS

Global Carbon Cycle

The source of the CO_2 that is accumulating in the atmosphere is the sum of human activities globally in burning fossil fuels and wood, and harvesting and transforming forests for agriculture or other purposes (Woodwell, 1983; Emanuel et al., 1984). In the longer term of centuries, a new equilibrium will be established between atmosphere and oceans as the current pulse of CO_2 is slowly transferred into very large oceanic reservoir. It is well known that oceans absorb a major part of excess of atmospheric CO_2, and possess an important feedback mechanism on climatic change (Bolin et al., 1989). However, the oceans and their carbonate system are not the only important sink for anthropogenic emissions of CO_2, as indicated above. At least for the coming decades the dominant factors are the release of CO_2 from fossil fuels and the reduction of ecosystems by human action.

The atmosphere is thought to contain about 700 billion tons of carbon CO_2. The biota (living organisms) contain, according to various estimates, 400-1,200 billion tons (Atjay et al., 1979; Rodin and Bazilevich, 1967; Olson et al., 1978; Box, 1988). Organic matter in soils is thought to contain 1,500-3,000 billion tons globally (Schlessinger, 1977). The total carbon estimated as residing in the biota and terrestrial humus of the earth is a minimum of about 3 times that held in the atmosphere. A small change in that pool is enough to change the CO_2 content of the atmosphere by more than 1 ppm. The net exchange of carbon depends on the balance between photosynthesis, respiration, decomposition, fossil fuel use and habitat destruction.

Various models are developed to calculate the net exchange between different compartments of the global carbon cycle, e.g., Moore et al. (1981); Goudriaan and Ketner (1984); Bolin (1988); Box (1988). However, the net balance between the atmopshere and the terrestrial biota is still uncertain, due to lack of knowledge on different parts of the biosphere.

CO_2 Enrichment

CO_2 is a natural resource for plants. The basis for this biological response is to be found in the primary plant process of photosynthesis, whereby light energy is converted into chemical energy in the presence of certain plant pigments to produce carbohydrates from a substrate pool of carbon dioxide. The CO_2 for this process comes primarily from the atmosphere. Consequently, increased CO_2 levels will have a stimulating effect on growth of plants.

High energy use scenarios show that CO_2 concentration might double from 345 to 700 ppm during the period of 1985 - 2030 (Krause et al., 1989). The growth-stimulating effect of elevated atmospheric CO_2 concentration has been reported by many authors, e.g., Carlson and Bazzaz (1980); Kramer (1981) and Cure and Acock (1986). Also, a change in respiration of 5-45% has been reported, which will affect growth and at the same time more CO_2 is re-emitted (Gifford et al., 1985). Poorter et al. (1988) showed that the growth reaction is time dependent as a consequence of the growth form: CO_2-enriched plants are larger and larger plants have a lower relative growth rate due to self shading. Corrected for this effect, it was shown that a high CO_2 concentration enhances the growth rate during an entire growing season (Poorter et al., 1988). A comprehensive review of agricultural crops by Kimball (1983) indicate that for all of the many species which have been studied in this regard, the mean increase in crop yield produced by a 330 to 660 ppm doubling of the air's CO_2 content is approximately 33%. Results of studies on increased growth rates of trees in natural ecosystems, however, are ambiguous, according to Kienast and Luxmoore (1988).

It is a well known phenomenon that species react individually under different CO_2 availability, e.g., as a result of a difference in carbon fixation of the photosynthesis, such as between C_3, C_4 and CAM plants. That is to say, C_3 photosynthesis is the basic mode of carbon fixation. C_4 plants, so called because the initial products of CO_2 fixation are 4-carbon organic acids, are able to maintain a relatively high photosynthesis capacity even while the stomata are partially closed due to water stress. The C_4 photosynthesis is found commonly in tropical grasses. The other photosynthetic pathway, termed Crassulacean Acid Metabolism (CAM), occurs mainly in certain desert plants, and is similar to C_4 photosynthesis. In typical CAM plants, the stomata open at night rather than during the heat of the day. It will be obvious, however, that there are also differences in response among plant species within the same physiological group, either C_3 or C_4 or CAM plants.

In addition to enhancing growth, atmospheric CO_2 enrichment tends to reduce the amount of water transpired by plants and thereby lost to the atmosphere. The mechanism responsible for this phenomenon involves the progressive partial closure of the stomatal pores of plant leaves as the CO_2 content of the air around them is increased. Kimbal and Idso (1983) concluded from a review of 46 experiments involving 18 different species that a CO_2 doubling produced a mean transpiration reduction of 34%. Like the stimulation of plant growth by atmospheric CO_2, this phenomenon has also been found to continue far beyond a CO_2 doubling, additionally indicating that plant water relations should continue to improve as the CO_2 content of the atmosphere continues to rise.

Different types of fertilization experiments with different ecosystems have shown that particular plant species, such as grasses in shrublands or in semi-natural grasslands, benefit more from an increase in availability of a resource than other plant species of the same vegetation (e.g., Heil and Diemont, 1983; Bobbink et al., 1988). This type of species (competitor: cf., Grime 1979) gradually increases in abundance and starts to dominate an ecosystem after a few years. Plants with a potentially high relative growth rate accelerate their growth at the expense of other plant species. Consequently, the plant species composition will change, and species diversity is likely to decrease with increased CO_2 concentration.

Obviously, there will be a large impact on ecosystems compared with the current situation as a result of a significant change in the carbon cycle.

Temperature Increase

It is generally believed that as a result of the increase in greenhouse gases mean global temperature will increase. Temperature increase affects the physiology of plants, e.g., the rates of photosynthesis, respiration and transpiration change under changed temperature regimes. A relatively small increase in temperature of 1 or 2 °C will cause a significant change in net photosynthesis of all plant species (Larcher, 1980). Similar to CO_2 enrichment, temperature increase will cause particular plant species to grow more vigorously than other plant species, and as a consequence the species composition of ecosystems will be affected.

Moreover, an increase in temperature has an effect on the hydrology of ecosystems, through a change in evaporation, a change in precipitation, or a change in both. For example, global measurements of annual rainfall (C) and the annual variability (V) of total rainfall are related as: $V = 148\ C^{-0.33}$ where variability V is in % and rainfall C is in mm (cf., Woodward, 1987). Variability therefore increases with decreasing rainfall. It is clear that higher temperatures change the water balance of the atmosphere.

It is also clear, however, that much more needs to be known about a number of aspects, particularly, how precipitation may alter, not only on an average annual basis, but from season to season. It is well known that the amount of water available is a crucial factor for growth and thus for the number of species that will be able to grow under prevailing circumstances.

The change in hydrology causes other important processes to respond. For instance, decomposition and mineralization are processes that react strongly to slight temperature changes, especially in combination with changes in moisture. Generally, higher decomposition and mineralization rates cause an increased nutrient availability for plants; plants react to this increased nutrient availability by an increase in growth. Thus, temperature increase influences the hydrology of ecosystems as well as the nitrogen cycle.

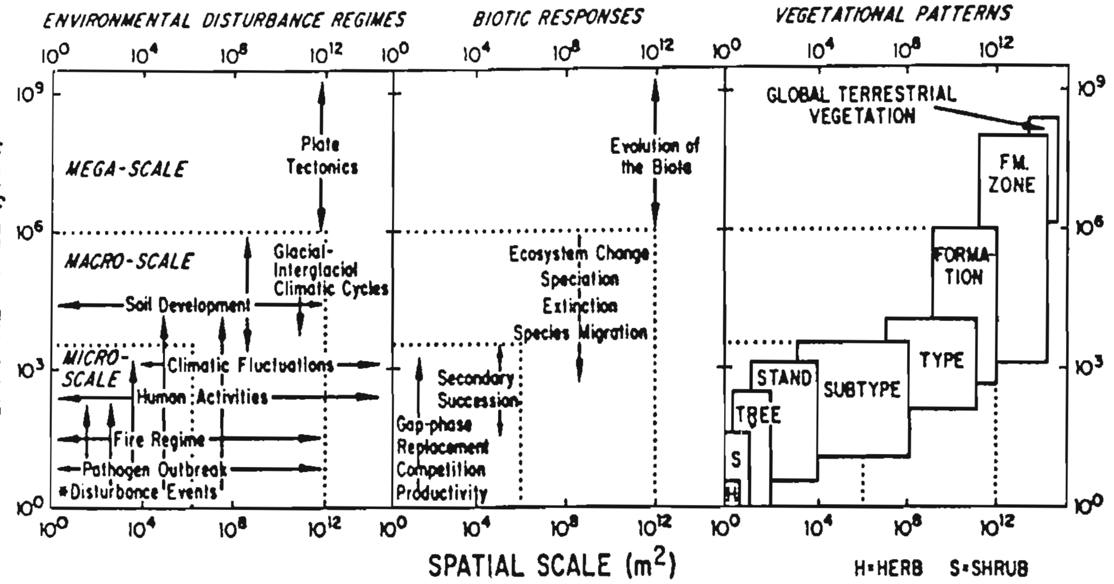
Temperature changes can also have direct effects on ecosystems, especially on tropical marine ecosystems, because under normal conditions these systems are subjected to relatively small temperature fluctuations. For example, Goreau & Macfarlane (1989) showed that when temperatures rose from 29.5 °C to above 30 °C mass bleaching of corals occurred. This happened because the majority of reef building species were affected, so the bright colors of corals were lost.

Feedback Mechanisms of Ecosystems upon Climatic Change

Terrestrial ecosystems are also a factor of importance for the climate system. The role of vegetation is shown schematically in Figure 2.2-1. While the canopy of vegetation can prevent part of the precipitation from reaching the ground by evaporation, part falls directly to the ground, and part reaches the ground via stemflow. Water reaching the surface of the soil leaves as surface runoff and may infiltrate into the soil profile. From there it may be absorbed by the roots of the vegetation, which brings it back into the atmosphere as transpiration, or it may perculate into ground water.

Foliage can reduce the surface albedo and thus change solar radiation to the ground and will change when the structure of the vegetation canopy changes. The canopy can also alter the energy balance processes at the atmosphere/vegetation boundary layer and so change evaporation from the ground, evapotranspiration and

Figure 2.2-1: Processes in a Canopy Model of Surface Evapotranspiration and Energy Balance



Source: Dickinson, 1984.

melting of snow. The canopy determines the surface roughness which also influences soil hydrology. When ecosystems are affected due to climatic change, the hydrology will be also changed, in turn possible affecting the climate again. These processes have been discussed in detail by Dickinson (1984).

STRUCTURE AND FUNCTION OF ECOSYSTEMS

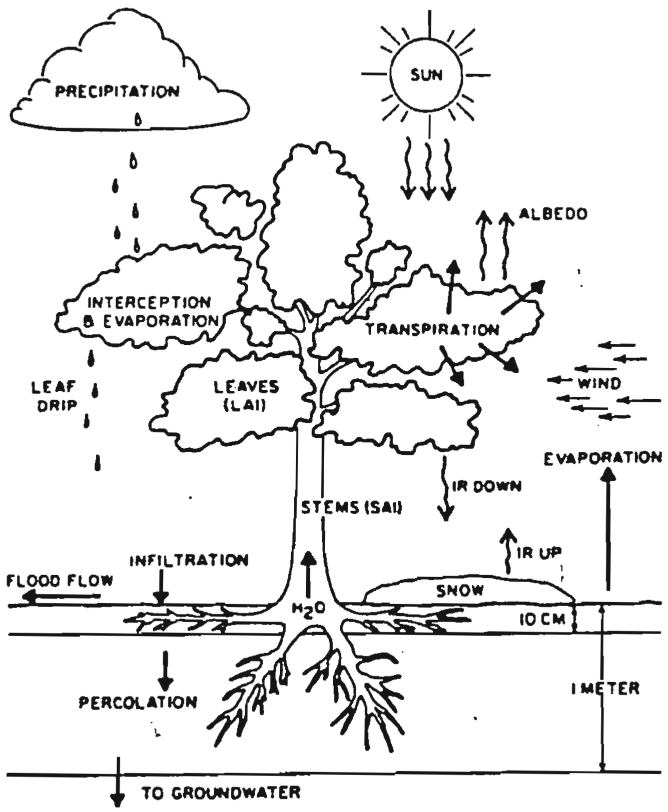
One of the most important consequences of biological regulation in an ecosystem as a whole is the phenomenon of ecological succession. Succession is the process whereby one plant community changes into another. It involves the immigration and extinction of species, coupled with changes in the relative abundance of different plants. Succession represents community dynamics occurring on a timescale of the order of the lifespans of the dominant plants. Succession occurs because, for each species, the probability of establishment changes through time, as both the abiotic and the biotic environment are altered (Crawley, 1986). At timescales shorter than the lifespans of the dominant plants, ecosystem dynamics are relatively constant (cf., Schindler, 1988).

Changes in the physical environment, such as climatic change, will change the pattern of succession. It is well known that the species composition of an ecosystem strongly depends on the degree of stress or disturbance (cf., Grime, 1979; Mooney and Godron, 1983). Stress includes conditions that restrict production, such as shortage of light or mineral nutrients, but also temperature extremes (Schindler, 1988). Disturbance includes conditions that lead to partial destruction of plant biomass, including physical destruction.

Large-scale disturbances generate much of the observed ecosystem dynamics in nature, see e.g., Pickett and Thompson (1978); White (1979). The CO_2 problem is but one of several. Ecologists have long recognized the similarities between natural and some man-made disturbances. The distinctions between natural and man-made disturbances are less important, but what matters are the nature and consequences of disturbance and how species respond to them over ecological and evolutionary times (Bazzaz, 1983).

Attention to scale is important to categorize climatic change in the right time and/or space scale domain. An example is the diagram of Delcourt et al. (1983) of the space and time domain of several different phenomena involved in the dynamics of forests. In Figure 2.2-2 the scale of exogenous factors, i.e., environmental disturbances, is related to the biotic responses of ecological systems, and the domain of vegetational patterns. This is viewed in the context of space-time domains in which the scale for each process or pattern reflects the sampling intervals required to observe it. The time scale for the vegetational patterns is the time required to record their dynamics. The vegetational units are graphed as nested series of vegetational patterns (after Delcourt et al., 1983).

Figure 2.2-2: Environmental Disturbance Regimes, Biotic Responses and Vegetational Patterns



Species are adapted to a particular mean and standard deviation of temperature and fluctuation in temperature and are replaced by other species when the climate system changes. For instance in a long-term plot experiment, plant species composition was monitored. Relatively warm years significantly affected the species number e.g., species composition showed a sharp increase in dominance of some plant species and decrease in diversity of the vegetation during these extreme years (Willems, 1983).

Obviously, there will be a clear relation between the mean (summer/winter) temperature and the species number of an ecosystem under "quasi-equilibrium' conditions (cf., Grime, 1979; Huston, 1979; Shugart and Urban, 1988) as suggested by Figure 2.2-3.

Theoretically, when a stationary situation has been developed in an ecosystem, the species number reaches its maximum as a result of maximum niche differentiation under those environmental constraints. However, under natural conditions the species number will fluctuate around its potential maximum as a result of variation from year-to-year in temperature and precipitation conditions.

Whether the mean temperature increases or decreases the species number will decrease (Figure 2.2-2). Within a small area of homogeneous vegetation, the component species exhibit a wide range of regenerative strategies. The species which will regenerate most successfully will change from year-to-year in accordance with fluctuations in climate. However, a gradual but systematic change in climate, i.e., increase/decrease in temperature, will favor particular species.

Other important processes affected by climatic change are plant-herbivore and plant-disease relations. Because of changes in biomass production and decrease in species number, more food will become available to some food specialists, such as particular herbivores and plant diseases. This in turn will result in a better growth of the herbivore or disease, in some cases to the extent of becoming pests. For example, it has been shown that outbreaks of heatherbeetle pests occur more frequently as a result of increase in food availability and food quality (Brunsting and Heil, 1985).

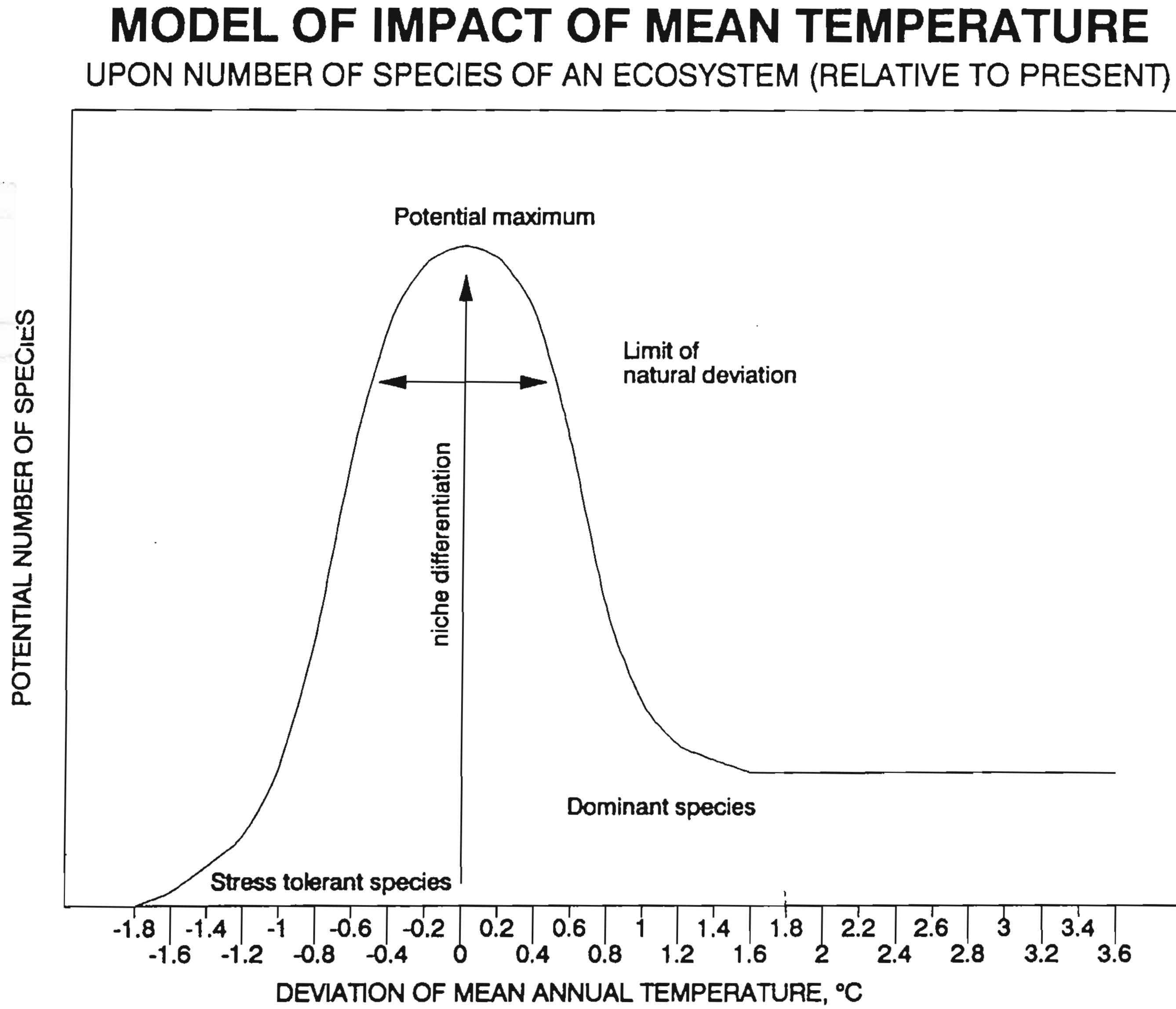
Experimental evidence on direct effects of climatic change on animals are scarce. Direct effects of CO_2 enrichment on animals, such as a disturbance of the feedback mechanism on the respiratory system, can only be speculative. Indirect effects on animals, however, are most probably related to effects on vegetation, because there is a clear relation between plant species diversity and animal species diversity (e.g., Brown, 1984).

It will be obvious that the competition-exclusion principle is one of the most important regulating mechanisms of ecosystems, and therefore it will play a significant role in climatic change.

SHIFT OF VEGETATION ZONES

Climatic change will have significant consequences for species composition, structure and the distribution of natural vegetation zones and for the conservation of ecosystems. Climate largely determines the distribution of plant species and vegetation, and it is well known that present vegetation patterns are more or less in balance with regional climate conditions. The distribution of the world's vegetation types has been known and documented with some degree of accuracy for at least 185 years (Von Humboldt and Bonpland, 1805).

Figure 2.2-3: **Model of Impact of Mean Temperature upon Number of Species of an Ecosystem (relative to present)**



From developments in plant physiology it was concluded (Schimper, 1898) that the climatic control of plant distribution must of necessity operate through basic physiological processes. The fluctuations of temperature on the month-to-month scale in mean temperature influence the distribution or occurence of species, particularly those with life-cycles of a year or less. There appears to be a close link between the time for the life-cycle to be completed and the temporal variation of the controlling climatic process (Woodward and Sheehy, 1983).

From results of different models it is expected that changes in regional climates will cause poleward shifts in the boundaries of the major vegetation zones. Therefore, it is suggested that climate-based vegetation classifications can be used to test the sensitivity of vegetation to climatic change at a global level (de Groot, 1988).

In general, the existing climate-related classification systems are based on typical climate diagrams characterized for the vegetation types in a certain 'Life Zone' or 'Biome', e.g., Holdridge (1967); Whittaker (1975); Walter (1985). These climate diagrams are graphic representations of the major climate factors determining vegetation growth, such as temperature and moisture conditions. With these diagrams it is possible to compare one set of conditions with another, or one area with another area, and thus to distinguish between different vegetation zones.

The system used by **Whittaker** (1975) is based on only two climate factors, namely, mean annual temperature and mean annual precipitation, resulting in 21 terrestrial vegetation zones (formation types).

The **Holdridge** Life-Zone Classification System (Holdridge, 1967) makes use of more detailed climate indices. Major parameters are biotemperature, mean annual precipitation, and a potential evapotranspiration (PET) ratio. The biotemperature is a temperature sum, related to growing degree days, and the PET ratio is defined as PET divided by annual precipitation. The three climate indices are represented in a triangular coordinate system. In addition, the occurrence of killing frost is taken into account in this system. In the Holdridge system 37 vegetation zones (Life Zones) are defined.

The Zonobiomes System of **Walter** (1985) is also largely based on climate but with additional information on typical local/regional soil characteristics and vegetation types. The major climate parameters of monthly average temperature and precipitation are used to characterize climate in each zonobiome. By depicting temperature and precipitation on coincident axes the ecological climate diagram by Walter provides an indication of the duration and intensity of relatively arid seasons, duration/severity of a cold winter, and the possibility of late or early frosts.

Some approaches (Box, 1981) have greater detail than that of Holdridge and the others, and also have more climatic correlates. They are not different from that of Holdridge in that vegetation types are predicted by correlation and not from a fundamental physiological basis. However, these approaches have established estimations of potential changes in global vegetation patterns for future climatic change under certain scenarios. In fact, the results of these estimations are quite enormous.

According to a GISS-2xCO_2 scenario, almost 50% of the world's vegetation will change due to global warming (Leemans, 1989). The largest vegetation change is estimated to occur in the polar regions. For example, tundra ecosystems will almost completely disappear and will be replaced by boreal forests. In turn, temperate forests will replace the boreal forests along their southern border, although the total area of boreal forests on a global scale is estimated to change less than 5% due to their northward expansion (Leemans, 1989).

Although the correlation approach fails to establish the mechanisms by which climate may control distribution, it does provide a logical point from which to start. The implications are that the availability of water may influence the mass of vegetation. The effects of temperature, on the other hand, are multifarious with effects within and beyond the range of plant tolerance. The use of models which simulate vegetation dynamics over time, can give specific answers for restricted regions (Solomon, 1986) or ecosystems (Overpeck et al., 1990; Bonan et al., 1990). To assess the actual impact on a global scale the results of a global dynamic model may elucidate important processes of climatic change (Prentice et al., 1989). However, such a model is not operational in the near future.

CONSTRAINTS TO RATE AND ABSOLUTE TEMPERATURE CHANGE

Present model calculations predict a poleward shift of climate zones, i.e., warmer climates to higher latitudes, leading to a shift in vegetation belts to higher latitudes and altitudes. Predicted climatic changes, however, will most probably not be large enough to cause direct extinction of plant species, but species will adapt to the new climate circumstances or move. Consequently, competition among species to establish at suitable places will increase, which is likely to lead to the extinction of some of the competing species. As discussed in the section on the structure and function of ecosystems, this emphasizes that the rate of climatic change is important with respect to the migration rate of individual species to their new habitats.

Results of simulation models show that vegetation shifts, i.e., changes of limits of growing seasons, may occur between 300 and 600 km per century in temperate climate zones (Parry et al., 1989). However, responses of individual tree species to climatic change in the past indicate that species such as American beech (Fagus grandifolia) or eastern hemlock (Tsuga canadensis) migrate at average rates of 20-25 km per century (Davis, 1989). Probably, this is not the maximum migration rate of these trees, and a migration rate of 50 km per century seems to be feasible (cf. Davis, 1989). However, results from palynological research have shown that tree-species are unlikely to be able to migrate rapidly enough to keep pace with climatic changes (Iversen 1973). Moreover, possibilites for future migration will be significantly limited, not only because of natural barriers such as mountains and rivers, but also because of man-made barriers such as roads, cultiviated areas and destruction of suitable habitats (Davis, 1989).

If temperature rises ecosystems will react through the competition-exclusion principle, resulting in changes in relative abundance of dominant species, and in decrease of species number. For ecosystems with longliving species such as trees, these changes would seem to lag decades behind climatic change. The grass and shrubs of the understorey, however, will respond much faster, so that also in this type of ecosystems the species composition will change. Ecological research in relation to climatic change should take into account the total species composition of an ecosystem.

Effects of an extremely warm year (1976) illustrate what may occur with ecosystems due to climatic change. Limestone grasslands belong to the most diverse grassland ecosystems in NW Europe (Willems, 1983). This species rich ecosystem is a good example of what may happen under climatic change, because the more species there are the more sensitive the species composition of an ecosystem is to environmental disturbances. In a long-term experiment it was shown that a sharp increase in dominance and decrease in biological diversity in all vegetation plots occurred in 1976 (During & Willems, 1984). The impact of the 1976 climate condition lasted for several years in spite of return in subsequent years to mean temperature conditions.

Parry et al., (1989) estimated that responses of crops to conditions in 1976, were similar to the response to an average warming of 0.5 ^{o}C. For example, the temperature limit for maize in the summer of 1976 lay approximately 100 km north of its normal position in NW Europe. This is most remarkable, because the growing limit of maize is only restricted by temperature, since in NW Europe water and nutrients are supplied artificially to these crops.

To avoid irreversible changes in ecosystems, climatic change should not exceed the extremes of natural variation in climate, such as in 1976, experienced with the current geologic time period.

TARGETS FOR ECOSYSTEMS

In order to prevent irreversible disturbances to natural ecosystems and to maintain bio-diversity, targets should be based on the adaptive capacity of ecosystems in regional climate and climate-related processes. As discussed in this paper, vegetation responses to climatic change indicate that migration of treespecies especially is limited to average rates of approximately 50 km per century, which corresponds to a temperature change of 0.5 ^{o}C by 2100 (Davis, 1989). Evidence of decrease of biological diversity as a result of year-to-year climate variation in limestone grasslands confirms that total temperature change should not exceed 0.5 ^{o}C (cf. During & Willems, 1984; Parry et al., 1989). It is very difficult to determine the impact of climatic change on agro-ecosystems (Parry et al., 1989) because of strong influences by man through irrigation, fertilization and soil cultivation. Targets for agro-ecosystems, however, most probably fall beyond those of natural ecosystems.

It is apparent that temperature change should be as gradual as possible to reduce the inability of species to respond to temperature change. It can be concluded from the literature that a rate of temperature change less than 0.1 ^{o}C per decade may be tolerable (Davis 1989; Krause et al., 1989), but total temperature change should be limited to 0.5 ^{o}C relative to the present to prevent unpredictable ecological responses and instability of ecosystems. In combination with the warming already realized since pre-industrial time, which is estimated to be 0.5 ^{o}C at present (Lashof & Tirpak, 1989), total temperature increase should be limited to 1.0 ^{o}C relative to pre-industrial global mean temperature.

POSSIBLE BIOLOGICAL INDICATORS

Species respond individually to climatic change and some species will increase at the expense of other species, so that a change in species composition of ecosystems will occur. Especially, warmth preferential species (thermophyles) at their northern limit will respond vigorously to temperature increase and extension of their growing season.

For instance, in southern areas of cool temperate regions sub-mediterranean half-woody species with their perennating buds above or very close to the soil surface (chamaephytes), such as *Clematis vitálba* and *Teucrium montánum* in Western Europe, are very sensitive to small temperature changes and will be able to expand their distribution to the north when temperature increases. These are also areas for which it was indicated that climatic change will occur more strongly than in other areas.

It seems reasonable to expect that the boundary of the distribution of numerous species will traverse many different ecosystems. Thus, it is of major significance to make an inventory of thermophyles in those ecosystems where a significant increase in temperature impact of climatic change may be expected. According to Leemans (1989), changes are most likely to occur at the southern and northern edges of boreal forest regions. It would be not be prudent, however, to focus on one type of ecosystem as a biological indicator.

Furthermore, it is important to monitor these thermophyle species in relation to other species in their most original habitat **and** in areas which they invade, to be able to identify the cause(s) of their increase. With respect to this identification, monitoring should include other indicators of climatic change, such as local mean temperature and precipitation, in addition to thermophyles. Methods to carry out this type of monitoring and to interpret the results have been refined in ecological research, e.g., Jongman et al., (1988).

An approach might be to set aside, as has been done in the U.S. (B.T. Bower, 1990, pers. com.), some natural areas representative of different types of ecosystems. Various ways of monitoring changes in these systems are available. They are to be used as "flags".

DISCUSSION

Although evidence of future climatic change is still debatable, it is generally believed that global climatic change will occur. The discussion is strongly focused on by how much temperature will change, and how much temperature change can be tolerated. The relation between greenhouse gases and temperature change is still uncertain, because of the sensitivity of the climate system. Moreover, it is hardly possible to estimate the impact of global temperature change on regional climates. However, the predictions of all kind of models are so threatening for the quality of the biosphere that they cannot be neglected.

Direct proof of effects of climatic change on ecosystems is not available, because significant effects will most probably not occur before the end of this century. Moreover, several perturbations, such as air pollution or habitat destruction, will make it difficult to distinguish between effects of climatic change and other ecological stress factors. In this chapter possible effects of climatic change on ecosystems have been discussed on the basis of existing knowledge of ecological processes and their implications for ecosystems. On the other hand examples of anomalies, which resemble possible effects of climatic change, are used to set targets for climatic change.

The ecological conceptions as described here are not discussed in detail. The different subjects are amply discussed in the handbooks on ecology. An attempt has been made to provide a framework which shows how climatic change will disturb ecological processes and how this ultimately affects ecosystems. It is important to emphasize that largescale changes of ecosystems are controlled by responses of individual species.

Attempts to estimate rates and limits of ecosystem change due to future temperature change have focused on distinctly different ecosystems that showed similar (potential) effects of temperature change. It is clear, however, that much more needs to be known about ecosystems before accurate biological indicators can be selected. Monitoring ecosystems is just one means of extending knowledge of ecosystem behavior. Ecological research should also be focused on understanding ecosystem processes, such as competition, in relation to responses to climatic change. Understanding the dynamics of ecosystems is essential to understand the full range of possible impacts of climatic change.

Present knowledge on the effects of climatic change on ecosystems is far from complete. Based on our understanding of impacts of past climatic changes on ecosystems, targets can be recommended, however. A target for maximum rate of change in global mean temperature of 0.1 °C per decade has been selected for realized warming. Two absolute temperature targets are identified. A maximum temperature increase of 1.0 °C above pre-industrial global mean temperature for committed warming is set on the basis of current understanding of the vulnerability of ecosystems to historical temperature changes. If global mean temperature increases beyond this target, unpredictable and non-linear ecological responses may occur, leading to extensive ecosystem damage. An absolute temperature limit of 2 °C can be viewed as an upper limit beyond which the risks of grave damage to ecosystems, and of non-linear responses, are expected to increase rapidly. The results of the approach to temperature targets taken by this *ad hoc* Working Group agree with the temperature targets suggested by the Deutsche Bundestag (1989).

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3. MONITORING STATUS AND DETECTING CHANGES

3.1. SOURCES AND SINKS, DIRECT FORCING, AND FEEDBACKS

D.A. LASHOF

Climate policies, which address emissions of greenhouse gases, must be developed to achieve environmentally-based targets for climatic change. These policies must be based on the best available information relating human activities to climatic change resulting from the buildup of greenhouse gases. The key linkages and uncertainties will be traced in this section, starting from climatic change impacts through climate forcing to anthropogenic emissions. The order of this presentation is dictated by the target setting approach of the report as a whole, and is the reverse of the usual procedure in which emission projections are translated into radiative forcing and resulting climatic change.

A schematic representation of the connection between human activity and environmental impacts is shown in Figure 3.1-1. The goal of policy should be to maximize well being while minimizing the chance that the climatic change targets identified in previous sections will be exceeded (I). This can be accomplished by policies to limit population (P) and to encourage low-emissions technology and modification of life style (E/D). This approach differs from a traditional cost-benefit framework in that it is assumed that not all environmental damages can be characterized by their impact on development (illustrated with the dashed arrow). Instead, development and environmental targets are set independently. Whether or not a given target can be achieved, is a function of (1) level of development and (2) policy. Given such targets and an assumed population level, the goal of policies can be expressed with the following variant of the Ehrlich-Holdren equation:

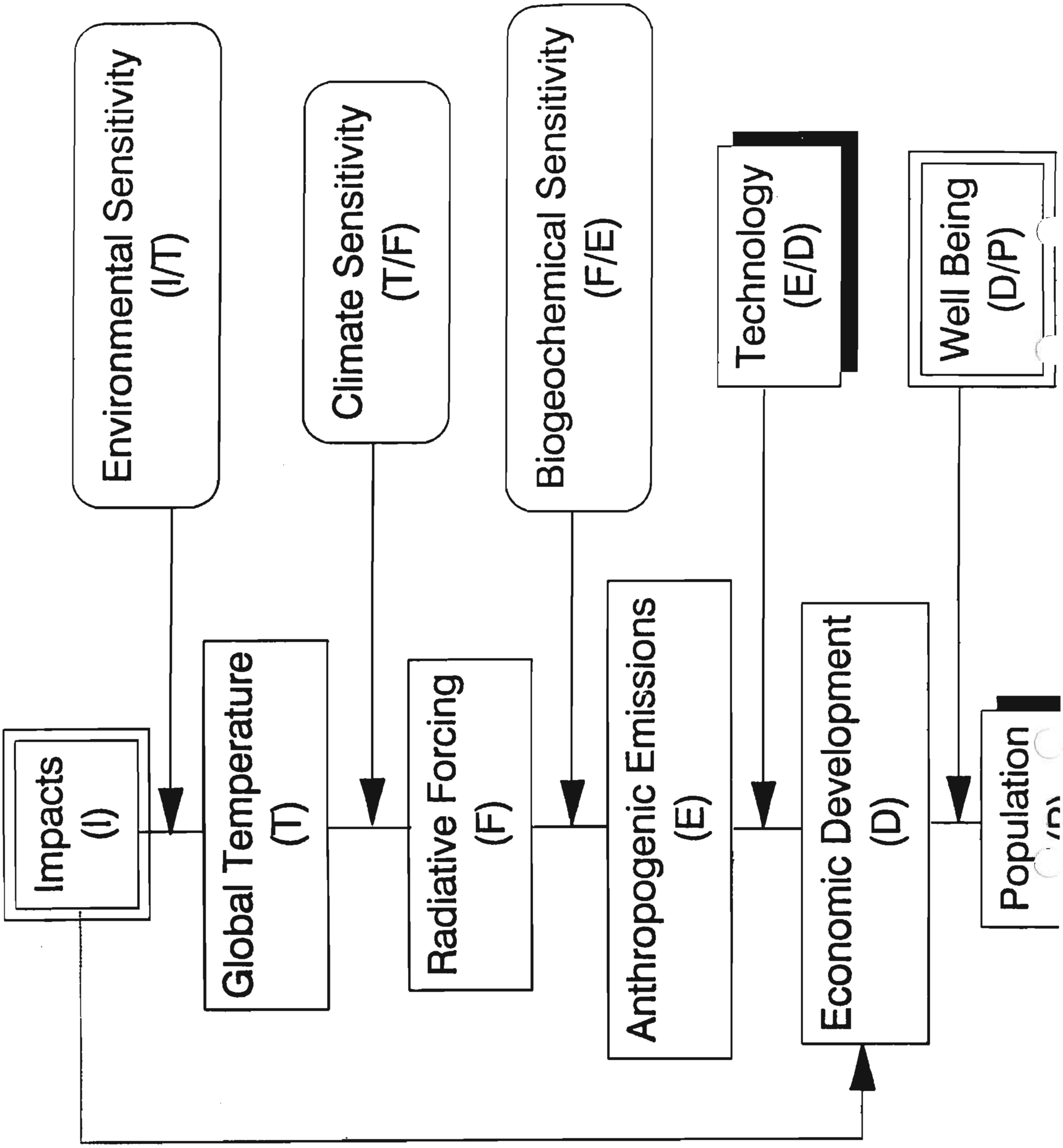
$$E/D^{*} = f\left(\frac{I'}{I/T,\ T/F,\ F/E,\ D/P',\ P} \right) \qquad (3.1.1)$$

where,

I	=	environmental targets, e.g., sea level, biodiversity;
T	=	global Temperature increase, °C;
F	=	radiative Forcing, W/m^2;
E	=	greenhouse gas Emissions, tons/year;
D	=	welfare level, e.g., GNP in US$; and
P	=	Population, billions.
*	=	policy variable
'	=	target variable

In this formula E/D is considered to be a policy variable; I and D/P are target variables. P but also D/P could be considered as policy parameters, since population control and limitation of quantitative economic growth can play a very significant role in slowing down climatic change. These sensitive issues however have a broader scope than climatic change and therefore in this report we focus

Figure 3.1-1: Relationship Between Human Activity and Environmental Impacts



on the other parameters. Also D/P and P could be considered to be part of the system that may be influenced by the impacts of environmental change. This undesirable potential feedback has not been taken into account in this report.

The formula implies that the greenhouse gas emissions per unit of economic development (E/D) must be low enough to ensure that the environmental targets (I) are not exceeded, given the environmental sensitivity (I/T), the climate sensitivity (T/F), the biogeochemical and physical sensitivity (F/E), the average well-being of the population (D/P), and the population (P).

This linear representation is for schematic purposes only. It must be recognized that the risks involved in perturbing this complex system may arise as much from the possibility of large unexpected feedbacks and sudden changes in system dynamics as from the expected impacts based on maximum likelihood estimates of each of the parameters. The most important non-linearities that have so-far been identified will be highlighted in the discussion below. True surprises, by definition, will arise in unexpected areas. This section focuses primarily on the physical and biogeochemical climate variables in the formula (T/F, F/E), other sections cover the climate impacts and the implementation aspects (E/D, D/P, I) in more detail.

ENVIRONMENTAL SENSITIVITY

Environmental sensitivity describes the relationship between climate, e.g., characterized by global temperature, and environmental values, such as ecosystem stability, agricultural productivity, and coastal zone property. Environmental sensitivity is determined by the full gamut of responses to climatic change, from purely geophysical, to biological and social. Key geophysical uncertainties include the rate and magnitude of sea-level rise, the extent of the shift in climatic zones, and changes in storm intensity. Changes in the hydrologic cycle are biogeophysical as are the related changes in forest fire frequency. Biological responses include changes in the composition and geographic distribution of ecosystems and the incidence of infectious diseases. Finally, how smoothly social systems adapt to climatic change will have a major impact on the severity of direct impacts on human welfare.

Estimating the environmental sensitivity of each system impacted by climatic change is a daunting task. Although estimates for some subsystems are presented in other sections, a comprehensive evaluation is clearly beyond present capabilities. Targets are therefore based largely on examining historic rates of change. This has been discussed in more detail in Chapter 2. This analysis suggests that small changes in global temperature are associated with dramatic environmental changes over thousands of years. The ice ages, for example, correspond to a global temperature of approximately 5°C. Unfortunately the proxy records used for this analysis do not have sufficient temporal resolution to provide much information on how systems adjust on a time-scale of centuries. There are indications, however, that very rapid shifts in regional climate and ecosystem makeup have occurred in the past (Street-Perrott and Perrott, 1990).

Particularly significant is the possibility that the mode of ocean circulation might suddenly change, profoundly affecting regional climates from the tropics to

Northern Europe. Models suggest that there may be two quasi-stable modes of ocean circulation, characterized by large differences in South-to-North heat transport by the thermohaline circulation (Manabe and Stouffer, 1988). Reduced ocean heat transport has been linked to drought in the Sahel as well as near-glacial temperatures in Northern Europe. There is strong evidence that the thermohaline circulation was much weaker during the last ice age, and that a temporary return to glacial circulation patterns was responsible for the Younger Dryas cold period in Europe and North America between 11,000 and 10,000 years before present (Street-Perrott and Perrott, 1990). While this last argument is controversial (Jansen and Veum, 1990), it is clear that climatic change since the last ice age did not occur in a gradual manner, but instead, the overall warming was punctuated by rapid climatic shifts (time scale of a century) driven by changes in ocean circulation and amplified by feedback processes. Such effects are generally precluded from occurring in climate simulations of future global warming by the simplifying assumptions built into current general circulation models. How to handle these issues in a policy context has been discussed in Chapter 1.

CLIMATE SENSITIVITY

Feedback processes and equilibrium sensitivity

Uncertainty about climate sensitivity has been the primary focus of debate about global warming. Equilibrium climate sensitivity can be defined as the eventual change in global temperature produced by a given initial radiative forcing. The consensus with respect to the bounds of uncertainty of estimates of eventual change in global temperature, i.e., 1.5 to 4.5°C for a doubling of CO_2 concentration, while broad, has remained constant for more than a decade. Climate sensitivity is determined by a number of feedback processes that produce gain (g) which amplifies ($g > 0$) or diminishes ($g < 0$) the initial forcing. The equilibrium response can be expressed as:

$$T = \frac{F}{\mathrm{Lambda}_0\,(1-g)}, \qquad (3.1\text{-}2)$$

where,

T = global temperature, °C;
F = radiative forcing, W/m^2;
g = gain.

The value of Lambda_o, namely, 3.5 $W/m^{2\circ}C$, is known to within 10%, while the range of values for g, corresponding to the temperature uncertainty bounds given above is 0.16-0.72. Theoretically as g approaches 1 the equilibrium warming approaches infinity, implying that the system becomes unstable. This non-linearity is important, because if the climate sensitivity from physical climate feedbacks is high, i.e., g is close to 0.7, then small additional feedbacks due to biogeochemical processes not included in the climate models could have a large impact in amplifying global warming (see below). Note that because a feedback system is highly non-linear, once the overall gain is large, small additional increments have a disproportionate effect on equilibrium warming.

To recast uncertainty about equilibrium climate sensitivity from the point of view of target setting, a 2.5°C equilibrium warming could be associated with a radiative forcing of between 7.3 and 2.4 W/m^2. The implications of this uncertainty are profound. If climate sensitivity is at or near the upper end of this range, then the earth may already be committed to a warming in excess of the targets identified here, because the radiative forcing from greenhouse gas increases between the middle of the 18th century and 1990 is 2.5 W/m^2. If the middle of the range is correct, then the targets can be achieved only with rapid reductions in emission levels, while the lower end of the range would imply somewhat more leeway.

An important feedback process is the change of the earth's reflectivity (albedo) due to changes in ice and snow cover which is responsible for the fact that models predict the largest temperature increase at high latitudes.

The largest factor contributing to uncertainty about equilibrium climate sensitivity is the role of clouds in amplifying or diminishing the initial forcing (Cess, 1989; Dickinson, 1986). Clouds both reflect sunlight (solar radiation), thereby shading the earth, and absorb and re-emit heat (infrared radiation) downward, thereby adding to the greenhouse blanket. The net radiative effect of clouds depends on their amount, geographic distribution, altitude, reflectivity and infra-red emissivity. All of these properties will change as climatic changes.

While the present impact of clouds is a cooling relative to a cloud-free earth, this does not indicate what impact changes in clouds will have as climate changes (Raval and Ramanathan, 1989). In fact, most climate models find that the impact of cloud feedbacks range from slightly negative to strongly positive. In other words, most of these models suggest that the net cooling effect of clouds in present climate may diminish in response to global warming, thus amplifying the warming. Given that both the theoretical and observational understanding of the factors responsible for the radiative impacts of clouds is currently poor, it is doubtful that the uncertainties regarding clouds can be significantly reduced in less than a decade.

Transient effects

The other key uncertainty in relating global temperature to radiative forcing is the role of the ocean in absorbing heat and thus determining the rate of warming at the earth's surface. The difference between the observed temperature trend at any given time (realized warming) and the equilibrium temperature that would occur if radiative forcing remained constant at the level in that year (equilibrium warming), depends on the history of the forcing, the pattern of ocean circulation, and the equilibrium climate sensitivity. In particular, the greater the equilibrium climate sensitivity, the larger the difference between the realized warming and the equilibrium warming. This implies that the range of forcing scenarios consistent with a given target rate of warming is probably much narrower than the range of forcing values corresponding to a given equilibrium temperature increase.

For example, the observed warming in this century of 0.55°C (Kuo et al., 1990) could represent 22% of an equilibrium warming of 2.6°C or 65% of an equilibrium warming of 0.85°C, given the current radiative forcing of 2.5 W/m^2 (compared to the pre-industrial level) and the range of equilibrium climate sensitivity given above. Other factors, such as changes in aerosol loadings and natural variability probably are also important in explaining the temperature record over the last 100 years. Similarly, a warming rate of 0.1°C per decade between 2000 and 2050 could be consistent with 61% of an equilibrium warming of 3.1°C or 74% of an equilibrium warming of 2.3°C, given a climate sensitivity of 2-4°C for doubling CO_2 (Lashof and Tirpak, 1990).

The pattern of ocean heat uptake also implies that regional rates of climatic change may differ dramatically from that of the global average. For example, one model simulation with coupled atmosphere and ocean general circulation models found that deep mixing in the circum-Antarctic ocean prevented much of the Southern Hemisphere from warming significantly for several decades (Stouffer et al., 1989).

BIOGEOCHEMICAL AND PHYSICAL SENSITIVITY

The biogeochemical and physical sensitivity can be characterized as the quantity of greenhouse gas emissions associated with a particular level of radiative forcing. It is determined by the sources and sinks for each greenhouse gas and the instantaneous forcing per molecule in the atmosphere. This sensitivity will be affected by biogeochemical feedbacks, which are changes in sources and sinks as a result of anthropogenic emissions and/or climatic change, including interactions between different emitted gases. Section 3.2 will deal in detail with translating emissions into an index of cumulative radiative forcing over various time horizons. Here the key factors influencing the accumulation and removal of the major greenhouse gases in the atmosphere, including feedbacks, are outlined.

Carbon dioxide

Carbon dioxide is the single most important greenhouse gas accumulating in the atmosphere, and perhaps the most complex to describe. Increases in CO_2 concentrations since the 18th century inferred from ice core data imply a radiative forcing of 1.5 W/m^2, 60% of the total from all greenhouse gas increases to date. Because of its long effective lifetime, CO_2 will be responsible for a larger share of the long-term cumulative climate forcing; see Section 3.2 and Lashof and Ahuja (1990). Current anthropogenic emissions of 6-8 petagrams (Pg = 10^{15}) of carbon per year are superimposed on gross natural fluxes to the order of 20 times as great. Furthermore, unlike the other important greenhouse gases, removal of CO_2 from the atmosphere is not through chemical destruction, but rather through transfer to other large carbon reservoirs, namely the ocean and terrestrial biota.

It is generally believed that the oceans are the dominant sink for atmospheric CO_2, although carbon cycle models have difficulty accounting for the full difference between cumulative anthropogenic emissions from fossil fuel combustion and excess atmospheric concentrations through ocean uptake alone. Net emissions from deforestation only increase the discrepancy. Recent analysis combining observations of the geographic pattern of CO_2 concentrations with direct observations of CO_2 penetration into the oceans strongly suggests that there is another large sink for CO_2, presumably in mid- and high-latitude forests. The implication is that it is risky, at best, to calculate emission budgets associated with a given concentration level based on simple diffusion models of ocean uptake or assumptions that a constant share of direct anthropogenic emissions will remain in the atmosphere. Nevertheless, given that these are the only approaches available, they can provide some guidance. For example, to keep CO_2 concentrations below a limit of 400 ppm, corresponding to a forcing of 2.3 W/m^2, a constant airborne fraction model implies an emission budget from 1985 to 2100 of about 200 PgC, while a box-diffusion model would suggest that 300 PgC could be released (Krause, et al., 1989).

At least three factors could significantly alter the characteristics of the natural carbon cycle over the next century. First, as discussed above, climatic change is likely to be accompanied by substantial changes in ocean circulation. This could have a major impact on carbon as well as on heat fluxes. A direct impact of surface warming will be to increase the stability of the ocean thermocline, thus decreasing the penetration of excess CO_2 into the ocean. Large-scale changes in circulation would have a more dramatic effect, and could even turn the ocean into a net source rather than sink for CO_2. Second, increases in CO_2 concentration have the potential to stimulate growth of the terrestrial biosphere. This mechanism has long been invoked to provide the apparently missing carbon sink. Competition for light and other resources, however, will strongly modify the direct effects of CO_2 fertilization in natural ecosystems, and there are no direct observations at the ecosystem level to constrain theoretical models. Third, climatic change will stimulate soil respiration and disrupt forest ecosystems, possibly resulting in large fluxes of CO_2 from the biosphere to the atmosphere (Woodwell, 1986; Lashof, 1989; Solomon and Leemans, 1989). The net effect of these feedbacks is difficult to estimate. Lashof (1989) found that the combination of these factors might produce a net gain of 0.05. If forest dieback and respiration dominate the effect of CO_2 fertilization, however, this feedback could be significantly greater. A further complication arises from the chemical attacks on land biota like acid rain and ozone, and from a likely reduction in photosynthesis activity of oceanic phytoplankton due to increase in UV-radiation because of stratospheric ozone destruction.

Methane and other gases that are chemically active in the troposphere

Methane, of which the atmospheric concentration has more than doubled, has accounted for the second largest contribution to radiative forcing since the 18th century, being responsible for a large proportion of the increase when its contribution to increasing stratospheric water vapor is included. Unlike carbon dioxide, methane plays a major role in the chemistry of the troposphere. Indeed, chemical interactions and feedbacks may be responsible for more than half of the radiative forcing from a given emission of methane. Similarly, a number of chemically important species, which themselves are not significant greenhouse gases, can produce radiative forcing by increasing the concentration of tropospheric ozone and contributing to the buildup of methane.

Methane is emitted as a result of anaerobic decomposition of organic matter, for instance during food production (rice, meat and dairy) and from fossil fuel production and distribution operations. Its lifetime in the atmosphere is currently about 10 years, where it is destroyed principally by reaction with OH molecules. As it is destroyed in the troposphere methane participates in the complex chemistry that leads to tropospheric ozone formation, while methane oxidation in the stratosphere is the major source of water vapor above the tropopause. Both tropospheric ozone (especially near the tropopause) and stratospheric water vapor are powerful greenhouse gases, but their effect is dependent on latitude.

Emissions of non-methane hydrocarbons (NMHCs), carbon monoxide (CO), and nitrogen oxides (NO_x) also participate in ozone and OH chemistry. These gases are short-lived and the reactions are non-linear. Therefore the impact of a given quantity of emissions depends on the background concentrations in the region of the emissions. For example, in highly polluted urban areas, NO_x emissions can actually decrease ozone concentrations. On a global basis, however, it is reasonable to assume that increased emissions of these compounds will add to radiative forcing by increasing ozone forcing and/or extending the lifetime of CH_4 (Thompson et al., 1989). However, if only NO_x is reduced, the effect of extending the lifetime of methane overbalances the reduction in tropospheric ozone production.

Climatic change will influence both the emissions of chemically active gases and the atmospheric chemistry itself. Anaerobic bacteria will respond directly to warming by increasing their output of methane, so emissions from wetlands and rice paddies are likely to increase. Similarly, natural and anthropogenic emissions of NMHCs are known to increase rapidly with temperature. An even greater potential feedback is the release of vast quantities of methane from continental shelf hydrates as these formations become unstable due to warming. Lashof (1989) found that this feedback could contribute a gain of 0.01 - 0.2 and could constitute the largest biogeochemical feedback in the climate system.

Global warming will influence atmospheric chemistry directly by changing reaction rates, and probably more importantly by influencing the abundance and distribution of OH. Increases in absolute humidity accompanying global warming will tend to increase OH formation by the reaction of water vapor with atomic oxygen (in an excited state). This reduces the lifetime of methane and tropospheric ozone, resulting in a small negative feedback. Other things being equal, this will decrease the concentration of methane and ozone, resulting in a negative feedback with a gain of roughly -0.04 (Lashof, 1989; Hameed and Cess, 1983).

Nitrous oxide

Increases in the concentration of nitrous oxide have contributed 4-5% of the increase in radiative forcing to date. While the concentration increase is firmly established, the sources and sinks of N_2O are highly uncertain. Inert in the troposphere, N_2O is destroyed in the stratosphere where it has a major influence on stratospheric ozone chemistry. Its lifetime is more than a century, with an uncertainty of about 50%, with values between 120 and 160 years commonly found in the literature. Because of this long lifetime, the increase in concentration of 0.3% per year represents an imbalance between sources and sinks of roughly 30%. While many sources of N_2O have been identified, it is difficult to derive a quantitative budget that accounts for this imbalance. Natural emissions appear to be dominated by biochemical processes in soils, suggesting that emissions could change substantially in response to global climatic change. Anthropogenic emission sources include fertilizer use, land clearing, and combustion of biomass and fossil fuels. Of these sources, biological formation appears to be more important than combustion, but global emission estimates are extremely difficult because of the variability of N_2O emissions in space and time.

Chlorofluorocarbons

Before the 1930s the atmosphere contained no chlorofluorocarbons (CFCs). Together these compounds now amount to almost 1 part per billion of the entire atmosphere. While this level is still orders of magnitude smaller than that of the other greenhouse gases, CFCs are responsible for about 10% of the total radiative forcing since pre-industrial times, and 20% of the forcing during the last decade. The most dangerous CFCs are likely to be phased out over the next decade because of their threat to stratospheric ozone, so the share of forcing attributable to CFCs is likely to decline in the future. However, because of their long lifetimes, i.e., decades to centuries, and because some of the leading substitutes still have a substantial global warming potential, halocarbons will continue to play an important role in the atmosphere for decades to come. Since halocarbons are mainly removed from the atmosphere by OH, their contribution is highly dependent on methane, carbon monoxide and nitrogen oxides. In turn, halocarbons influence the concentration of methane via: a) stratospheric ozone destruction; b) increase in penetrating UV; and c) OH increase in the troposphere. Changes in vertical ozone distribution usually cause a small negative feedback.

TECHNOLOGY

Broadly speaking, the level of economic development that can be supported with a given rate of greenhouse gas emissions is determined by technology. The central focus of policies aimed at limiting climatic change to the targets outlined above must be to reduce the emissions associated with producing the goods and services that consumers desire. The level and form of economic development, i.e., the mix of final goods and services produced by an economy, are also important, but probably much less amenable to influence by policy choices.

WELL BEING

The goal of sustainable development is to increase the welfare of individuals in a manner that can be sustained indefinitely. Economic growth, defined as expanding economic activity, inevitably comes into conflict with environmental protection, given a finite capacity to assimilate wastes. In addition, the sustainable level of material throughput is finite, and thus -- at some point -- increases in population will result in reductions in per capita well being. Whether or not this point is rapidly approaching in a given region, or indeed has already been reached, is very controversial. In any case, policies aimed at limiting population growth by providing universal access to means of voluntary family planning will make it easier to increase or maintain well being for any given set of emission limits.

CONCLUSION

Climate policies, which address emissions of greenhouse gases, must be developed to achieve environmentally-based targets for climatic change. This requires traversing a cascade of uncertainties involving the sensitivity of environmental, climatic, and biogeochemical systems. Although this can be conceptualized with a linear decomposition, as expressed in equation (3.1-1), it has been shown that there are many non-linear interactions and feedbacks that could play key roles. Prudent policy must be based on minimizing the risk of extreme consequences as well as examining most likely outcomes. Thus conservative, though not necessarily worst-case assumptions, should be used when faced with the uncertainties described here. It must be remembered that future research is at least as likely to show that the threat of climatic change is greater than currently thought, as it is to show that the threat is less. This discussion underlines the importance of conducting a scientific research program in **parallel** with rather than instead of the implementation of measures to reduce greenhouse gas emissions.

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3.2 MODELS FOR ESTIMATING CLIMATE CHANGE

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INTRODUCTION

In the following sections of Chapter 3 relationships among emissions, ambient concentrations, global mean temperature increases, and sea-level changes have been evaluated. Since the 1985 Villach meeting, consensus has been reached as to the general features of climatic change, such as the expected increasing global average temperature. This consensus has been reached based on results of static equilibrium climate models (Global Circulation Models, or GCMs). Historical evidence underscores the linkage between temperatures and concentrations of carbon dioxide and methane, as detailed in Section 2.1. Because of the many uncertainties which are still unresolved, no agreement exists with respect to the timing and extent of the changes, especially with respect to the regional distribution of precipitation, and temperature changes.

An overview of these uncertainties and feedbacks is given in Section 3.1. One might argue that continuing emissions of greenhouse gases and associated significant climatic changes could induce feedback mechanisms that may change the basic features of the earth system with respect to climate, ocean fluxes, and behavior of the biosphere. While in the present models many geophysical feedbacks are included, in some cases unsatisfactorily, biochemical feedbacks are generally not included. Increasing temperatures are likely to influence carbon dioxide emissions from respiration and methane release rates from wetlands, as indicated in Section 3.1, and decrease uptake by oceanic organisms such as coral reefs. These climatic feedbacks may prove to be uncontrollable. The models presently being used may then not be valid, and hence could not be used for operational target setting. However, target setting and consequent preventive measures at levels derived from the present models will decrease the risk of occurrence of such events and are therefore useful even without complete understanding of the possible instabilities. Taking the risk of these instabilities into account would lead to even lower targets and thus to the need for even more emission reductions than those advocated based on the present models.

In Section 1.3 it has been argued that the traditional way of developing strategies based on a gradually changing world (sensitivity approach) should be complemented by strategies geared towards the avoidance of system instabilities. Since the idea of putting such a stability approach into practice still has to be worked out, in this section we will focus on the sensitivity approach.

POSSIBILITIES AND LIMITATIONS OF MODELS

Because of their size and scope, the equilibrium models referred to above (GCMs) are not suitable for quick evaluation of different policies. Therefore various dynamic, simplified models have been developed to capture the total cause-effect relationships involving climatic change. These models are applied in a policy context to assess the implications of different climate policies. For these models to be useful in the policy process, it is necessary that policy makers understand what the models can do with what level of accuracy. They can perform quick dynamic calculations over time on relatively small computer systems. Using simplified parameterizations of complex relationships they are indispensable for the evaluation of policy scenarios. They are also useful for identifying gaps in existing scientific knowledge, for conducting sensitivity analyses and for communicating the results of different options to policy makers. They cannot, however, project the development of possible important feedbacks in natural systems or answer questions about the level of climate sensitivity to greenhouse gas buildup.

Crucial factors such as ocean heat transport, ocean circulation, changes in hydrological cycles, in cloud cover, or in atmospheric chemistry are only incorporated in the most rudimentary fashion. The parameters for these models have been taken from ranges published in the international literature in order to mimic the historical record of instrumental data. The systems are assumed to function in the future as they have in the past. An example is the carbon cycle. More CO_2 is taken from the atmosphere than can be explained by conventional analysis of the ocean uptake. Some models attribute this 'missing sink' to the biosphere, others to additional uptake by the oceans. Both approaches can be made to fit the development of the historical estimated global concentration of carbon dioxide. Hence, estimates of future developments are highly uncertain. Fortunately, both approaches do produce similar results in terms of estimates of future concentrations.

USABLE MODEL TOOLS

Mathematical models that simulate the linkage between economic activity and environmental processes are the principal tools for evaluating the impacts of alternative policy responses on the rate of future climatic change.

A number of hierarchical models can be distinguished that describe the cause-effect relationship of climatic change: economic activities, emissions, concentrations determined by the carbon cycle and atmospheric chemistry, radiative absorption, climatic change, sea-level rise and finally ecological or economic impacts. Some models capture a part or the total of this sequence as depicted in Figure 3.2-1 in a general form. At different levels of this hierarchy targets could be tied into the models. The upper part dealing with economics has the weakest predictive powers, since the social sciences still have to come to grips with even more uncertainties than the natural sciences.

The integrated models, also referred to as policy models in this section, generally begin with an attempt to simulate the effects of specific policies (such as energy taxes, performance standards, or agreements to phase out the use of particular chemicals) on the behavior of overall national and regional economies. The first phase of such an analysis includes an estimate of the energy demands associated with the resulting pattern of economic activity. The mix of fuels required to meet these energy demands is evaluated and the greenhouse gas emissions implied by their consumption is projected over time.

In most current models, the emissions scenarios which result from these calculations are the inputs to a second phase of analysis. The emissions estimate for

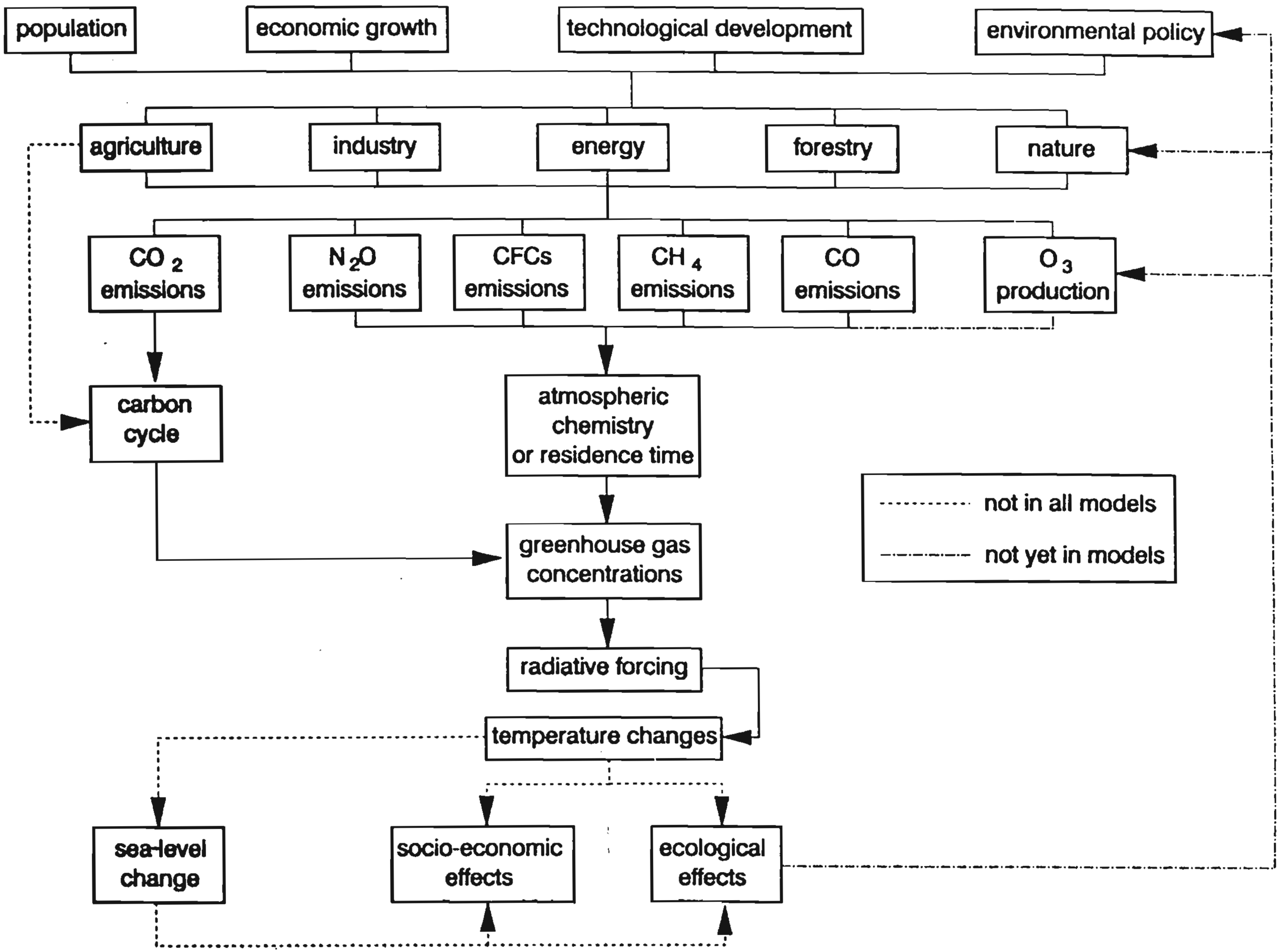


Figure 3.2-1: General Structure Greenhouse Effect Policy Models

each gas becomes an input to a linked set of simplified models that simulate the biological and chemical processes which remove these compounds from the atmosphere. The result is a set of time-dependant atmospheric concentration trajectories for the principle radiatively-active trace gases, also known as greenhouse gases. Some recent models, including those of Nordhaus (1990), Manne and Richels (1989), Nordhaus and Yohe (1983), Edmonds and Reilly (1986), conclude the analysis at this point, using future concentrations of greenhouse gases, especially CO_2, as the proxy for future rates of climatic change.

Some other models, including those of EPA (1989), RIVM (Rotmans et al., 1990) and Mintzer (1987), carry the analysis a step further. In such models, the third phase of the analysis uses the concentration trajectories for greenhouse gases as inputs to simplified (usually one-dimensional) models of the radiation balance of the atmosphere. Such physical models of the atmosphere are used to estimate the global temperature effects of the scenarios defined by the policies identified in the first phase. The temperature effects may be presented in either of two ways. In one approach, the warming effect is stated in terms of the ultimate or equilibrium warming effect of future trace gas concentrations. Alternatively, the projections of future concentration can be used to estimate the realized or observable temperature that may be expected at some future date.

Finally, in some models, including that of Rotmans et al. (1990), the estimates of future temperature change are used to project secondary impacts on climate. The most readily estimated of these impacts are projections of future sea-level rise.

Models of the type described above can be used for a variety of purposes. One approach is to generate a set of scenarios corresponding to a range of future policy options and assess the results. This was the mode of analysis represented in the early studies by Nordhaus and Yohe (1983) and Mintzer (1987). The second approach is to start with a set of specific targets for future emissions reductions, greenhouse gas concentrations, or rates of temperature change and to use the models iteratively until a set of policies can be identified which define scenarios that meet the targets. This is the approach that was taken by the joint Dutch--US team in preparing scenarios for the Intergovernmental Panel on Climate Change.

The models described above vary widely in terms of scope of coverage, computational complexity, degree of abstraction, and ease of use. Nonetheless, there are many similarities and important common elements.

MODELS OF THE ECONOMY AND ENERGY SYSTEM

One of the principle structural differences among the models is in the way that they represent national and regional economies. For the purpose of target setting, the energy models themselves are relevant only because they enable the evaluation of the technological and economic implications of a target. In Chapter 4, particular attention will be paid to these implications. The following discussion focuses on the structural differences among the most prominent policy models in use during the last decade.

Nordhaus and Yohe (1983) used a compact global model (the NY model) to analyze CO_2 emissions over a 125 year period. The NY model uses a generalized Cobb-Douglas production function and represents all economic activity as occurring in a single global "region" with common relationships between the principle economic inputs of land, labor and capital. Energy use is divided into two types, fossil and non-fossil, with a weighted average coefficient of CO_2 emissions. In this simple and transparent model, demand for each type of energy is based entirely on price. Future concentrations of CO_2 are calculated using a simple atmospheric model that assumes a constant "airborne fraction" of CO_2 emissions.

In the more recent work by Nordhaus, the world is still represented as a single region but additional gases are incorporated into the picture. A single consumption function defines future economic activity and simple fixed, time-independent curves are used to estimate the cost of future reductions in emissions. The CO_2-equivalent effect of a buildup of methane, nitrous oxide, and chlorofluorocarbons are calculated. A lagged structure is used to estimate the effect of future trace gas buildup on global surface temperatures. An optimization model is used to determine the most reasonable emissions reduction target, given this unchanging cost structure.

The Manne-Richels (MR) model also uses a simplified production function but limits its scope of coverage to the US economy. The production function is stated in a nested, non-linear form. A non-linear optimization approach is used, assuming deterministic knowledge of the future costs of various energy technologies and fuels as well as the rate of future improvement in efficiency. The key demand parameters are the growth of the labor force (and thus of potential GNP), the constant elasticity of substitution between electric and non-electric energy, and the autonomous (non-price induced) rate of efficiency improvement. The model has been used to estimate the level of tax that would have to be applied to achieve a specified target reduction in CO_2. Like the recent Nordhaus analysis, this model ignores the potential benefits of policies to reduce greenhouse gas emissions and suggests that the costs to the economy of significant (i.e., greater than 20 percent) reductions in CO_2 will be painfully high.

Many of the other models in use today (including the work of EPA (ASF), Rotmans et al. (IMAGE), and Mintzer (MWC)) employ an alternative approach. Each of these three models uses a partial equilibrium macro-economic model (a version of the Edmonds-Reilly (E-R) model) to simulate energy-economy interactions. This model disaggregates global economic activity into nine regions and represents the energy sector through the use of five conventional and four non-conventional energy sources. The key parameters are the rate of non-price induced efficiency improvements, the rate of growth in labor productivity, and the income elasticity of demand for energy (especially in developing countries). In this model, the rate of future growth in energy demand is only loosely coupled to the rate of increase in regional GNP.

The ASF and MWC models also have a secondary capability to model the future near-term growth in energy demand using a set of disaggregated, end-use oriented, sectorally-specific models of individual countries. The estimates developed using these country-specific models can then be used to benchmark the macro-economic analysis developed with the E-R model.

RELATING EMISSIONS TO CLIMATIC CHANGE

The ASF, IMAGE, and MWC models each couple the E-R energy model to models of the chemistry and physics of the atmosphere. The MWC uses the simplest representation of these processes. The carbon cycle can be represented in the MWC either by a fixed airborne fraction model or by a box-diffusion model. Emissions of nitrous oxide are linked directly to the rate of increase in fossil fuel consumption, especially to the use of coal. The rate of increase in methane and tropospheric ozone concentration are estimated exogenously. In the MWC, the production and use of chlorofluorocarbons can be estimated using a region-specific, end-use oriented market development model or by using a policy model that simulates the terms of the Montreal Protocol on Substances that Deplete the Ozone Layer. Future concentrations of long-lived gases (e.g., CFCs, and N_2O) are estimated assuming a fixed atmospheric lifetime for such gases. The impact of future trace gas buildup is evaluated in terms of the ultimate commitment to future warming, using a one-dimensional radiative convective model of the atmosphere.

The IMAGE model incorporates a dynamic carbon cycle model consisting of a realistic ocean and an interactive biosphere to estimate future atmospheric CO_2 concentrations. The biosphere plays an important role as a sink for CO_2. Both the fertilization effect and the carbonization of soils is represented.

The IMAGE model also uses a simplified representation of methane emissions and atmospheric chemistry to estimate future concentrations of methane endogenously in the model. Emissions scenarios for non-methane hydrocarbons are used to estimate the production of carbon monoxide from the oxidation of these compounds. Estimates of the future concentrations of NOx and ozone are used to estimate the rate of change in concentration for OH radicals.

The parameterized radiative convective model used in IMAGE to estimate future temperatures is based on work by Wigley et al. (1987). The resulting estimates of realized temperature changes are used as an input to the sea-level rise module. In the sea-level module, based on work by Oerlemans, the effects of global warming on sea-level rise are determined by the impacts on changing ice caps, on thermal expansion of sea water combined with the observed natural variations in sea level. The effect of the global sea-level change is not yet disaggregated regionally. In addition, however, four elements of inland water management (salt intrusion, seepage, drainage, and lake management) are modeled for the Netherlands.

The Atmospheric Stabilization Model (ASF) was developed by the US EPA. It couples the E-R model of future energy supply and use to a sophisticated, multi-compartment box diffusion model of the carbon cycle. Future emissions of CFCs are estimated using a detailed, regionally disaggregated, end-use oriented model. Future emissions of N_2O are estimated as a function of combustion and fertilizer use. The estimated emissions of CO_2, N_2O, methane, and CFCs are inputs to an elaborate model of atmospheric chemistry developed by Prather (1988). First and second-order relationships are derived from detailed chemical process models and from observations of the atmosphere. A radiative-convective model developed by Hansen and Lacis is used to estimate the realized change in temperature as a function of future greenhouse gas concentrations.

COMPARISON OF MODEL RESULTS

The results of the ASF, IMAGE, and MWC models have recently been compared for a consistent set of scenarios. For this comparison the emission scenarios prepared by the US EPA and the Netherlands RIVM for the Response Strategies working Group of IPCC and a scenario recently developed by Mintzer (1990) have been selected. For the details of these scenarios one is referred to the original reports. The first three IPCC scenarios were designed to achieve a doubling of CO_2 equivalent concentrations relative to pre-industrial levels in the years 2030, 2060, and 2090. These scenarios are named 'high emissions', 'low emissions' and 'control policies', respectively. Two alternate IPCC scenarios were designed to achieve a stabilization of CO_2 equivalent concentrations 'well-below doubling', but for different time horizons. These alternates have been named 'accelerated policies', 'slow' and 'fast', respectively. The sixth, the 'Agressive Policies' scenario explores the options to meet social, economic and political goals while minimizing greenhouse gas emissions. The input emission scenarios, the resulting (equivalent) concentrations and the warming commitment are given in the following tables. The results in terms of equivalent carbon dioxide concentrations and global mean temperature change are given in Figures 3.2-2 and 3.2-3. In the Model of Warming Commitment it has been assumed that 1.3 °C would be in the pipeline due to emissions to date, a parameter that is calculated by the other models.

The ASF and IMAGE models produce small variations in the estimates of future greenhouse gas concentrations and slightly larger variations in the estimates of future temperature change. In general, the agreement among these models is quite good; the variations in results are substantially less than the uncertainty in the physical and economic processes that are represented in the models. Although in the higher scenarios there is good agreement between the results, for the response scenarios Mintzer's model gives somewhat more pessimistic results in terms of carbon dioxide concentrations. In the ASF and IMAGE calculations approximately 50 % reduction of present-day carbon dioxide emissions are necessary to stabilize atmospheric concentrations, Mintzer's model requires larger reductions to achieve this objective. This illustrates the different possible futures as predicted by different types of carbon models, based on the same emissions scenarios. The fact that Mintzer's values for temperature change are somewhat higher than the results of the other models is partly due to the fact that for these calculations tropospheric ozone is also taken into account.

In the case of temperature change estimates, the good agreement is in part due to the very similar basis on which the radiative calculations are made. The existing differences reflect the slight differences in approach applied by Hansen and Ramanathan in the original source models. A somewhat larger difference is due to the difference in handling of feedback effects. This difference is to be expected due to the ongoing disagreement in the scientific community concerning the magnitude and direction of various feedback effects.

As a result of this analysis, it is concluded that integrated policy simulation models can and should play a role in the evaluation of international response options. An important example of such a role is in the evaluation of future policy targets. Application of simulation models of the type described here make it possible to link broad policy targets stated in terms of rates of change in emissions or temperature to specific policy options such as taxes, performance standards, or

Figure 3.2-2: Comparison of Simulation Results of Equivalent CO_2 Concentrations for Three Models

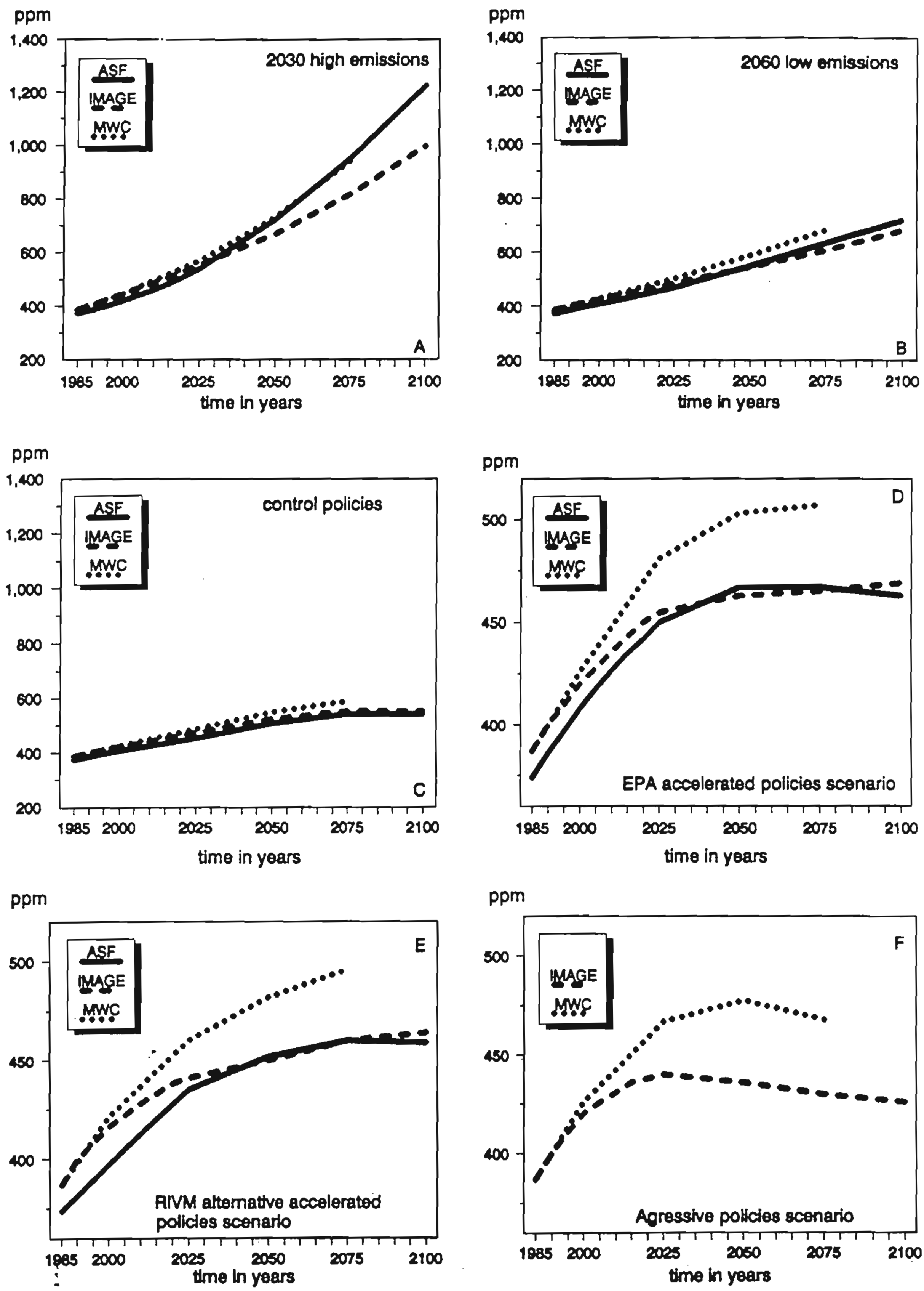
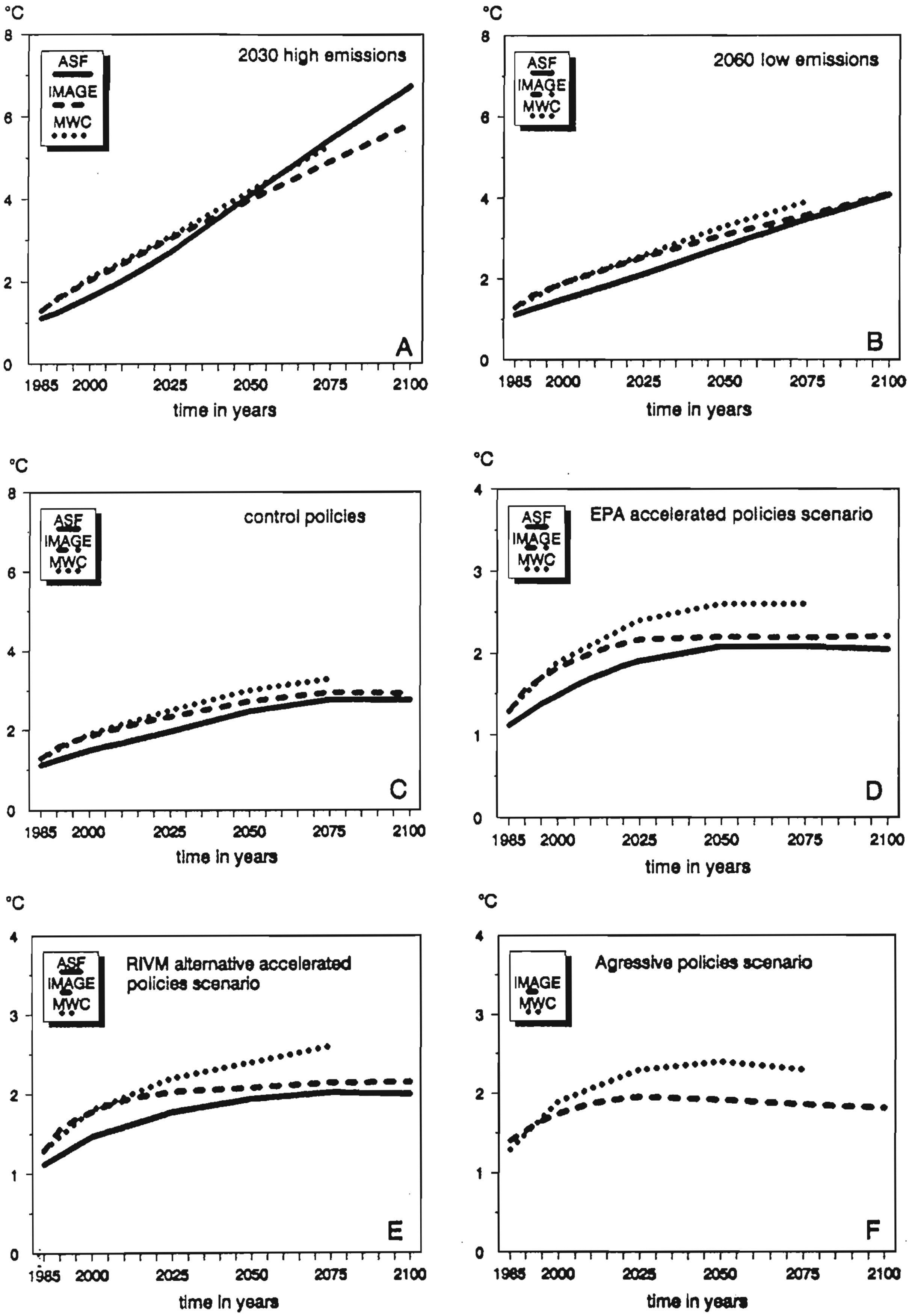


Figure 3.2-3: Comparison of Simulation Results of Equilibrium Global Mean Temperature Increase for 3 °C Climate Sensitivity for Three Models



technological developments. It has not been assessed whether models of the type described here can be used to link targets, stated in terms of such secondary impacts as sea-level rise, to specific policies applied to trace gas emissions or energy use. In the previous section on sea-level rise it has been argued that in principle this possibility exists, although the uncertainties involved increase when wandering further from the causes of climatic change toward the effects. It has also been shown that it is not likely that emission targets derived from maximum allowable sea-level rise will be stricter than those derived from temperature targets.

As they become increasingly integrated into the decision-making process the limitations of policy models should be re-emphasized. They cannot describe the complex non-linear feedback processes associated with cloud formation or ocean atmosphere interaction. Although they do enable the analyst to evaluate indicators of climatic change over time as a function of different emissions scenarios, their absolute accuracy as predictive tools is extremely limited. Their usefulness could be gradually improved over time through the development of simulation experiments and cross-calibration against three-dimensional coupled atmosphere-ocean models.

Despite these limitations, integrated, or policy models may be very useful for target-setting exercises. Such models make it possible to link emissions reduction goals to specified targets such as "tolerable" levels of greenhouse gas concentration or temperature. These targets take many known feedback processes into consideration but do not take into account the possibility of uncontrollable positive climatic feedbacks from the biosphere which could reduce allowable emissions in the future.

Target setting may become an important future use of integrated policy models. Several initial applications suggest the value of such tools for this type of activity. The IPCC scenarios developed by the RIVM and US EPA demonstrate the range of possible outcomes that can be simulated with such tools to support ongoing international discussions. Krause et al., have used similar techniques to suggest a prudent policy of risk minimization. Mintzer's Agressive Policies scenario is an example of a future climate scenario designed to meet other social, economic, and political goals while minimizing the risks of rapid climatic change. The use if policy models to develop and evaluate such scenarios for the purpose of target setting can enrich future discussions of international policy response options and highlight areas where significant additional scientific research is required.

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Table 3.2-1: Fossil and Biotic CO_2 Emissions, Gt C/yr, for Six Scenarios

Scenario	1985	2000	2025	2050	2075	2100
fossil						
2030 doubling	5.4	7.6	10.2	13.8	18.0	22.0
2060 doubling	5.4	6.0	6.8	7.8	8.9	10.5
2090 doubling	5.4	6.0	6.7	7.4	5.3	3.7
well below doubling slow	5.4	6.1	5.6	3.2	3.1	2.9
well below doubling fast	5.4	4.8	4.2	3.9	3.5	2.7
agressive policies	5.4	4.4	3.4	1.4	0.8	-
biotic						
2030 doubling	0.7	1.0	1.4	1.4	0.7	-
2060 doubling	0.7	-0.2	-0.5	-0.3	-0.2	-0.2
2090 doubling	0.7	-0.2	-0.5	-0.3	-0.2	-0.2
well below doubling slow	0.7	-0.2	-0.5	-0.3	-0.2	-0.2
well below doubling fast	0.7	-0.2	-0.5	-0.3	-0.2	-0.2
aggressive policies	1.0	1.0	0.5	0.0	-0.8	-

Table 3.2-2: CO_2 Concentrations, ppm, for Various Scenario-Model Combinations

Scenario-model combination		1985	2000	2025	2050	2075	2100
2030 doubling	MWC	345	375	436	517	614	-
2030 doubling	IMAGE	345	382	451	531	635	761
2030 doubling	ASF	345	371	437	540	679	860
2060 doubling	MWC	345	367	405	449	502	-
2060 doubling	IMAGE	345	377	423	464	509	568
2060 doubling	ASF	345	366	398	440	492	558
2090 doubling	MWC	345	367	405	448	483	-
2090 doubling	IMAGE	345	374	414	451	478	490
2090 doubling	ASF	345	372	398	437	469	485
well below doubling slow	MWC	345	367	403	421	429	-
well below doubling slow	IMAGE	345	372	399	406	422	421
well below doubling slow	ASF	345	365	393	407	413	420
well below doubling fast	MWC	345	363	386	404	420	-
well below doubling fast	IMAGE	345	369	387	395	408	416
well below doubling fast	ASF	345	363	381	395	407	415
agressive policies	MWC	345	370	397	405	397	-
agressive policies	IMAGE	348	368	381	378	373	-

Table 3.2-3: CH_4 Emissions, Tg CH4/yr, for Six Scenarios

Scenario	1985	2000	2025	2050	2075	2100
2030 doubling	541	614	761	899	992	1063
2060 doubling	541	577	665	723	732	736
2090 doubling	541	558	608	622	562	505
well below doubling slow	541	566	583	553	530	502
well below doubling fast	541	566	583	553	530	502
aggressive policies	-	-	-	-	-	-

Table 3.2-4: Anthropogenic Emissions of CO, Tg C/yr, for Six Scenarios

Scenario	1985	2000	2025	2050	2075	2100
2030 doubling	537	616	781	882	839	928
2060 doubling	537	428	336	285	280	281
2090 doubling	537	427	336	285	274	270
well below doubling slow	541	411	341	287	285	281
well below doubling fast	541	411	341	287	285	281
aggressive policies	-	-	-	-	-	-

Table 3.2-5: CH_4 Concentrations, ppb, for Various Scenario-Model Combinations

Scenario-model combination		1985	2000	2025	2050	2075	2100
2030 doubling	IMAGE	1736	2131	2819	3339	3681	3919
2030 doubling	ASF	1600	1884	2489	3158	3623	3914
2060 doubling	IMAGE	1736	1903	2058	2268	2392	2389
2060 doubling	ASF	1600	1777	2097	2405	2504	2456
2090 doubling	IMAGE	1736	1880	2008	2143	1978	1573
2090 doubling	ASF	1600	1745	1926	2057	1913	1572
well below doubling slow	IMAGE	1736	1878	1924	1820	1609	1407
well below doubling slow	ASF	1600	1671	1893	1799	1627	1440
well below doubling fast	IMAGE	1736	1878	1924	1820	1609	1407
well below doubling fast	ASF	1600	1671	1893	1799	1627	1440
aggressive policies	MWC	1650	1805	2029	2198	2311	-

Table 3.2-6: N_2O Emissions, Tg N/yr, for Six Scenarios

Scenario	1985	2000	2025	2050	2075	2100
2030 doubling	12.5	14.2	16.4	17.3	17.3	17.6
2060 doubling	12.5	13.1	13.9	14.1	14.4	14.6
2090 doubling	12.5	12.9	13.2	13.0	12.5	12.2
well below doubling slow	12.5	12.9	13.1	12.7	12.5	12.3
well below doubling fast	12.5	12.9	13.1	12.7	12.5	12.3
aggressive policies	13.2	9.4	6.9	0	0	-

Table 3.2-7: N_2O Concentrations, ppb, for Various Scenario-Model Combinations

Scenario-model combination		1985	2000	2025	2050	2075	2100
2030 doubling	MWC	-	327	366	403	436	-
2030 doubling	IMAGE	312	323	349	378	405	429
2030 doubling	ASF	300	314	343	374	403	429
2060 doubling	MWC	-	325	359	389	415	-
2060 doubling	IMAGE	312	322	339	356	372	387
2060 doubling	ASF	300	312	333	352	368	383
2090 doubling	MWC	-	325	357	384	407	-
2090 doubling	IMAGE	312	321	337	351	361	367
2090 doubling	ASF	300	312	331	347	358	366
well below doubling slow	MWC	-	325	357	384	406	-
well below doubling slow	IMAGE	312	320	340	349	358	366
well below doubling slow	ASF	300	312	331	345	356	364
well below doubling fast	MWC	-	325	357	384	406	-
well below doubling fast	IMAGE	312	321	340	349	358	366
well below doubling fast	ASF	300	312	331	345	356	364
aggressive policies	MWC	303	308	312	308	304	-

Table 3.2-8: CFC-11 emissions, Gg/yr, for six scenarios

Scenario	1985	2000	2025	2050	2075	2100
2030 doubling	278	305	245	252	253	253
2060 doubling	278	302	227	223	223	223
2090 doubling	278	197	11	0	0	0
well below doubling slow	278	197	11	0	0	0
well below doubling fast	278	197	11	0	0	0
aggressive policies	335	190	6	1	1	-

Table 3.2-9: CFC-11 concentrations, ppt, for various scenario-model combinations

Scenario-model combination			1985	2000	2025	2050	2075	2100
2030 doubling		MWC	230	370	540	630	700	-
2030 doubling	IMAGE/	ASF	220	370	498	561	607	640
2060 doubling		MWC	230	370	530	600	650	-
2060 doubling	IMAGE/	ASF	220	369	486	531	557	574
2090 doubling		MWC	230	340	300	210	150	-
2090 doubling	IMAGE/	ASF	220	346	301	205	137	91
well below doubling slow		MWC	230	340	300	210	150	-
well below db. slow	IMAGE/	ASF	220	346	301	205	137	91
well below doubling fast		MWC	230	340	300	210	150	-
well below db. fast	IMAGE/	ASF	220	346	301	205	137	91
aggressive policies		MWC	230	380	330	240	170	-

Table 3.2-10: CFC-12 emissions, Gg/yr, for six scenarios

Scenario	1985	2000	2025	2050	2075	2100
2030 doubling	362	376	303	314	316	316
2060 doubling	362	372	279	278	278	278
2090 doubling	362	262	10	0	0	0
well below doubling slow	362	262	10	0	0	0
well below doubling fast	362	262	10	0	0	0
aggressive policies	460	182	4	1	1	-

Table 3.2-11: CFC-12 concentrations, ppt, for various scenario-model combinations

Scenario-model combination			1985	2000	2025	2050	2075	2100
2030 doubling		MWC	400	650	960	1200	1400	-
2030 doubling	IMAGE/	ASF	375	616	885	1083	1255	1400
2060 doubling		MWC	400	640	970	1100	1300	-
2060 doubling	IMAGE/	ASF	375	615	867	1034	1169	1281
2090 doubling		MWC	400	600	590	500	420	-
2090 doubling	IMAGE/	ASF	375	588	592	498	415	345
well below doubling slow		MWC	400	600	590	500	420	-
well below db. slow	IMAGE/	ASF	375	588	592	498	415	345
well below doubling fast		MWC	400	600	590	500	420	-
well below db. fast	IMAGE/	ASF	375	588	592	498	415	345
aggressive policies		MWC	400	630	610	520	440	-

Table 3.2-12: CO_2 equivalent concentrations, ppm, for various scenario-model combinations

Scenario-model combination		1985	2000	2025	2050	2075	2100
2030 doubling	MWC	-	446	569	733	943	-
2030 doubling	IMAGE	388	446	554	672	820	997
2030 doubling	ASF	374	421	540	724	954	1224
2060 doubling	MWC	-	429	504	589	684	-
2060 doubling	IMAGE	388	426	487	546	607	682
2060 doubling	ASF	374	410	472	551	635	721
2090 doubling	MWC	-	426	487	550	591	-
2090 doubling	IMAGE	388	422	475	524	553	553
2090 doubling	ASF	374	408	455	509	544	542
well below doubling slow	MWC	-	426	481	503	507	-
well below doubling slow	IMAGE	388	420	455	463	465	469
well below doubling slow	ASF	374	408	449	466	467	463
well below doubling fast	MWC	-	421	460	482	496	-
well below doubling fast	IMAGE	388	416	441	450	460	464
well below doubling fast	ASF	374	405	436	452	461	459
aggressive policies	MWC	-	426	467	478	468	-
aggressive policies	IMAGE	388	420	440	436	431	-

Table 3.2-13: Global average equilibrium temperature increase from pre-industrial levels, 3°C, for various scenario-model combinations

Scenario-model combination		1985	2000	2025	2050	2075	2100
2030 doubling	MWC	1.30	2.10	3.10	4.20	5.30	-
2030 doubling	IMAGE	1.41	2.02	2.95	3.79	4.65	5.50
2030 doubling transient	IMAGE	0.66	1.03	1.70	2.37	3.07	3.75
2030 doubling	ASF	1.12	1.63	2.73	4.10	5.46	6.74
2060 doubling	MWC	1.30	1.90	2.60	3.30	3.90	-
2060 doubling	IMAGE	1.41	1.82	2.39	2.89	3.35	3.85
2060 doubling transient	IMAGE	0.66	1.00	1.49	1.93	2.32	2.70
2060 doubling	ASF	1.12	1.51	2.13	2.82	3.48	4.08
2090 doubling	MWC	1.30	1.90	2.50	3.00	3.30	-
2090 doubling	IMAGE	1.41	1.78	2.29	2.71	2.94	2.95
2090 doubling transient	IMAGE	0.66	0.98	1.40	1.74	1.99	2.09
2090 doubling	ASF	1.12	1.49	1.96	2.47	2.76	2.75
well below doubling slow	MWC	1.30	1.90	2.40	2.60	2.60	-
well below doubling slow	IMAGE	1.41	1.75	2.10	2.18	2.20	2.24
well below doubling slow transient	IMAGE	0.66	0.97	1.33	1.50	1.56	1.61
well below doubling slow	ASF	1.12	1.49	1.91	2.08	2.08	2.05
well below doubling fast	MWC	1.30	1.80	2.20	2.40	2.60	-
well below doubling fast	IMAGE	1.41	1.71	1.97	2.06	2.14	2.19
well below doubling fast transient	IMAGE	0.66	0.98	1.33	1.50	1.56	1.61
well below doubling fast	ASF	1.12	1.47	1.78	1.94	2.02	2.00
aggressive policies	MWC	1.30	1.90	2.30	2.40	2.30	-
aggressive policies	IMAGE	1.41	1.75	1.96	1.92	1.86	1.82
aggressive policies transient	IMAGE	0.71	0.97	1.24	1.34	1.36	1.36

3.3. GLOBAL WARMING POTENTIAL

J. ROTMANS, D.A. LASHOF, AND M.G.J. DEN ELZEN

INTRODUCTION

Specific climate policies must ultimately be developed to limit emissions of greenhouse gases if the targets are to be achieved. Tradeoffs among the various greenhouse gases should be considered in formulating such policies, either implicitly in establishing performance standards or emission limits for individual gases, or explicitly by setting emission limits using a "basket of gases" approach. In order to develop environmental long-term targets with respect to climate change, an index to compare the temperature increasing effect of greenhouse gas emissions can be useful. This section presents the concept of a Global Warming Potential (GWP) of radiatively important gases, as a greenhouse pendant to the ozone depletion potential (ODP).

The Need for an Index

Greenhouse gases are most commonly compared in terms of the direct radiative impact of a given change in their concentrations or their contribution to increases in radiative forcing over a particular period (Ramanathan et al., 1985). Such comparisons, however, do not accurately reflect the relative impact of a given quantity of emissions over time. The need for an index of Global Warming Potential (GWP) of emissions that would take into arcount differences in atmospheric lifetimes and indirect impacts of emissions was discussed by Swart et al. (1989a) and mentioned in the Noordwijk declaration (1989).

The most ambitious use of such an index would be to establish emission reduction requirements in terms of the total GWP of a set of gases, rather than in terms of requirements for each gas individually. This approach would be similar to the use of Ozone Depletion Potential (ODP) in the Montreal Protocol, but may be more difficult to implement in the case of greenhouse gases.

Another use of such an index would be for comparing the greenhouse implications of different technologies/fuel cycles by expressing the total emissions associated with accomplishing a particular task on a CO_2-equivalent basis. For example, DeLuchi et al. (1987) examined the implications of different transportation fuels per verhicle mile travelled, and Wilson (1990) estimated emissions per kWh of electricity generated for a number of fuel-technology combinations.

Previous Work on ODP and GWP

Analysis of the relative impact of different greenhouse gases arose in two different contexts over the last few years. Researchers concerned with CFCs and other halocarbons, including substitutes for fully halogenated CFCs, examined halocarbon GWPs (Rogers and Stephens, 1988; Fisher et al., 1990) in analogous fashion to the ozone depletion potential (ODP) defined by Wuebbles (1981). At the same time, the importance of examining the total greenhouse implications of various energy technologies/fuel cycles has been recognized. DeLuchi et al. (1987) estimated equivalency factors for CH_4 and CO_2 using simple descriptions of their atmospheric retentions over a 75-year period. Okken and Kram (1989) used the relative contributions to forcing increases during the 1980s as a basis for expressing emissions on a CO_2-equivalent basis. Lashof and Ahuja (1990) introduced a general definition of the global warming potential relative to carbon dioxide. Derwent (1990) presented GWPs for three different time horizons, and introduced estimates of the indirect global warming potential of NO_x and non-methane hydrocarbon emissions. Finally, Rotmans and den Elzen (1990) produced GWPs, using a somewhat different definition, based on simulations with the integrated assessment model IMAGE.

METHODOLOGY

The radiative forcing from a given greenhouse gas emission varies over time as a function of the atmospheric residence time of that gas, and of subsequent emissions of that and other gases. Any method of collapsing these relationships into a single index will require assumptions about background concentrations and emission scenarios and will be arbitrary to some extent. To achieve a direct relationship between an emission of a greenhouse gas and the corresponding temperature response, both analytical and model-based methods can be used. Analytical approaches have the advantage of being transparent, but simplify the many nonlinear relationships within the atmosphere. Model-based or numerical, approaches can analyze the implications of emission scenarios which influence the radiative forcings and residence times, needed to calculate GWPs. This can be accommodated by superposing emission pulses of each gas on baseline emission scenarios and numerically performing the integration in an assessment model. The disadvantage of using computer models is that they can be opaque and cumbersome to use. Both analytical and numerical methods will be treated in the following sections.

DEFINITION OF THE GLOBAL WARMING POTENTIAL (GWP)

The definition of GWP introduced by Lashof and Ahuja (1990) can be expressed as follows:

$$GWP_i(T,r) = \frac{\int_0^T [a_i(t)\ c_i(t)\ e^{-rt}dt]}{\int_0^T [a_c(t)\ c_c(t)\ e^{-rt}dt]} \qquad (3.3.1)$$

where,

T	=	time horizon, in years;
$a_i(t)$	=	the instantaneous radiative forcing due to emission of one unit of gas i, in °C/ppm;

$c_i(t)$	=	the fraction of the radiative forcing from gas i remaining at time t; and
r	=	the discount rate for weighting future forcing, in percent.

The corresponding values for CO_2 are in the denominator. The discount rate is a method of weighting future forcings through the reduction of the effective atmospheric residence time of gases.

An alternative definition is given by Rotmans and den Elzen (1990):

$$GWP_i(T) = \frac{cf_i * a_i * \int_0^T [em_i(t) - rm_i(t)dt]}{cf_c * a_c * \int_0^T [em_c(t) - rm_c(t)dt]} \qquad (3.3.2)$$

where,

cf_i	=	conversion factor of trace gas i, in ppm/Gt;
a_i	=	radiative forcing factor of trace gas i, in °C/ppm;
T	=	time horizon, in years;
$em_i(t)$	=	global emission of trace gas i at time t, in Gt/yr; an emission pulse of 1 or 10^{-3}Gt for t=0 and 0 thereafter
$rm_i(t)$	=	atmospheric removal of trace gas i at time t, in Gt/yr.

cf_c, a_c, l(c), em_c, rm_c are the corresponding values for CO_2 in the denominator. The definitions of (3.3.1) and (3.3.2) are identical for a discount rate r = 0. A third definition is given by Fisher et al. (1990), based on reaching equilibrium following a step-function change in emissions. For constant residence times, linear radiative forcing, T approaching infinity, and r = 0, these three definitions are identical.

The GWP of greenhouse gases can also be calculated by superposing emission pulses of each gas on emission scenarios (Rotmans and den Elzen, 1990):

$$GWP_i(T) = \frac{\int_0^T [DT_i^{im}(t) - DT_i^{wim}(t)]dt}{\int_0^T DT_{CO2}^{im}(t)dt} \qquad (3.3.3)$$

where,

$DT_i^{im}(t)$	=	equilibrium temperature change with an emission pulse of trace gas i, at time t, in °C;
$DT_i^{wim}(t)$	=	equilibrium temperature change without an emission pulse, at time t, in °C;
$DT^i_{CO2}(t)$	=	equilibrium temperature change with an emission, in °C; pulse of CO_2, at time t.

The definitions given in (3.3.1), (3.3.2) and (3.3.3) can be solved analytically as well as through the use of integrated assessment models. The results will be more transparent for analytical solutions but the processes then have to be approximated by simple functions.

INTEGRATED FORCING OF CFCS AND N_2O

For CFCs, the assumptions of constant radiative forcing per molecule and exponential decay of concentrations are quite reasonable. Destruction of N_2O, which also occurs almost solely in the stratosphere, is also well described by an exponential function. However, the radiative forcing from N_2O depends on its own concentration as well as the concentration of CH_4, because of saturation and overlap of the absorption bands. The different calculations in this part are based on the radiative forcing equations given by Wigley (1987), Ramanathan et al. (1985), and Hansen et al. (1988), with methane concentrations fixed at 1.70 ppm.

CO_2 INTEGRATED FORCING

Atmospheric retention of CO_2 is complex. Rather than being destroyed, CO_2 is transferred into other reservoirs, e.g., oceans and biota, from which it can return to the atmosphere. The result is that CO_2 removal cannot be described by a simple residence time. After an initial uptake of CO_2 in the mixed layer, i.e., approximately the top 100 meters, of the ocean, further CO_2 removal requires transport of excess carbon to the deep ocean, a process that occurs much more slowly. Uncertainty about the carbon cycle itself leads to a range of possible values for atmospheric CO_2 retention. It is generally believed that the oceans are the dominant sink for anthropogenic CO_2 emissions. Ocean models typically do not absorb as much CO_2 as is necessary to balance the carbon budget. This discrepancy increases with increasing estimates of emissions from deforestation.

Recently Tans et al. (1990) combined measurements of the geographic distribution of atmospheric CO_2 concentrations, direct measurements of the partial pressure of CO_2 in the oceans, and an atmospheric transport model. They concluded that the oceans are taking up less than half as much CO_2 as most carbon cycle models suggest, implying that there should be a substantial terrestrial carbon sink in the Northern Hemisphere. While this result is controversial, it points out that estimates of atmospheric retention of CO_2 based on current models are uncertain. An indication of the uncertainty can be obtained by numerically calculating CO_2 retention using any of a variety of carbon cycle models. It is important to recognize that none of the available models is consistent with the analysis of Tans et al. (1990).

CH_4 INTEGRATED FORCING

The GWP of chemically active gases is complicated by their transformations in the atmosphere and their influence on tropospheric chemistry. At least three impacts can be distinguished. First, as carbon compounds are oxidized in the atmosphere the reaction products - carbon dioxide and stratospheric water vapor - are themselves greenhouse gases. Second, greenhouse gases, particularly tropospheric ozone, may be generated as a result of the chemical interactions. Third, the lifetimes of greenhouse gases may be altered by perturbations of tropospheric chemistry, in particular depression of OH concentrations.

Methane generates indirect global warming potential through all three of these mechanisms, in addition to its direct greenhouse forcing. All methane is eventually oxidized to CO_2 in the atmosphere, but if the methane were generated by decay of organic matter recently produced by photosynthesis, then this does not represent a net addition to atmospheric CO_2. The GWP of methane must therefore distinguish between fossil (natural gas, coal seam) and living (cattle, rice paddies, landfills) methane sources. For fossil sources the integrated forcing from CO_2 should be added to that from methane.

The other final oxidation product of any hydrocarbon is water vapor. In the troposphere water vapor concentrations are controlled by exchange with the surface and will not be significantly affected by emissions. The tropopause is a very effective trap for water, however, so the stratosphere is strongly influenced by in situ sources. Long-lived hydrocarbons (and HCFCs) can reach the stratosphere before being oxidized and have a significant impact on the stratospheric water budget. Wuebbles et al. (1989) estimated that this increases the direct forcing from methane by 30 %.

The reactions in which methane participates before it is completely oxidized to carbon dioxide and water also lead to net ozone formation. While net ozone production is strongly dependent on background concentrations of NO_x and other hydrocarbons, most of the volume of the troposphere is characterized by relatively low concentrations of these compounds. Estimates of the enhancement of methane's direct forcing from ozone production vary from 60 % (Derwent, 1990) to 40 % (Lashof and Ahuja, 1990). The latter value is based on calculations of Thompson et al. (1989) and Prather (1988). Here a value of 40 % is adopted, yielding a total enhancement due to net ozone formation and stratospheric water vapor of 70 %. This is comparable to other estimates of 76 % given by Owens et al. (1985) and 58 % given by Brasseur and de Rudder (1987).

Methane oxidation also depresses OH concentrations, therefore increasing its own atmospheric lifetime. Thompson and Cicerone (1986) calculated that a 100 % increase in the flux of methane leads, in equilibrium, to more than 150 % increase in its concentration. The lifetime of other species oxidized by OH will also increase, notably the HCFCs, which are strong greenhouse gases. If methane concentrations are 1.7 ppm and HCFC-22 concentrations are 1 ppb, reasonable values for early in the next century (Lashof and Tirpak, 1990), and the concentration of each were increased 1 % due to OH depletion, the added instantaneous forcing from the increase in HCFC-22 would be 30 % of the added forcing from this increase in CH_4.

The global warming impact of excess CH_4 and HCFC-22 due to OH depletion should be added to the direct CH_4 forcing and the indirect forcing from ozone formation. Based on the calculations for current conditions discussed above, this amounts to a 50 % enhancement of the direct forcing from CH_4. Increasing tropospheric methane will proportionally increase the water vapor produced by methane oxidation in the stratosphere. therefore, the water vapor impact due to methane should be multiplied by 1.4. The water vapor contribution from HCFC-22 is negligible compared to that from methane. The terms contributing to the GWP of methane are summarized in Table 3.3-1.

Table 3.3-1: Contributions to Forcing from Methane Emissions for a Time Horizon of 100 Years

FACTOR TIME HORIZON IS 100 YEARS	INTEGRATED FORCING ($W\ m^{-2}\ yr\ Pmole^{-1}$)
Direct CH_4	20.4
Ozone formation	8.8
Stratospheric water	6.2
CH_4 and HCFC-22 from OH depletion	10.6
Stratospheric H_2O from OH depletion	2.4
CO_2 formation (fossil only)	4.2
TOTAL, living and fossil	52.6
TOTAL, living	48.4

INDIRECT FORCING FROM CO, NMHCS AND NO_x

The global warming potential due to CO, NO_x, and non-methane hydrocarbon (NMHC) emissions involves considerations similar to those involved in the indirect impacts of methane emissions, except there will be no direct forcing or direct contribution to stratospheric water vapor. Thompson et al. (1989) found that the sensitivity of OH and O_3 to CO emissions was - 0.21 and 0.11 respectively. The OH depletion will contribute to greenhouse forcing both by increasing the tropospheric concentrations of CH_4 and HCFCs and by increasing water vapor formation in the stratosphere from methane oxidation. Table 3.3-2 lists the terms contributed to CO forcing, based on the values from Thompson et al. (1989).

Table 3.3-2 Contributions to Forcing from Carbon Monoxide Emissions for a Time Horizon of 100 Years

FACTOR TIME HORIZON IS 100 YEARS	INTEGRATED FORCING ($W\ m^{-2}\ yr\ Pmole^{-1}$)
Ozone formation	3.5
CH_4 and HCFC-22 from OH depletion	5.0
Stratospheric H_2O from OH depletion	1.3
CO_2 formation (fossil only)	4.2
TOTAL, fossil	14.0
TOTAL, living	9.8

The impact of NMHC emissions was not tested by Thompson et al. (1989), but impacts on ozone concentrations were estimated by Derwent (1990) to be 0.6 ppm/Pmole (given an average molecular weight of 16.67 implied by his assumption that 1 kg NMHC is oxidized to 3.14 kg CO_2). Given the above assumption with respect to ozone forcing, which is equivalent to 10 W m^{-2} ppm^{-1}, implying a forcing of 6 W m^{-2} yr $Pmole^{-1}$ for living NMHC emissions.

Estimating the impact of NO_x emissions may be the most problematic of all gases considered here, because the results depend strongly on the spatial distribution of the emissions as well as on the perturbations to OH and O_3. Thompson et al. (1989) found that NO_x emissions generate substantial quantities of OH throughout most of the troposphere. In most regions increased destruction of CH_4 and HCFCs would more than compensate for increased O_3 formation, implying that increased NO_x emissions could have a net cooling effect. On the other hand, in heavily polluted urban areas, where most of the emissions originate, NO_x is much less efficient at perturbing tropospheric chemistry. Increased NO_x has a negligible or negative impact on OH in these regions according to Thompson et al. (1989). Based on the foregoing, the conclusion is that an "average" GWP for NO_x emissions is not meaningful. Understanding the climatic implications of NO_x emissions will require more detailed analysis and may always require consideration on a case-by-case basis.

ANALYTICAL APPROACH

The definitions given above can be solved analytically. This can be accomplished by approximating the radiative forcings with representative radiative forcing values and approximating the atmospheric removal processes with simple (exponential or multiple exponential) forms. For the CFCs and N_2O, it is assumed that their removal processes from the atmosphere are in proportion only to its concentration, represented by a negative exponential function. The fraction remaining at time t is then: e^{-t/Γ_1}, where Γ_1 is the average residence time. The cumulative forcing that each unit of emission will contribute over its atmospheric life is $a_1\Gamma_1$, where a_1 is the average radiative forcing.

As to CO_2 the removal process is not well described by a single process. Therefore, Lashof and Ahuja (1990) follow Maier-Reimer and Hasselmann (1987), who used a sum of five exponentials to fit the response of their General Circulation Model to an instantaneous injection of CO_2 equal to 25 % of the current atmospheric burden. Using their fit,

$$c_C(t) = \sum_{0}^{4} \alpha_j e^{-t/\Gamma_1} e^{-rt} : \quad \sum_{0}^{4} \alpha_j = 1 \qquad (3.3\text{-}4)$$

where,

$c_C(t)$	=	fraction of CO_2 remaining at time t;
α_0-α_4	=	0.131, 0.201, 0.321, 0.249, 0.098;
Γ_0-Γ_4	=	inf., 362.9, 73.6, 17.3, 1.9; and
r	=	the discount rate.

For T = inf., r = 0 these parameters yield $\int c_C(t)dt$ = inf. Γ_0 is arbitrarily set at 1000 years, which effectively discounts very long term retention of a small fraction of the original emissions.

The integrated forcing from CO_2 is very sensitive to the choice of r_0, or alternatively, to the choice of T or r. Table 3.3-3 gives results for a range of values for T and r. The table is quasi-symmetric, revealing that limiting the time horizon to T gives nearly the same result as applying a discount rate of $r = 1/T$.

Another possibility of representing the atmospheric removal process of CO_2 is by introducing a remnant fraction, defined as the fraction of the CO_2 emission that remains in the atmosphere. Rotmans and den Elzen (1990) simply assumed this remaining fraction to be constant at 60 %.

As for CH_4, it is not very realistic to suppose that the atmospheric removal of CH_4 is proportional to the atmospheric concentration of CH_4, as described earlier. The chemical interactions with CO and OH, as well as the enhancement of the direct radiative forcing of methane by stratospheric water vapor, ozone formation, and OH depletion should be taken into account. To roughly account for increases in the atmospheric lifetime of methane, and for the enhanced radiative forcing of methane, these processes are parameterized (Table 3.3-1). In this way, the GWP of CH_4 is determined by a negative exponential relationship, reflecting the atmospheric removal, combined with a parameterized representiation of increases in atmospheric lifetime of CH_4, and the enhanced radiative forcing.

MODELING APPROACH

An alternative method of estimating the GWPs of greenhouse gases is using integrated greenhouse models, which relate emissions to global temperature rise. Presently there are three such integrated greenhouse models: the Atmospheric Stabilization Framework of the U.S. Environmental Protection Agency (EPA, 1989), the Integrated Model for the Assessment of the Greenhouse Effect (IMAGE) of the National Institute of Public health and Environmental Protection (Rotmans et al., 1990a) and the Model of Warming Commitment of the World Resource Institute (Mintzer, 1987), which have been compared in Section 3.2. The models produced very similar concentration and temperature results for the same emission inputs for different gases, even though different approaches have been chosen for the representation of the carbon cycle, atmospheric chemistry processes, and other model aspects (see Section 3.2). Therefore, notwithstanding the fact that these models contain many uncertainties, international consensus on assumptions and methodologies should be possible, based on the best available knowledge (Swart et al., 1989b).

In this section the Integrated Model for the Assessment of the Greenhouse Effect, IMAGE, is used to determine the relative radiative potential of the greenhouse gases CO_2, CH_4, N_2O, and CFCs.

For each trace gas stabilizing emission scenarios have been developed, resulting in steady-state concentrations in the second half of the next century. In each case two stabilization scenarios are compared in pairs, one with and one without an emission pulse of a specific trace gas. An example of several of these emission stabilization scenarios is given in Figure 3.3-2, where a CO_2 emission scenario with and without pulse is depicted. Figure 3.3-3 gives the concentrations in pairs for CH_4. Two equilibrium temperature responses are simulated, again with and without emission pulse. By subtracting these two temperature responses,

Table 3.3-3: **Excess CO_2 Concentration Integral (ppm-yr)**

r/T	infinite	1000	500	100	50	20	10
0	infinite	227.4	148.1	52.7	31.8	15.3	8.4
0.001	210.9	161.5	123.3	50.5	31.1	15.1	8.3
0.005	73.5	73.3	70.8	43.0	28.6	14.6	8.2
0.01	46.3	46.3	46.2	35.8	25.7	13.9	8.0
0.02	28.3	28.3	28.3	26.2	21.2	12.8	7.6
0.05	14.0	14.0	14.0	13.9	13.2	10.0	6.7
0.1	7.8	7.8	7.8	7.8	7.8	7.0	5.4

the influence of the scenario choice is reduced, yielding the net temperature effect. This net temperature effect is integrated from time 0 (in 1900) to the atmospheric lifetime of the greenhouse gas (or time horizon in case of CO_2). Dividing the integrated net temperature effect of CH_4, N_2O, CFC-11 and CFC-12 by that of CO_2, gives the GWP.

Specifically to simulate the GWP concept, the usual simulation time span, covering 200 years, from 1900 to 2100, is extended to the year 2500. The year 2500 relates to the chosen "endless" CO_2 atmospheric residence time of 500 years.

For CO_2 the atmospheric stabilization scenario is fed into the integrated carbon cycle module of IMAGE, consisting of the coupled ocean, terrestrial biota, and deforestation module. The latter module is described extensively in Swart and Rotmans (1989).

As Figure 3.3-2 shows the stabilization scenario includes a sharp decrease of fossil fuels as well as a moderate deforestation scenario.

In the CH_4-CO-OH cycle module of IMAGE the concentrations of OH radicals and CO are maintained at a constant 1985 level. A substantial fraction of the increase in the methane concentration in the atmosphere is most probably caused by CO competing for OH radicals (Rotmans et al., 1990b). To measure this influence of CO on CH_4, also an emission pulse of CO; 1 Gt in 1986 only, is generated. Because methane emissions have an increasing effect on tropospheric ozone and stratospheric water vapor concentrations, the temperature effect of CH_4 is assumed to be enhanced by 70 % (Lashof and Ahuja, 1990), represented by a factor 1.7. Then the temperature effects of CH_4 with and without a CO emission pulse are compared to each other.

The CFCs module in IMAGE addresses next to CFC-11 and CFC-12 also CFC-113, CFC-114 and CFC-115, Halon-1211 and Halon-1301, HCFCs and HFCs, CH_3CCl_3 and CCl_4, includes a delay time between production and emission, which is assumed to be different for different applications. The extra pulse is added to the emission and not to the production, and so has no time delay.

Finally N_2O concentrations are computed from emissions by taking into account an exponentially delayed emission mechanism, and a constant atmospheric

Figure 3.3-1: The Integrated Model for the Assessment of the Greenhouse Effect (IMAGE)

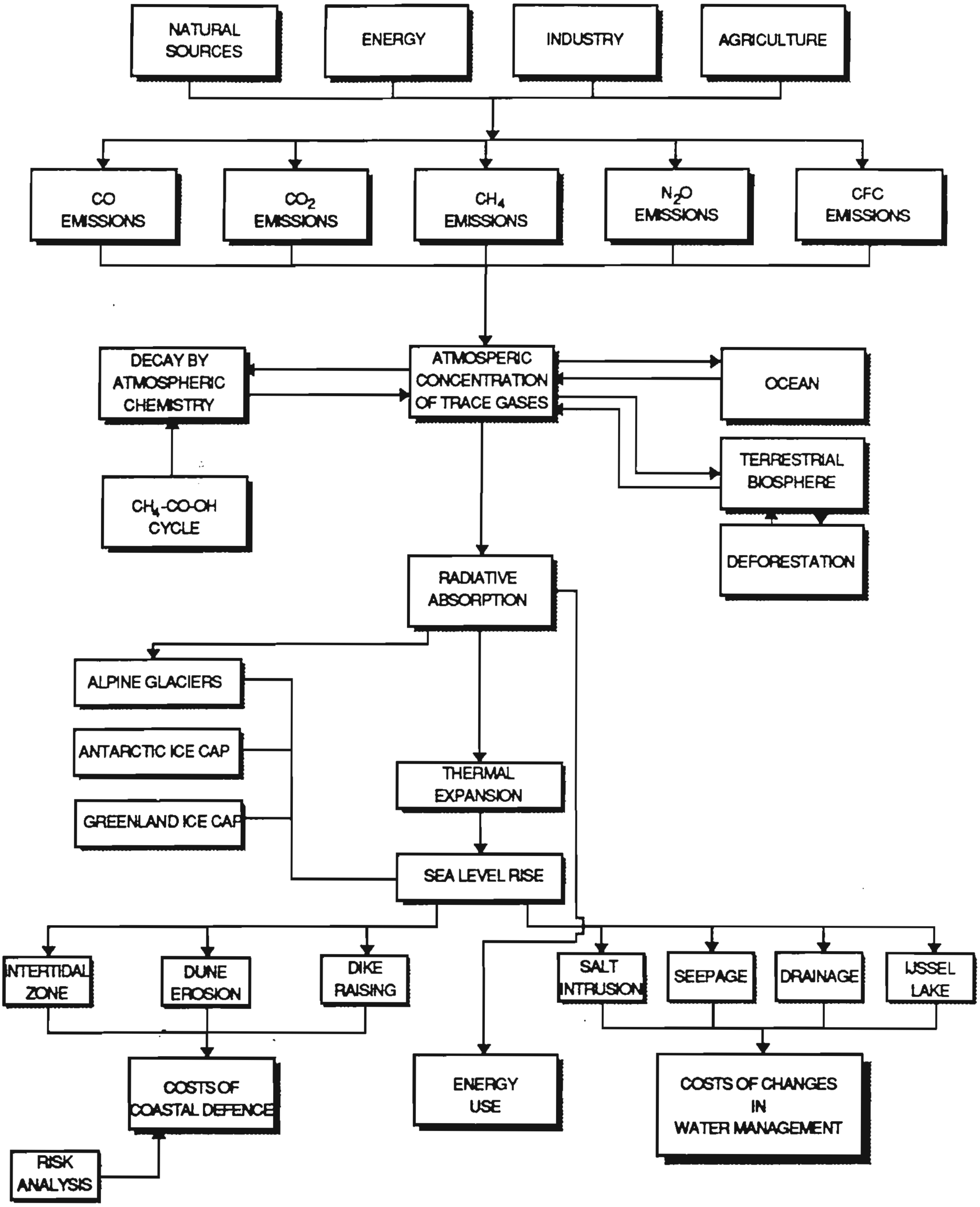


Figure 3.3-2: CO_2 Emission Scenario with and without Pulse

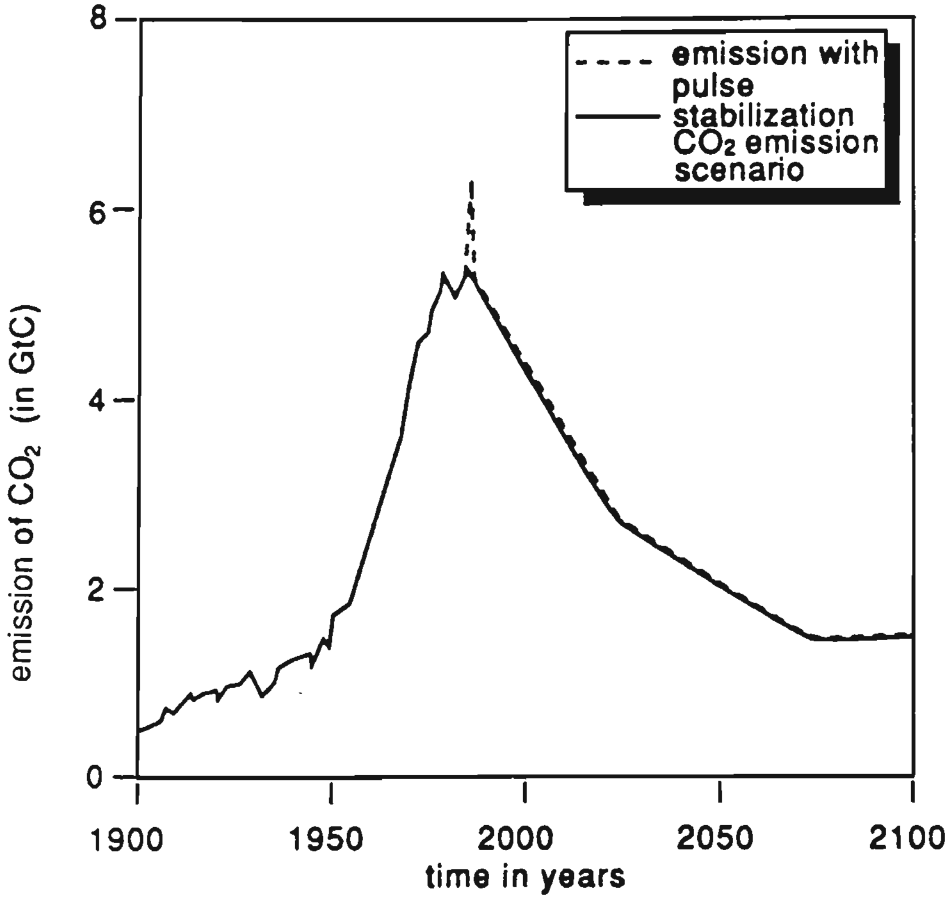
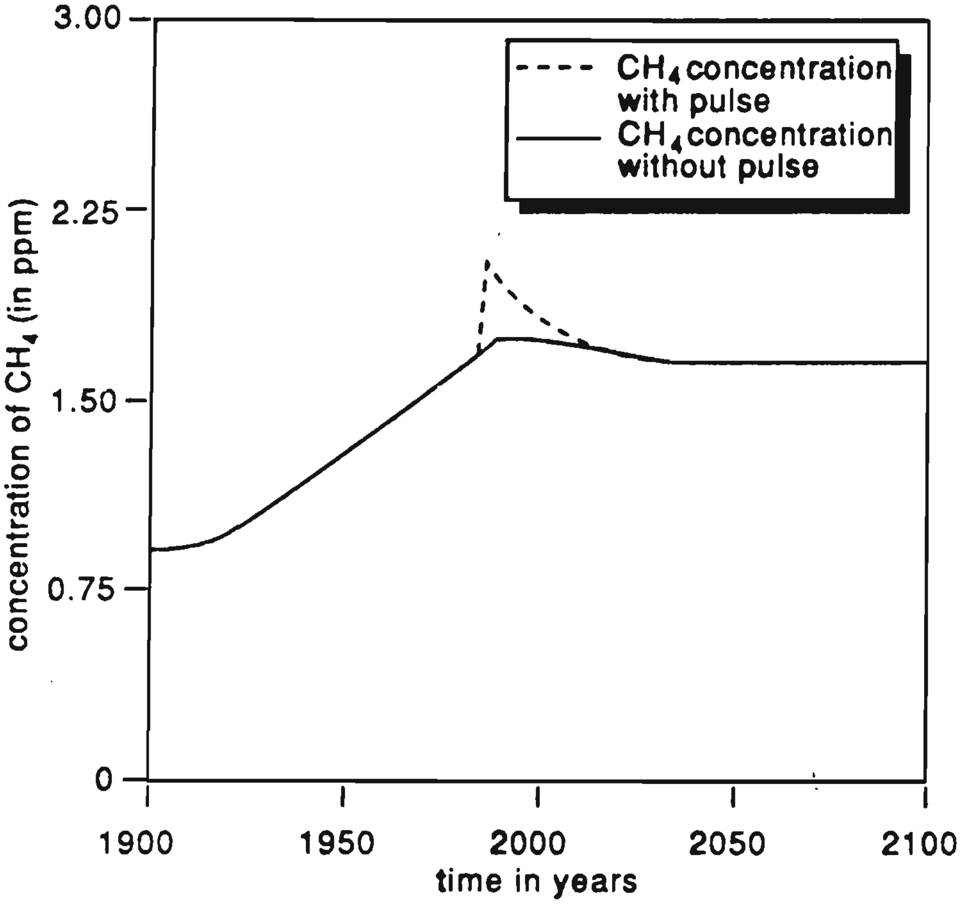


Figure 3.3-3: CH_4 **Concentration with and without Pulse**



lifetime of 160 years. In Table 3.3-4 the various assumptions for the different trace gases are given.

Table 3.3-4: Overview of Parameter Values in IMAGE

	Concentration in 1985	Residence Time	Instantaneous Forcing	Conversion Factor
CO_2	350 ppm	100-1000 yrs	0.0107 °C/ppm	0.471 ppm/Gt
CH_4	1.70 ppm	time dependent	0.333 °C/ppm	0.376 ppm/Gt
N_2O	306 ppb	160 yrs	1.83 °C/ppm	0.200 ppm/Gt
CFC-11	0.22 ppb	60 yrs	190 °C/ppm	0.046 ppb/Tg
CFC-12	0.38 ppb	120 yrs	220 °C/ppm	0.048 ppb/Tg
CFC-113	0.030 ppb	90 yrs	190 °C/ppm	0.032 ppb/Tg
CFC-114	0.005 ppb	200 yrs	210 °C/ppm	0.035 ppb/Tg
CFC-115	0.004 ppb	400 yrs	190 °C/ppm	0.038 ppb/Tg
HCFC-22	0.089 ppb	140 yrs	50 °C/ppm	0.069 ppb/Tg
CCl_4	0.004 ppb	80 yrs	80 °C/ppm	0.039 ppb/Tg

The radiative forcing factors are instantaneous radiative perturbations and are based on Ramanathan (1985), and Wigley (1987). These values are only valid for certain ranges, for instance 280 - 390 ppm for CO_2, 0.90 - 1.70 ppm for CH_4, 285 - 500 ppb for N_2O, 0 - 30 ppb for CFC-11, 0 - 40 ppb for CFC-12. These radiative perturbations imply a climate feedback sensitivity of 1.44 $W/m^2.°C$.

For the radiatively active gases CO_2, CH_4, N_2O, emissions of 1 Gt (10^9 ton) are used, emitted in a single year. For CFC emissions a pulse of 10^{-3} Gt (10^6 ton) is used, because the emissions of CFCs are of magnitude 10^3 to 10^4 lower than of the other gases, and a pulse of 1 Gt might lead to system instabilities. The corresponding pulse of CO_2 in the case of CFCs is also equal to 10^{-3} Gt. To test the sensitivity of this modeling approach to variations in the emission pulses, simulation runs with variations in both magnitude and time span of the emission pulse have been carried out. It appeared that the method is fairly robust for variations in magnitude and time span of emission pulses (Rotmand ans den Elzen, 1990). Grams and not moles are used, because in the international literature emissions are mostly expressed in grams.

RESULTS

For the following greenhouse gases: CO_2, CH_4, N_2O, CFC-11, CFC-12, CFC-113, CFC-114, CFC-115, HCFC-22 and CCl_4, the Global Warming Potentials have been calculated according to the three definitions given in equations (3.3-1), (3.3-2), and (3.3-3). Table 3.3-5 contains the potentials, based on definition (3.3-1) by Lashof and Ahuja (1990), for two time horizons, 100 and 500 years. Their radiative forcings from CO_2, CH_4, and N_2O are based on Hansen et al. (1988), while halocarbon forcings are from the AER model given in Fisher et al. (1990) where available, otherwise from Prather (1989) or Ramanathan et al. (1987).

Table 3.3-5: GWP for Analytical Approach, According to Definition (3.3-1)

ANALYTICAL APPROACH (3.3-1) GWP (mass)	CO_2 time horizon is 100 years	CO_2 time horizon is 500 years
CO_2	1	1
CH_4	34	14
N_2O	370	271
CFC-11	3568	1565
CFC-12	8011	4963
CFC-113	4133	2184
CFC-114	6834	5673
CFC-115	6724	7718
HCFC-22	1535	547
CCl_4	1402	577

In Table 3.3-6 the potentials based on definition (3.3-2) by Rotmans and den Elzen (1990) are presented. The radiative forcing factors are identical to those used for the modeling approach and are given in Table 3.3-4.

The relatively high GWP of CFC-113, and low value of HCFC-22, compared to the GWP values of these gases in Table 3.3-5 is due to differences in radiative absorption factors. Radiative absorption factors of Table 3.3-5 are based on the AER model given in Fisher et al. (1990) where available, otherwise from Prather (1989) or Ramanathan (1987), whereas radiative absorption factors of Tables 3.3-6 and 3.3-7 come from Ramanathan et al. (1985), and UNEP/WMO (1989). The

Table 3.3-6: GWP for Analytical Approach, According to Definition (3.3-2)

ANALYTICAL APPROACH (3.3-2) GWP (mass)	CO_2 time horizon is 100 years	CO_2 time horizon is 500 years
CO_2	1	1
CH_4	26	5
N_2O	330	140
CFC-11	5150	1270
CFC-12	8690	3090
CFC-113	4400	1307
CFC-114	6930	3235
CFC-115	7810	5038
HCFC-22	634	127
CCl_4	1619	375

Table 3.3-7: GWP for Modeling Approach, According to Definition (3.3-3)

IMAGE APPROACH GWP (mass)	CO_2 time horizon is 100 years	CO_2 time horizon is 500 years
CO_2	1	1
CH_4	22	8
N_2O	310	240
CFC-11	3923	1878
CFC-12	9295	5861
CFC-113	3770	1570
CFC-114	6138	4310
CFC-115	6637	7570
HCFC-22	1141	475
CCl_4	1185	495

potentials which have been calculated with the integrated assessment greenhouse model IMAGE are presented in Table 3.3-7. The radiative forcing factors which were used are given in Table 3.3-4.

From Tables 3.3-5, 3.3-6, and 3.3-7 it follows that, considering a CO_2 time horizon of 100 years, the results of both analytical methods correspond reasonably with the IMAGE results. Comparing the analytical and modeling GWP values for a CO_2 time horizon of 500 years reveals a structural difference between the methods. The GWP values based on the analytical approach of definition (3.3-1), and on the modeling method according to definition (3.3-3) appear to be considerably higher than the GWP values which are based on definition (3.3-2). This is due to the simple representation of the atmospheric retention of CO_2 in this approach, by a fixed remaining fraction. This causes a linear increase in CO_2 contribution in this analytical method, contrary to the more realistic, non-linear way CO_2 is modeled by using a carbon cycle model in IMAGE (Rotmans et al., 1990a), or using a multiple-exponential parametrization of an ocean general circulation model (Lashof and Ahuja, 1990). Consequently, the time horizon of CO_2 appears to be of crucial importance. This dynamic feature of the GWP is clearly demonstrated in Figure 3.3-4, which shows the GWP of CH_4 as a function of the time horizon, which has been varied from 1 to 500 years. When the time horizon is varied from 1 to 100 years, the GWP value of CH_4 sharply decreases.

DISCUSSION

For each trace gas, future global temperature increases, based on GWPs, can be estimated directly. In this way, these GWPs can be used to define quantified environmental targets which can serve as reference values for the development of international climate policies. In determining the GWP, both analytical and computer simulation methods can be applied. Both methods have been compared, and although there appeared to be differences, both methods can be used in calculating GWP values.

Frequently targets have been suggested in terms of maximum concentrations of individual greenhouse gases, or equivalent carbon dioxide concentrations. The equivalent CO_2-concentrations express the combined effect of all trace gases in a single concentration of CO_2 that would have an equivalent temperature increasing effect. Concentration targets have the advantage that they can be monitored more easily. The IMAGE model has been used to estimate CO_2-equivalent concentrations for which the temperature targets given in Chapter 2 would not be surpassed. Current CO_2-equivalent concentrations are estimated at 380, 390, and 410 ppm for 4, 3 and 2 °C climate sensitivity, respectively. According to our estimates, an equilibrium temperature target of 1°C above pre-industrial levels would not be exceeded if equivalent concentrations would be stabilized at levels at or below 330, 360, or 400 ppm for 4, 3, and 2°C climate sensitivity, respectively. For the 2°C temperature increase target these equivalent concentrations are 400, 450, and 560 ppm, respectively. This implies that the lower temperature target would be exceeded for all IPCC scenarios, while the higher target allows for limited increases over present concentrations. If the higher estimates of climate sensitivity are appropriate, however, there is very limited room to manoeuvre for climate policies.

The development of indices of global warming potential was driven by the desire to have a convenient way of comparing the climatic implications of different technologies, each of which may emit a suite of greenhouse gases. More recently there has been interest in using GWP indices to define national or regional greenhouse gas emission inventories and perhaps as a basis for regulations. Lashof and Ahuja (1990) calculated greenhouse gas shares of total GWP based on global emission estimates and Derwent (1990) provide a GWP inventoyy for the U.K. for different time horizons. Such inventories are quite useful in providing an overall indication of the relative importance of different gases and activities contributing to global warming.

Using such inventories as the basis for national or international regulations, however, is much more problematic at this time. While current industrial emissions of CO_2, CFCs, CO, and NO_x are reasonably well quantified, and control strategies can be identified, it is much more difficult to deal with area sources. Activities such as biomass burning, deforestation, fertilizer use, rice cultivation, and meat production contribute significantly to emissions of CO_2 and CO, and probably dominate the budgets of CH_4 and N_2O. Not only are current emission rates from these activities poorly quantified, but it would be difficult if not impossible to verify claims that such emissions had been reduced. An attempt to regulate all greenhouse gases as a group at the outset risks delaying implementation of any controls, and creates a danger that hypothetical reductions in area emission sources could be used to justify real emission increases from industrial sources.

More limited emission basket approaches could prove productive, however. Including net CO_2 from deforestation and logging activities is a possibility that should be considered. While direct measurement of emissions is lacking, it should be possible to infer emissions from land-use inventories which could be verified with remote sensing techniques. An advantage of including CO_2 from deforestation in emissions inventories is that industrialized and developing countries would be placed on a more equal footing in negotiations over the allocation of emission reductions.

While using GWPs as a basis for comprehensive regulation of greenhouse gas emissions may not be workable in practice, GWPs can be an important tool in relating emissions to environmental targets, at least on a conceptual level.

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3.4 SEA-LEVEL RISE POTENTIALS

J. ROTMANS

INTRODUCTION

In Chapter 2 targets for global mean sea-level rise have been proposed. In this section the possibilities to derive practical emissions control targets from these sea-level rise targets is evaluated. An attempt to quantify the dominant processes that determine sea-level rise has been made with the Integrated Model for the Assessment of the Greenhouse Effect (IMAGE) (Rotmans et al., 1990). IMAGE contains a sea-level rise module in which the complex processes of ocean expansion, glacier melting, and ice cap dynamics are represented by very simple relationships or parameters. After a brief description of both the modeling aspects of these relationships and the uncertainties involved, the model is used to calculate various global climatic change scenarios. More specifically, sea-level rise is computed for the IPCC scenarios. Finally, the model is used to obtain a relationship between the emission of a greenhouse gas and its associated effect on sea-level rise, called the Sea-level Rise Potential (SRP).

BASIC TREND IN SEA-LEVEL

The global rise of 100-150 mm in the last century (Barnett, 1983; Barnett, 1985; Gornitz et al., 1982) cannot yet be fully explained. Therefore, in this study a basic, or natural, rise is assumed to be the unexplained part of the observed rise. Assuming a rate of 150 mm per century for the Netherlands over the period, the rise in the period 1900-1985 would be almost 130 mm. IMAGE simulates for this period an anthropogenic sea-level rise of 82 mm, yielding a natural sea-level rise of 46 mm. This corresponds to a simulated basic rise of about 54 mm per century.

FACTORS CONTRIBUTING TO SEA-LEVEL RISE

Thermal Expansion

Thermal expansion of the ocean is thought to be a major contributor to sea-level rise. To calculate the thermal expansion effect, a simple box diffusion model is used, as described in Rotmans (1990). This approach, also used by Hoffman et al., (1983) and Oerlemans (1989), ignores the upwelling effect. Wigley and Raper (1987) use an upwelling diffusion model to calculate the thermal expansion effect. In the latter model one single ocean column is used, since Oerlemans (1987) shows that when the ocean is split into a warm and a cold column, the thermal expansion effects in both columns are similar. As described in Rotmans (1990), the diffusion equation is discretized, and numerically solved for a mixed ocean layer of 75 m, and in 37 deep ocean layers of 25 m each. The diffusivity coefficient is kept constant, i.e., 4000 m^2/yr. Using the negative exponential temperature profile as given by Oerlemans (1989), each of the 38 ocean layers has its own thermal expansion coefficient and consequently its own contribution to thermal expansion. For each layer the sea-level change due to thermal expansion can be described as:

$$SLR_{th}(i) = \int_0^{T(i)} [\, DV(i) / V(i) \,]\, dz, \qquad 3.4\text{-}(1.a)$$

and

$$DV(i) = Td(i) * ec(i) * V(i), \qquad 3.4\text{-}(1.b)$$

where,

$SLR_{th}(i)$	=	sea-level rise by thermal expansion of layer i;
V(i)	=	volume of ocean layer i;
T(i)	=	thickness of ocean layer i;
Td(i)	=	transient temperature response in ocean layer; and
ec(i)	=	thermal expansion coefficient in layer i.

At a certain time the total contribution of all layers is then:

$$SLR_{th} = \sum_{i=1}^{38} SLR_{th}(i). \qquad 3.4\text{-}(1.c)$$

Integrating these contributions for the simulation period yields the total sea-level rise by thermal expansion.

Glaciers and Small Ice Caps

Although the ice mass of glaciers and small ice caps seems to be negligible in comparison with the immense ice masses of Antarctica and Greenland, their contribution to sea-level rise may be substantial. Robin (1986) estimates the total area of mountain glaciers, all ice except for Greenland and Antarctica, as $0.54*10^6$ km^2 and $0.12*10^6$ km^3 water equivalent. The numbers represent about 0.4 % of total land ice, and correspond to a potential sea-level increment of about 330 mm. Oerlemans (1986) estimates the total land ice mass at $0.6*10^6$ km^2 and $0.18*10^6$ km^3 water equivalent, corresponding with about 500 mm sea-level increment.

Over the last hundred years there has been a worldwide retreat of glaciers. The most comprehensive study in this field has been done by Meier (1984), who examined the mass balance of 13 glaciers. Meier (1984) estimated the contribution of glacier melting to sea-level rise in the last hundred years to be 10 to 50 mm. Oerlemans (1988) argues that the greenhouse warming is responsible for about 50 % of the glacial retreat over the last hundred years. Low volcanic activity accounts for the remaining 50 % of the glacial retreat.

Because local circumstances determine the specific character of each glacier, a global approach to estimate the entire melting of glaciers and small ice caps is rather precarious. So far, however, attempts to simulate the historic glacial retreat during the last hundred years, by using local data, have failed. Thus, for lack of a more sophisticated approach, a simple global approach is chosen, that of Oerlemans (1989). Based on the assumptions of: (1) a constant characteristic response time of glaciers; (2) proportionality of melting rates to both temperature increase and remaining glacier volume; and (3) an exponential decrease of glacier volume with surface temperature, the volume of glaciers and small ice caps can be described as follows:

$$Vglac(t) = Vglac(t-1) + \int_{t-1}^{t} [\alpha * Ts *(Vglin * e^{-Ts/\beta} - Vglac)], \qquad 3.4\text{-}(2)$$

where,

Vglac	=	ice volume of glaciers, m sea-level equivalent;
Vglin	=	initial ice volume of glaciers given a starting simulation time of 1900, and a chosen initial glacier volume of 0.45 m sea-level equivalent;
α	=	constant, which involves a characteristic response time of glaciers, assumed to be 0.05 $(yrK)^{-1}$;
Ts	=	global transient surface temperature response, °C; and
ß	=	constant that determines the global temperature increase for which the ice volume becomes e^{-1} of the initial value, assumed to be 4.5 °C.

The constants are taken from Oerlemans (1989); the global transient surface temperature increase is calculated with the climate module of IMAGE (Rotmans, 1990).

Greenland Ice Cap

The Greenland ice cap covers an area of $1.8*10^6$ km^2, and contains a volume of $3*10^6 km^3$, corresponding to a sea-level equivalent of about 7.5 m (Oerlemans, 1989). Due to lack of data, it is not clear whether or not the Greenland ice cap is in its equilibrium state. In any case it is generally assumed that the Greenland ice cap is not far from its equilibrium state. In Rotmans (1986), three possibilities are distinguished, based on USDOE (1985).

One, according to the budget method, i.e., estimation of the total of accumulation, melting, and calving, the Greenland ice cap should be in equilibrium, i.e.:

accumulation	: +500	±	100 km^3 /year
melting	: -295	±	100 km^3 /year
calving	: -205	±	100 km^3 /year
Net balance	: 0		km^3 /year

Two, recent research indicates that the Greenland ice cap is in a disequilibrium state, varying from an increase of +0.3 mm/yr to a decrease of -0.7 mm/yr.

Three, extrapolating recent observations result in an ablation of 0.2 to 0.3 mm/yr and an accumulation of -0.1 mm/yr. The net effect then would be a thinning of -0.1 mm/yr.

In the model it will be assumed that in the initial phase, in 1900, the

Greenland ice cap was in equilibrium, i.e., the net balance was 0.

A very simple budget estimating method will be used to obtain a simple relationship between a global temperature increase and the change in the mass balance of the Greenland ice cap. Assuming a global average temperature increase of 3.5 °C, this will elevate the height of the equilibrium line, by which the ablation surface area increases about 25 % and the melting rate increases about 50 % (Robin, 1986). Together, these two factors would cause an increase in melting of about -184 km^3. The accumulation area would decrease by about 5 %; the accumulation rate would stay constant or increase by about 10 % (USDOE, 1985), yielding an extra accumulation of 0 or 47 km^3. The decrease in accumulation area and increase in accumulation rate would lead to an accumulation volume of -24 km^3 to +23 km^3. Ultimately, for a 3.5 °C temperature increase, the net budget decrease would vary from -208 km^3 to -161 km^3. Supposing a linear relationship, the net effect per °C would vary from -46 km^3 to -59 km^3, corresponding to a sea-level rise of 0.128 mm/yr°C to 0.166 mm/yr°C, with an average value of about 0.147 mm/yr°C. The contribution to sea-level rise is modeled by multiplying this average melting rate of 0.147 mm/yr°C by the simulated transient surface-air temperature increase.

In Rotmans (1986), the global temperature response is differentiated into several zones and into summer and winter values, roughly based on GCM data. Because the melting process will occur only in the summer period, the average summer temperature increase is used, which, however, is chosen equal to the global average temperature increase.

Oerlemans (1989) summarizes several estimates which have been made for the change in mass balance of the Greenland ice cap per °C. He states that the contribution of the Greenland ice cap to sea-level change can be estimated as 0.5 mm/yr per °C, with an uncertainty range of about 50 %. This value is high compared to the value estimated herein of 0.147 mm/yr per °C. The difference is mainly caused by the accumulation rate, which is a maximum of 10 % in the this analysis and it is kept constant, leading to the 0.5 mm/yr per °C estimate.

Antarctic Ice Cap

The Antarctic ice sheet covers an area of $11.97 \cdot 10^6$ km^2, and contains a volume of $29.33 \cdot 10^6$ km^3. This amount is more than 90 % of the total amount of land ice, and corresponds to about 65 m sea-level equivalent. As for the Greenland ice sheet, it is generally supposed that the Antarctic ice sheet is not far from its equilibrium state. However, there is an estimated uncertainty of about 20 %. According to a simple budget method, the Antarctic ice sheet should be slightly increasing, i.e.:

Accumulation	:+2000			km^3/year
Ice flow	: -1600	to -2000		km^3/year
Net balance	:	0	to +400	km^3/year.

On the Antarctic ice cap the ice flow is primarily caused by calving; melting is negligible, because of the extremely cold climate. With a temperature increase the accumulation is expected to increase, resulting in a drop in sea level. To calculate roughly the effect of a temperature rise on the Antarctic mass balance, again a simple budget estimation is used (Rotmans, 1986).

Assuming once more a global average temperature increase of 3.5 °C results in an estimated increase in accumulation of 10 to 25 %, corresponding to +200 to +500 km^3 /year. On the other hand, the ablation rate would double over twice the ablation area, implying a quadrupling of ablation. To determine the net effect as a result of the assumed global temperature rise, several options are possible (Rotmans, 1986): a) an initial net balance of zero; b) a net balance of +20 %; or c) a 10 % or 25 % accumulation increase. Taking into account these several options, the range --- expressed in mm/yr°C --- varies from -0.1088 mm/yr°C to -0.3648 mm/yr°C. The average net value of -0.237 mm/yr°C is multiplied by the simulated transient surface-air temperature increase in summer, which value is parameterized as 1.5 times the global transient surface-air response. The resulting net value is then -0.36 mm/yr°C.

Oerlemans (1989) estimated the contribution to sea-level change in two different ways. One was by using a model for the Antarctic ice sheet (Oerlemans, 1982), which resulted in an estimated -0.5 mm/yr°C. The other was by directly considering the mass balance effect, which resulted in a -0.43 mm/yr°C estimate. The latter is not too different from the value of 0.36 mm/yr°C used in this study.

The possible disintegration of the West Antarctic Ice Sheet (WAIS) is not taken into account in this analysis, because it seems unlikely that this disintegration will occur in the next century. Even if this happens the effects in the coming hundred years will be small (National Health Council, 1986). Although there is ample qualitative knowledge about the ice sheet system, it is hard to make quantitative projections. Various attempts have been made to model the WAIS system (Thomas and Bentley, 1978; Van der Veen, 1986). Oerlemans (1982; 1989) argues that the results of the earlier modeling estimates are too high. He estimates the contribution of the WAIS to be about 0.1 mm/yr for the next century. However, this estimate is very uncertain and consequently is ignored in this study.

Uncertainties

The uncertainties with respect to projections of future sea-level rise are very significant. The uncertainties in the various contributions to future sea-level rise are: about 50 % for changes of the Greenland and Antarctic ice cap; about 50 % for glacial melting; and about 30 % for the thermal expansion effect. The uncertainties of the individual contributions are assumed to be independent. With respect to the total or accumulated uncertainty, Oerlemans (1989) argues that 40 % of this uncertainty is caused by uncertainty in climate modeling, and the remaining 60 % is due to lack of data and inadequacy of models that explain sea-level rise.

SEA-LEVEL RISE AS A TARGET

In Section 2.2 of this report a target for the maximum rate of increase in global mean temperature of 0.1°C per decade has been derived. Using this global temperature increase target as an input value for IMAGE, a global sea-level rise of about 200 mm per century is estimated. Thus, a global temperature increase target of 0.1 °C per decade would correspond to a global sea-level rise target of 20 mm per decade. The latter target is the lower, or strictest, target for sea-level rise derived in Section 2.1. This implies that, based on the IMAGE results, one could conclude that for the global average, sea-level rise targets would be reached if the temperature target is achieved. Local sea-level rise may, however, reach higher levels than the global average.

If sea-level rise is to be used as a target, it should be possible to derive the implications for emission reductions from this target. Therefore, an index to compare the effect on sea-level rise of greenhouse gas emissions would be useful. By analogy with the Greenhouse Warming Potential (GWP), which is in turn the greenhouse analogue to the Ozone Depleting Potential (ODP), the concept of a Sea-level Rise Potential (SRP) is introduced. To obtain a relationship between an emission and its associated effect on sea level, the IMAGE model is used. The complexity of the processes involved would appear to make an analytical approach, as used for determining the GWP concept, difficult. However, in view of the strong resemblance between the GWP and the SRP, calculation of both potentials will be based on the same methodology. GWP modeling approach is described in detail in Section 3.2.

In contrast to the equilibrium states used in the GWP concept, the complex nature of the forcing processes in simulating the SRP requires the use of transient responses.

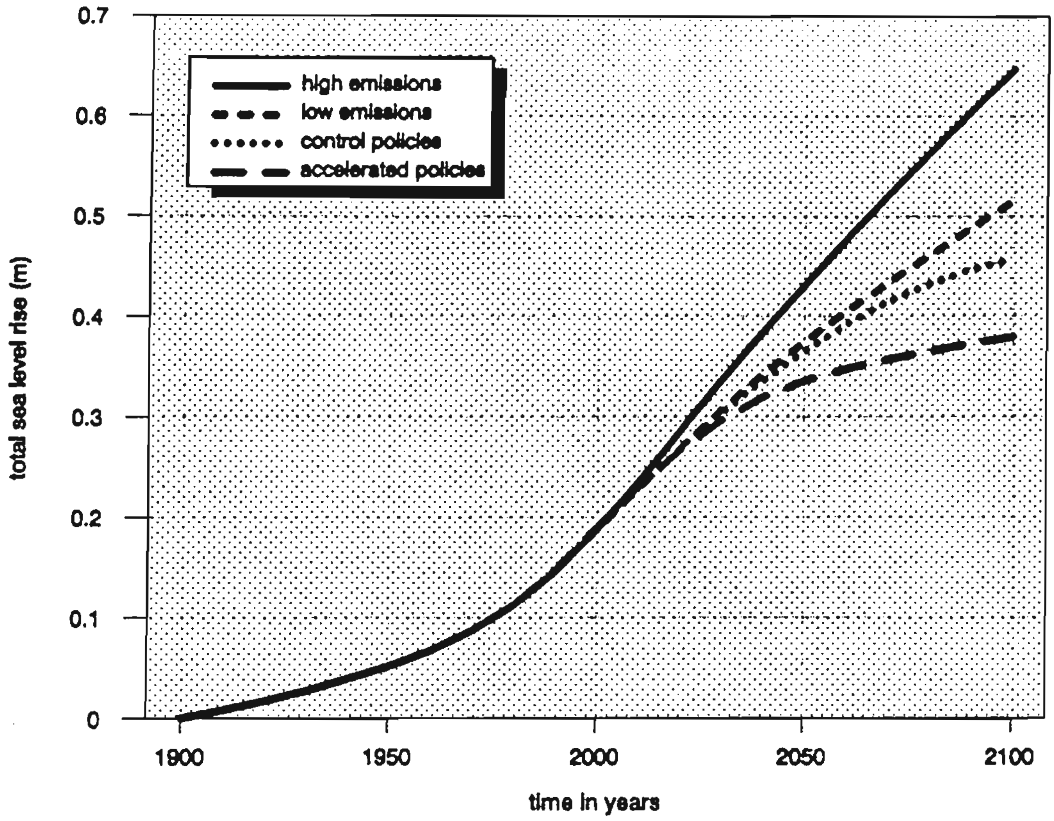
ESTIMATED SEA-LEVEL RISE

Total sea-level rise is calculated for the four IPCC scenarios (see Section 3.2) and the resulting sea-level rises are presented in Figure 3.4-1. The estimated sea-level rise varies from about 0.65 m for the IPCC 2030 scenario to about 0.38 m for the low risk scenario.

Figure 3.4-2 shows the different components of the sea-level rise of about 0.65 m for the IPCC 2030 scenario. Clearly, the thermal expansion contribution dominates. Next to thermal expansion, melting of glaciers and small ice caps play an important role. The melting of the Greenland ice cap and the accumulation of Antarctica are of minor importance in this simulation.

Figure 3.4-3 depicts the relative contributions of the different components to sea-level rise. These simulation results show primarily an increasing share attributable to thermal expansion and glacial melting, and a decreasing share attributable to natural sea-level rise. For 1985, the total simulated sea-level rise is about 128 mm, of which 82 mm has an anthropogenic origin and the remaining 46 mm forms the basic trend. This is consistent with the rationale for the sea-level rise of about 95 mm over the last 150 years found by Oerlemans (1989). The major contributor is thermal expansion, representing about 60 mm of rise. This is

Figure 3.4-1: Total Sea-level Rise for the Different IPCC Scenarios



fairly high compared with Oerlemans' estimate of 50 mm, and compared with the estimated range of 20-50 mm by Wigley and Raper (1987) for the thermal expansion effect over the last hundred years. The reason for the difference probably is the use of a constant diffusion coefficient and larger expansion coefficients.

Other important contributors are glaciers and small ice caps, with 23 mm. Oerlemans gives about 35 mm, while Meier (1984) gives a range of 10 to 50 mm over the past hundred years.

Generally the simulated sea-level rise for 1985, as well as the separate contributions of different components, are reasonably in line with results given in the literature.

Based on the foregoing methods and results, the Sea-level Rise Potentials (SRPs) of the different greenhouse gases are presented in Table 3.4-1.

Comparing these SRP values with the GWP values presented in Section 3.3, it can be seen that for a CO_2 time horizon of 100 years the SRP values are slightly lower than the GWP values. Only for CH_4 is the SRP much lower than the GWP, i.e., 15 compared with 22. For a CO_2 time horizon of 500 years, however, the SRP values are higher than the GWP values. This can be explained by the fact that the SRP is based on transient states, whereas the GWP indicates an equilibrium phase. The transient response induces a delay effect, which causes a shift towards the time horizon of 500 years. For instance, the SRP for N_2O is higher for the 500 years time horizon than for the 100 years horizon.

Figure 3.4-2: **Different Components of the Estimated Total Sea-level Rise for the IPCC 2030 Scenario**

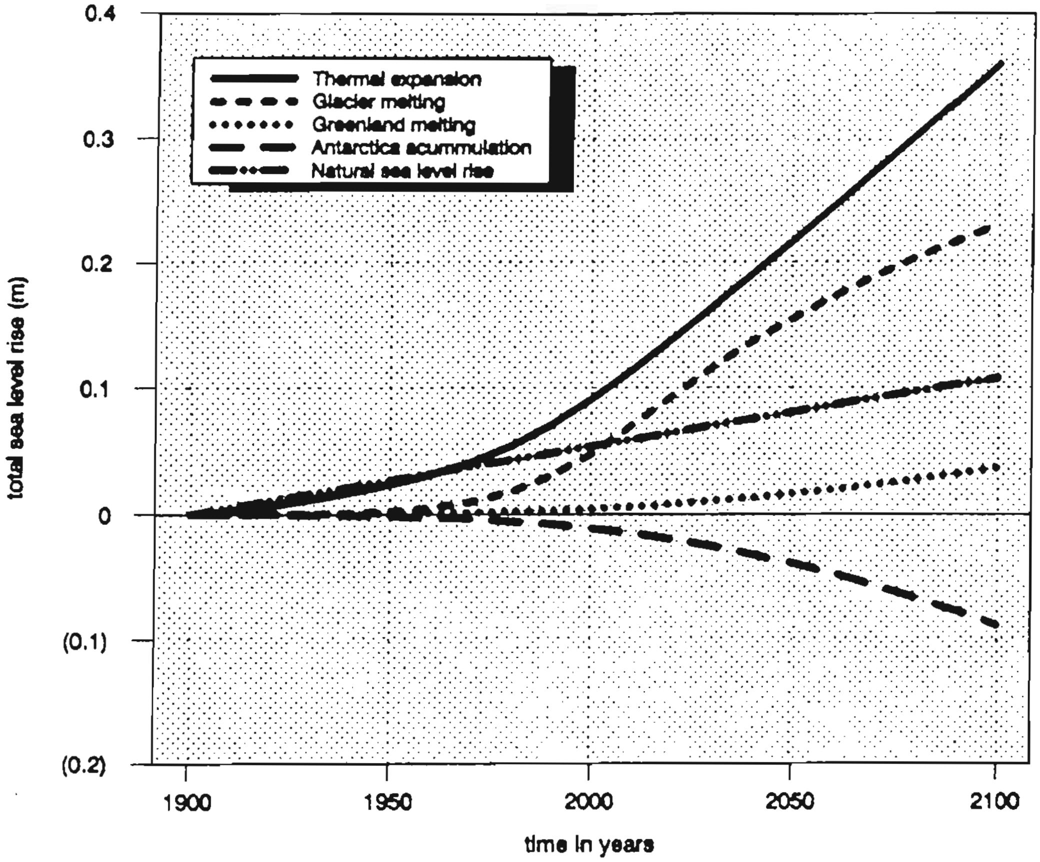
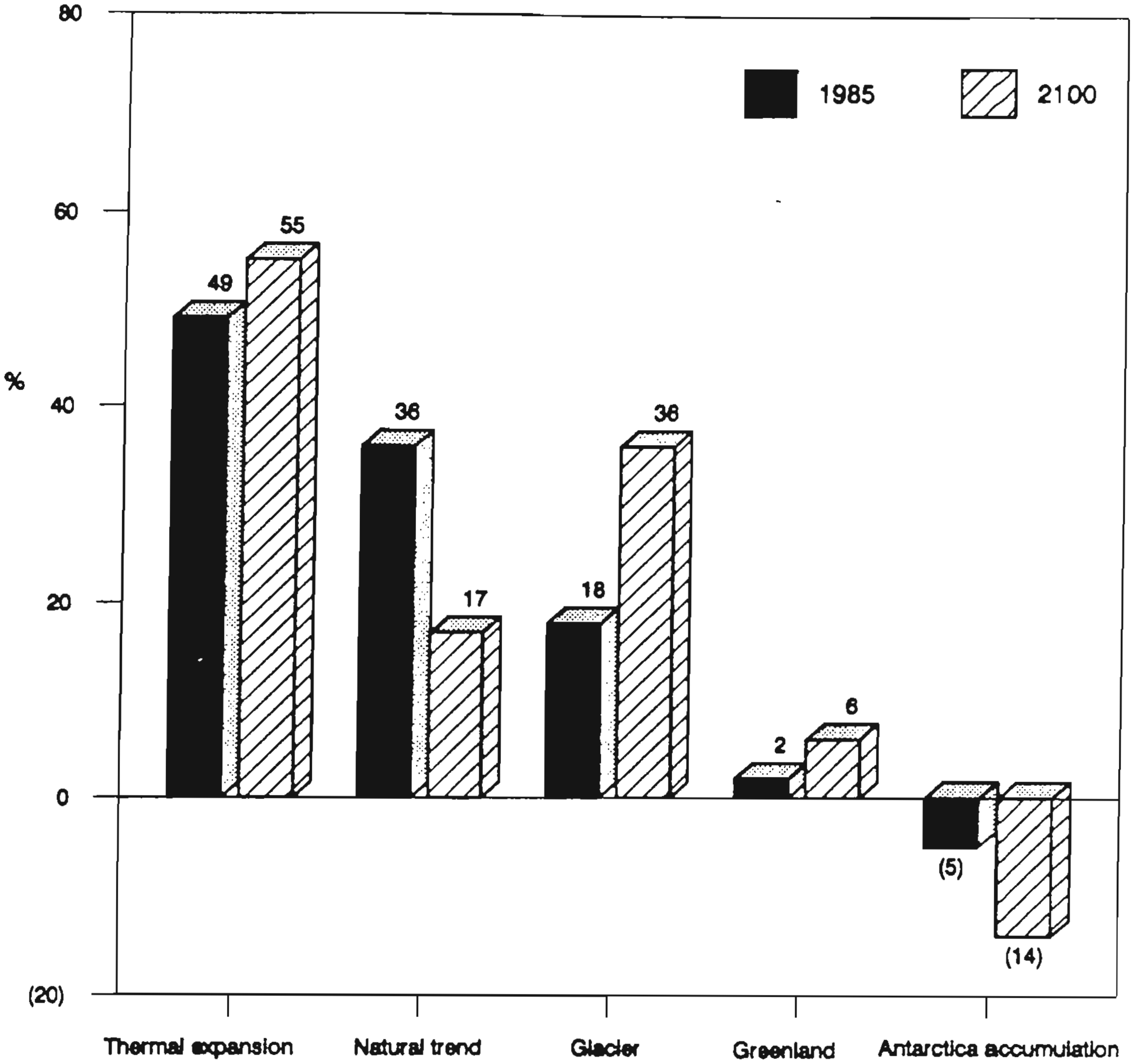


Table 3.4-1: **SRPs Calculated with IMAGE for Different Time Horizons**

SRP value	CO_2 time horizon of 100 years	CO_2 time horizon of 500 years
CO_2	1	1
CH_4	15	6
N_2O	275	330
CFC-11	3780	2560
CFC-12	8250	5000

Figure 3.4-3 **Relative Contribution of the Different Components of Sea-level Rise for 1985 and 2100 (IPCC 2030 scenarios)**



CONCLUSION

In this section the sea-level rise component of the IMAGE model has been decribed. IMAGE is an integrated model of all relevant climate change components from emissions to impacts of climatic change. The model was developed to allow rapid simulations of the impact of various climate policies with a relatively simple model. The results presented in this section show that, for the IPCC scenarios, the IMAGE results for sea-level rise compare well with the results of the more complex models on which IMAGE is based.

The IMAGE model has been used to develop Sea-level Rise Potentials (SRPs) for the greenhouse gases, analogous to the Greenhouse Warming Potentials (GWPs) described in the previous section. SRPs could be used to estimate greenhouse gas emissions associated with a specific sea-level rise target. The results presented in this section show that it is possible to derive SRPs for the various greenhouse gases. The SRPs are not identical to the GWPs because the SRPs are based on transient responses, whereas GWP is calculated for the equilibrium response. As a result, the SRP estimates are relatively more uncertain than the GWP estimates.

Simulations carried out with the IMAGE model also show, that the target for rate of global temperature increase of 0.1°C per decade, derived in the previous Chapter, is equivalent to the lower of the two targets for rate of sea-level increase (2mm per year). In view of: a) the additional uncertainty associated with the SRP compared with the GWP; and b) the fact that achieving the rate of change of temperature target implies achieving the stricter sea-level rise target, it would appear that it is preferable to base emission estimates on the GWP rather than SRP estimates.

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4. TOOLS TO ENABLE PREDICTING EMISSION REDUCTIONS NECESSARY TO ACHIEVE SPECIFIED TARGETS

4.1. IMPLICATIONS OF THE TARGET APPROACH FOR OECD COUNTRIES

I.M. MINTZER and R.J. SWART

INTRODUCTION

The preceding chapters suggest that to preserve the ecological base of the world, and consequently of human society, policies to control climatic change should be developed for which targets should be set with respect to the rise of temperature and sea level. Model calculations suggest that in order to achieve the proposed targets major changes in the emission of greenhouse gases are necessary.

Achieving these international targets requires the implementation of policies that will involve stabilizing or reducing emissions of greenhouse gases. This will require significant changes in industrial technology and may have profound economic impacts on modern societies.

The quantity of any greenhouse gas released to the atmosphere can be viewed as the product of three factors -- a technological factor, an economic factor, and a social factor. The technological factor can be represented by the quantity of emissions produced per unit of economic activity (e.g., tons of CO_2 per unit of GNP). The economic factor can be represented by the level of economic activity (e.g., GNP per capita). The social factor can be represented by the level of regional or global population. This approach reflected in the general relationship presented in Section 3.1 that also includes environmental impacts and climate processes.

Reducing the **rate of growth** in emissions can be accomplished by reducing the **sum of the rates** of change in the three factors. To reduce the **quantity** of greenhouse gas emissions, however, governments must reduce the **product** of these three factors. Assuming that most governments will continue to strive to increase the level of domestic economic activity (represented as GNP per capita) and that human populations will at least remain stable (but more likely will generally increase), reductions in the absolute level of emissions can primarily be achieved through improvements in the technology factor of this equation. This is not to say that control of the population growth or structural changes in the economy are not important methods to control greenhouse gas emissions, but they are not likely to be driven primarily by greenhouse concerns like the technological factor.

EFFICIENCY IMPROVEMENTS CRUCIAL

Speaking in general terms, reducing the quantity of emissions generated per unit of economic activity can be accomplished in a number of ways. The simplest, fastest, cheapest, and safest way to reduce emissions per unit of GNP is to increase the efficiency of resource use (Mintzer, 1990). This approach, amounting to pollution prevention, may take the form of reducing the energy intensity of key activities by changing technology or changing the character of certain activities through behavioral adjustments.

The key questions may well prove to be issues of equity rather than efficiency: How will the responsibility for future reductions in greenhouse gases be allocated among countries? What, indeed, will be allocated? A number of ways have been suggested for allocating reductions in greenhouse gases. One approach assumes that the target for reductions can be expressed in some simple single unit, e.g., a decline of 20% in the emissions of CO_2 to the atmosphere (Environment Canada, 1988). But the previous discussion of models and model results indicates clearly that the current risk of rapid global warming is not a CO_2 problem but a trace gas problem involving several families of greenhouse gases (U.S.EPA, 1989).

This has suggested the need for an alternative approach. The second approach requires a target that is not set in terms of reductions in emissions of CO_2 but rather is expressed in terms of a CO_2-equivalent reduction, leaving it to the discretion of each government as to where and how the reduction will be achieved (Lashof and Ahuja, 1990).

Most approaches that have been proposed to control international greenhouse gas emissions require the setting of policy targets. For instance, this does not only apply to simple percentages of reduction by region or countries but also to the establishment of the amount of marketable or leasable emission permits to be set out (Grubb, 1989). Initial emission control targets are likely to represent a commitment to respond to the threat of climatic change rather than to be effective in reaching the long term goals suggested in earlier sections of this report. When the perception of what is feasible changes, when more scientific evidence is found or when the frequency and severeness of events related to climatic change increases, these policy targets can be periodically revised. Also instruments to reach these policy targets such as carbon taxes or emission regulations will have to be introduced gradually to avoid economic disruptions. This is similar to the approach followed for acidifying substances, chlorofluorocarbons (CFCs) and other pollutants.

EQUITABLE SHARE OF THE BURDEN

Irrespective of which gas is reduced to achieve the desired effect, another important question must be addressed. Should all countries make equal emissions reductions or proportionate reductions, based on some formula? If the latter is to be the case, who will determine how much each country must reduce its contribution to future global warming and on what basis should it be determined?

In the recent discussions of the IPCC, several representatives of developing countries have suggested that future reductions should be in proportion to cumulative contributions from historical emissions. Under this approach, those who have emitted the greatest quantities of pollution in the past would have to make the greatest reductions in the future. Under stringent GHG emission controls this may leave the industrialized countries having eaten their piece of the pie already.

By contrast, analysts from industrialized countries have begun to suggest that future reductions should be made on a constant per capita basis or perhaps at a fixed rate relative to the economic intensity of energy use. The Montreal Protocol (UNEP, 1987), often cited as a precedent for such discussions concerning the greenhouse problem, uses a two-tiered formula for future reductions: (1) high consumption countries must make fixed percentage reductions in their production and use of the controlled compounds while (2) low-consumption countries would be allowed to increase their level of use up to a maximum threshold level. Each of these approaches has significant political consequences and may result in quite different patterns in the transfer of economic resources or competitive advantage.

The situation is further complicated by the differences in the physical characteristics of various gases. Emissions of certain gases are easy and simple to reduce. Others are more difficult and complex. Beyond emissions reductions, however, are other important differences. For certain gases, like methane, even the small reductions in emissions that could result from reordering market incentives to spur better management practices could produce an almost immediate reduction in atmospheric concentrations. In the case of long-lived gases (including the fully-halogenated CFCs and nitrous oxide), emissions reductions made today may have no measurable impact on atmospheric concentrations for years to come.

From this brief discussion it is clear that while setting a global target in the form of an international conference statement may be relatively easy, achieving it may be quite complicated. In those situations where nations do not immediately recognize their self-interest in achieving reductions, some international process will be necessary to evaluate the potential for reductions in each state and to allocate responsibility for reductions over time. Once the allocation is negotiated, extensive technical analysis will be required to identify the optimal methods for achieving the reduction. Substantial transfers of resources and technology may ultimately be necessary to encourage and facilitate the achievement of these goals. In a period when many countries perceive themselves to be in a time of limited and shrinking resources, encouraging this initiative may prove quite difficult. To be successful the initiative has to be made profitable or be perceived as such. Different approaches are being further elaborated by the Working Group on Performing Assessment of Adaptation and Limitation Strategies.

IMPLICATIONS FOR OECD COUNTRIES

Existing Opportunities

In all countries substantial opportunities now exist to employ currently available cost-effective technologies to improve the efficiency of energy use. Efficient lighting, better motors, tighter buildings, less fuel-hungry vehicles can all be applied to reduce national energy budgets and improve global competitiveness.

In many countries, opportunities also exist now to alter consumer behavior in ways which will lead to no decrease in the quality of life but may substantially improve the efficiency of resource use. Turning off unnecessary lights, repairing leaky faucets, turning off the water while shaving, carpooling, etc., can decrease energy demand and capital investment requirements for major infrastructure without reducing the services provided to consumers. Taken together, these small individual changes can add up to large changes in aggregate consumption.

Action to be initiated in the industrialized countries

Clearly, however, all countries are not equally well-positioned to take advantage of these opportunities. Shortages of capital, the press of other critical development needs, and an on-going transition from bio-fueled to fossil-fueled societies in developing countries make it difficult for these countries to conceive of stabilizing or reducing the absolute level of their future greenhouse gas emissions. If these conditions continue, especially during a period of rapid population growth in developing countries, how can real reductions be achieved on a global basis?

Thus, for emissions of any greenhouse gas to be stabilized or reduced in aggregate at the global level will mean that industrialized countries will have to achieve reductions that exceed the global target. That is, if the target is a reduction in global emissions of CO_2 from fossil fuel combustion of 20%, for example, industrialized countries may have to achieve an average reduction of more than 30%. This does not mean, however, that each individual country must achieve this reduction in its annual emissions.

Aware that national situations differ markedly, avoiding an approach that is simple, clumsy, and inefficient may require that an international agreement be reached that allows the contribution to global reductions from different industrial countries to be quite different. It may be more efficient and faster overall, for example, if one country that is particularly inefficient achieves domestic reductions that far exceed the global target while another that is more efficient than the average **at the outset** contributes capital or advanced technology to the efforts of other countries to achieve their own reductions.

Forestry important

Tropical deforestation is second only to the combustion of fossil fuels as a source of greenhouse gases. The forestry sector offers attractive opportunities for greenhouse gas control by utilizing the carbon sequestering potential of woody biomass. Most efficient is the arrest of tropical deforestation. Tropical deforestation is at least partly due to the grave economic situation of the countries involved. Selling out natural resources to serve foreign debts is certainly not the best way of aiming at long-term sustainable development. In order to protect the global environment, industrialized countries should play a role in facilitating the solution to the debt problems. Although FAO's Tropical Forestry Action Plan deserves support, its implementation will not take away the underdevelopment that causes the inefficient utilization of the forest resources. Intensification of agriculture in a sustainable way is also essential to limit the demand for additional arable land from valuable ecosystems (Swart and Rotmans, 1990).

In terms of greenhouse gas control it is much more efficient to stop deforestation than to establish forest plantations. This also conserves biodiversity, reduces erosion and local climatic change and protects indigenous people. Nevertheless forest plantations can play an important role as carbon sinks. Since the establishment of forest plantations for carbon sequestering purposes only is bound to fail, the plantations should primarily address local needs like fuel wood supply and erosion control. On a global scale reforestation can only be effective as a sink for carbon when large areas are planted. Because of management skills and smaller population pressure the temperate and boreal zones are as at least as important for this purpose as the tropical zones.

Non-CO_2 Greenhouse Gases

For many years, the risk of rapid climatic change due to the greenhouse effect had been conceived of as a CO_2 problem. Modern atmospheric science has now demonstrated that the current situation is not a one-gas problem but a problem involving increasing concentrations of many trace substances. Thus, even if an international agreement on the stabilization or reduction of fossil-fuel derived and deforestation-related emissions of CO_2 could be realized, it would not be sufficient. Risk reduction in this environment thus means that measures must be taken to reduce the rate of emissions growth (and ultimately the level of emissions) of each of the other greenhouse gases as well. It also necessitates that some index be developed to keep track of the effect of reductions of emissions of quite different magnitudes of these trace gases. Such an index has been discussed in Section 3.2.

In a recent study, the U.S. EPA (1989) estimated that stabilizing atmospheric temperatures would require a reduction in annual CO_2 emissions of approximately 50-80% from the 1988 level. Achieving this goal would require, in addition, a reduction of 20% in methane emissions and a stabilization in the rate of release of carbon monoxide. It would also require a reduction of nitrous oxide emissions by 80-85% and a full phaseout of CFCs. Further calculations done for the IPCC using the EPA Atmospheric Stabilization Framework and the Dutch IMAGE model suggest that a 30% reduction in carbon monoxide emissions would, in fact, be required to stabilize methane concentrations. Furthermore, to achieve the overall goal of temperature stabilization, the study suggests that reductions in non-methane hydrocarbon emissions that act as chemical pre-cursors for tropospheric ozone production should also be pursued. In fact, because of the physical and chemical interactions it is desirable to reduce the emissions of all gases contributing directly or indirectly to the greenhouse effect at the same time. Strict reductions for only one component can have the consequence that the concentrations of other greenhouse gases rise faster.

One simple approach for accomplishing these goals is to set target levels of reduction of each gas for each country, e.g., 20% reduction for CO_2, 50% reduction for CFCs, etc., and to track them independently. Another alternative is to establish generally accepted equivalencies among the gases (e.g., 1 ton of CFC reduction equivalent to 1000 tons of CO_2 reduction), reach international agreement on the amount of CO_2-equivalent reductions required and let each country decide how best to achieve the desired level of reductions. The latter approach is substantially more difficult to implement and to monitor but it offers the potential of allowing each country to develop a mix of options that best fit local needs while simultaneously achieving the desired goals at the global level.

Technology-specific analyses (such as those summarized in the report of the Working Group 1 on Analysis of Limitation Strategies) indicate that there is sustantial existing potential for cost-effective net reductions in emissions of CO_2 and other greenhouse gases in industrialized countries. For CO_2, these options consist of (1) improvements in the efficiency of energy use, (2) shifts in the mix of fuels consumed, moving away from carbon-intensive fuels like coal toward hydrogen-intensive fuels like natural gas and, ultimately, to "smokeless" fuels, and (3) increasing the biotic uptake of CO_2 by planting trees and other long-lived plants. For nitrous oxide, the principle means of reducing net emissions in the short term will have to involve improvements in the efficiency of the application of nitrogenous fertilizers or shifts to types with low nitrous oxide emissions.

Discussions pursued in conjunction with the Montreal Protocol on Substances that Deplete the Ozone Layer suggest the potential to phaseout the production and use of the most dangerous CFCs rapidly and completely. Even more encouraging, recent research into CFC substitutes indicates that the phaseout of CFCs may be accomplished with a net financial savings in many high-consumption countries.

Throughout the discussions of opportunities to reduce the risk of rapid climatic change, methane has received remarkably little attention. Nonetheless, there are several important reasons for addressing methane at this time. First, methane molecules are 20-30 times more effective as trappers of heat than are molecules of CO_2 and the current rate of increase in methane concentration is faster than that of any greenhouse gas except the CFCs. Second, a relatively small reduction in the rate of increase in methane emissions is sufficient to stabilize concentrations in the short term. And third, it may be possible to reduce the emissions rate of methane even before all the sources and sinks are completely characterized. Different from carbon dioxide, the dominant sources of methane are in the non-OECD countries.

Some of the most important measures that could help to slow the atmospheric buildup of methane make sense in their own right, are cost effective today, and could be implemented quickly in a number of industrialized countries. These include: worldwide introduction of Western-style standards for CO emissions from automobiles; localization, control and recovery of natural gas leakage from coal mining operations, gas and oil wells and gas distribution systems; capture of biogas from landfills, animal waste systems and waste water treatment plants; and reduction of CO emissions from residential burning of coal, lignite, or wood, especially in Eastern Europe.

Many of these options are feasible and cost-effective with technology available today. Since both methane and carbon monoxide have value as fuels, their recovery captures immediate economic benefits. Transfer of the health and safety technology developed in the Western market economies to the economies of Eastern Europe offers the potential to achieve substantial benefits quickly and cheaply while improving the efficiency and effectiveness of these economies.

CONCLUSIONS

The rapidly evolving economies of Eastern Europe offer important opportunities for mutually beneficial technology transfer. Similarly attractive opportunities will soon open up for trade between industrialized and developing countries. Taking full advantage of these opportunities will be crucial to maintaining the benefits that might accrue from improving the technology factor of the emissions equation for advanced industrialized countries. Unless the technologies that are developed to reduce emissions in the advanced countries are shared and transferred on favorable terms to the growing economies of Eastern Europe and the developing world, the emissions reductions achieved by the advanced industrial economies will soon be dwarfed by the emissions increases associated with industrial growth in Eastern Europe and the developing world. Only by building private and public partnerships to transfer these technologies in the near future can this frustrating outcome be avoided.

The transfer of technologies to these countries however, will not be sufficient to achieve global reductions. In order to sustain the gains that such technologies represent, industrialized countries must strike a new economic bargain with those in Eastern Europe and the developing world. This new bargain must open up the home market in the industrialized countries to those products which the emerging economies of Eastern Europe and the Third World have a comparative advantage to produce. Only if markets in the First World are opened up to the new industrial products of the Third World can these countries ever hope to pay for the technology they receive to reduce their domestic emissions and sustain their own future economic growth.

Thus, meeting international targets for emissions reductions will have profound social, economic, and political consequences for the industrialized world. It will require increasing the pace of capital stock replacement and introducing the most cost-efficient low-pollution technologies available. It will also require a deliberate and systematic effort to transfer the best of these technologies on favorable terms to the emerging economies of Eastern Europe and the Third World. Finally, it will require opening up the home markets of the industrialized world to the output of developing country economies, giving these countries a way to pay off their debts without burning down or digging up all their capital assets.

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4.2 FEASIBILITY OF THE TARGET APPROACH FOR DEVELOPING COUNTRIES AND CENTRALLY PLANNED ECONOMIES

KILAPARTI RAMAKRISHNA and E.O. OLADIPO

This paper examines the feasibility of limiting contributions from developing and centrally planned economies to rapid increases in greenhouse gases through a target approach. There are very few empirical studies on the socio-economic impact of limiting conventional methods of energy production on the economies of the developing world and those that are centrally planned. For this reason as a first step in addressing some of the questions likely to be raised, it is necessary to look at the patterns of energy use in developing countries (DCs) and centrally planned economies (CPEs) in comparison with industrialized countries (ICs). The socio-economic, political, technological, and environmental constraints that developing nations and countries with centrally planned economies face in attempts to limit trace gas emissions by reducing energy use are then discussed. Towards the end alternate strategies that can be used to enhance economic growth and preserve the atmosphere are examined, and conclusions follow in the last section.

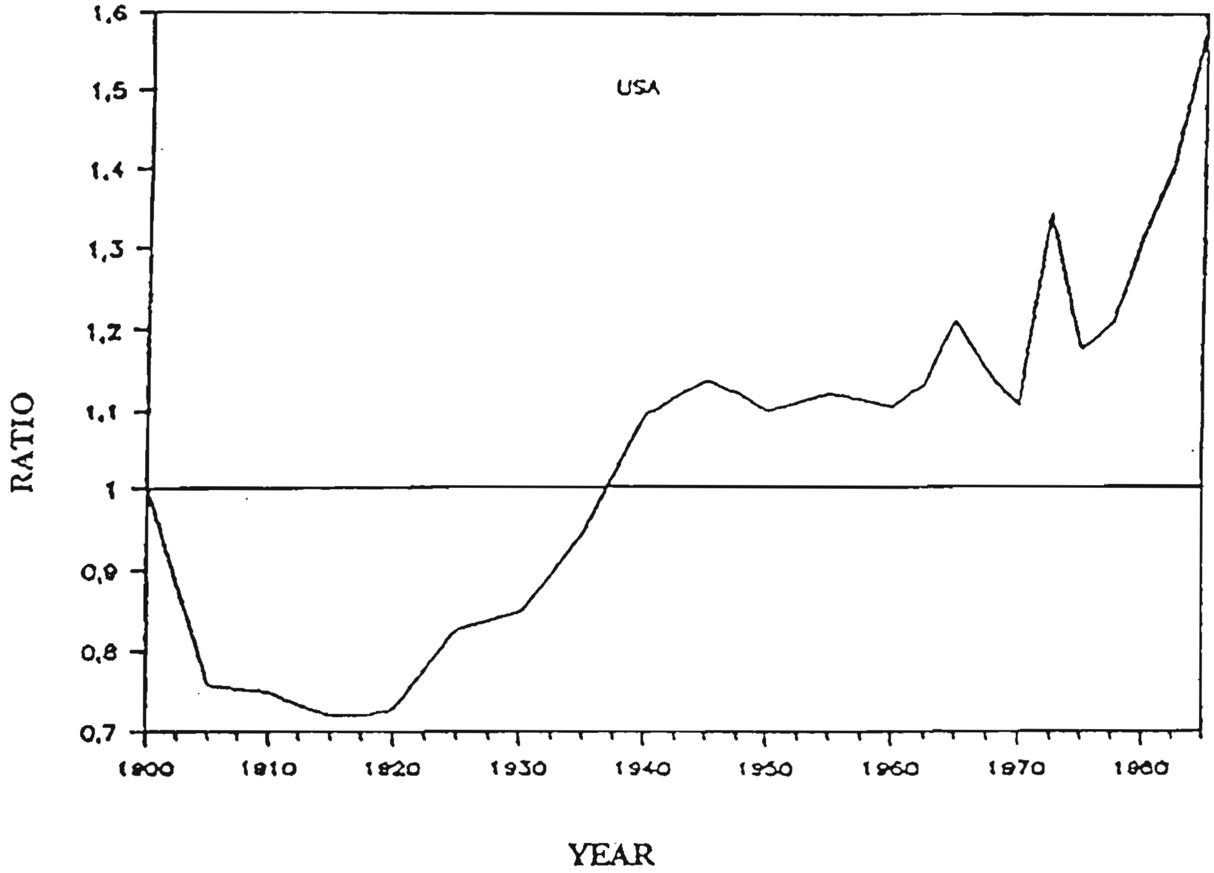
PATTERNS OF ENERGY USE AND TRACE GAS EMISSIONS

It is conventionally believed that energy use is directly related to economic progress. It is often asserted that there can be no increased industrial or agricultural production and no improvement in basic living conditions of the population without increased energy use. Consequently, material progress, a basic objective of development in DCs and CPEs, has usually been linked to increasing energy use per capita. However, a look at the relationship between energy use and GDP in industrialized countries presents a different view. An example of this for the USA is given in Figure 4.2-1.

There are two basic sources of energy in DCs and, to some extent, in CPEs, such as China. They are: the use of commercial energy sources (e.g. coal, oil, gas, etc.) and traditional energy sources (e.g. firewood, crop residue, animal waste, etc.). Worldwide, traditional energy accounted for about 5 percent of total energy use in 1980[1]. However, traditional energy is a major source of energy for many developing countries, providing 30 to 90 percent of their total use, especially in rural areas where more than 70 percent of the population of these countries live.

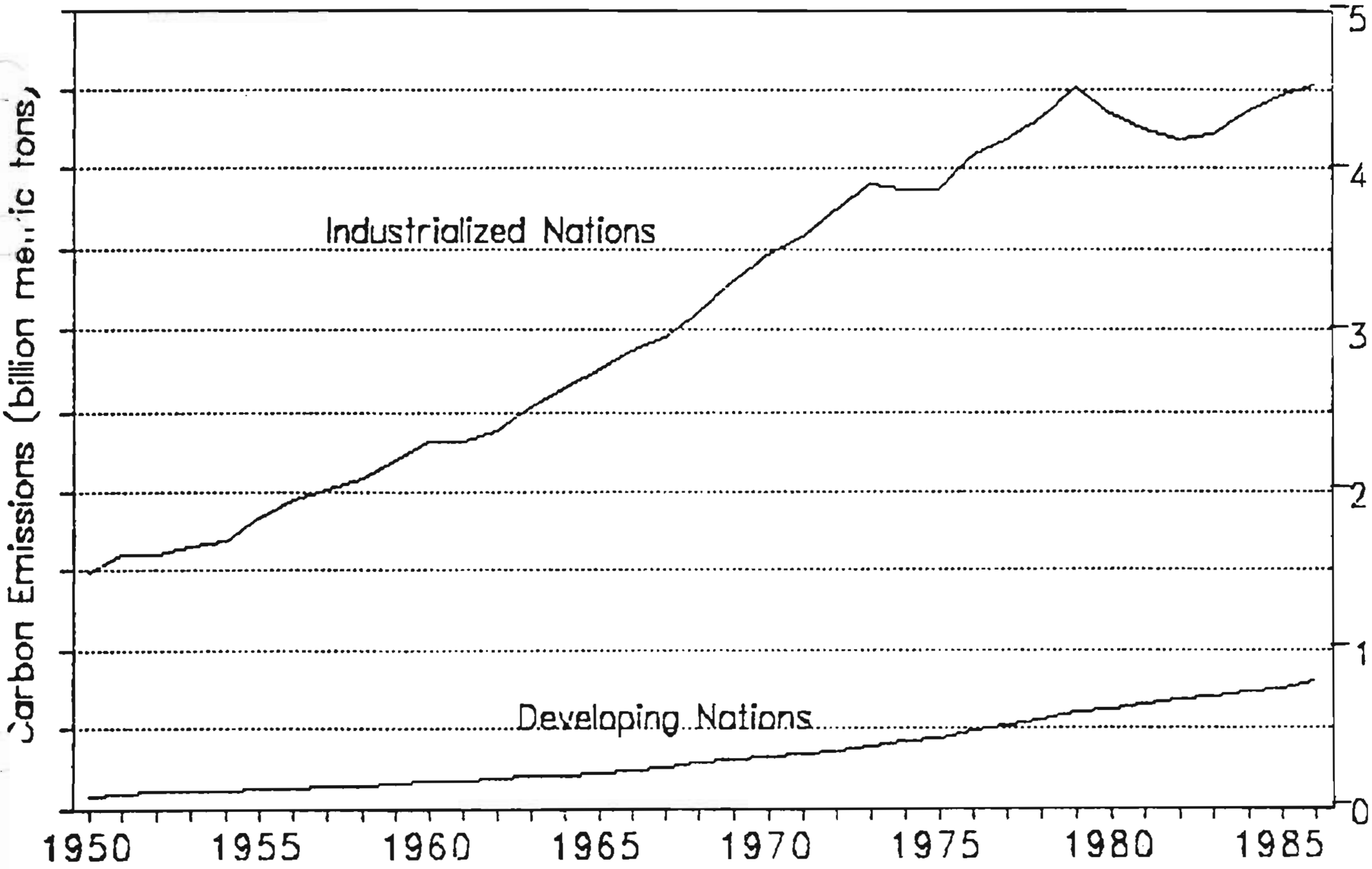
On a global basis, commercial energy supplies are disproportionately shared. Figure 4.2-2, which illustrates carbon emissions from fossil fuels for 1950-1986, clearly demonstrates this inequality. The United States, with less than 6 percent of world population, uses about 30 percent of global energy each year. Western Europe, which has about 12 percent of the world's people, uses about 23 percent of the world's annual energy. In general, about 25 industrial states with approximately 30 percent of world population use nearly 85 percent of the annual energy pie. The remaining 125 countries or so, accounting for about 70 percent of humanity, must scrape along on what is left[2].

Figure 4.2-1: Ratio GNP/Energy Use for the USA from 1900 to 1985



Source: Goldemberg, Jose. 1988. Perspectives from the Developing World. In: *Steps Toward an International Convention Stabilizing the Composition of the Atmosphere: Proceedings of the Workshop on Global Climatic Change.* Massachusetts: Woods Hole.

Figure 4.2-2: Carbon Emissions from Fossil Fuels from 1950 to 1986



Source: Houghton, R.A. Massachusetts: Woods Hole.

Regional percentages of the global distribution of energy use are given in Tables 4.2-1 and 4.2-2. An examination of these and other available sources indicates that, while historically the developing and centrally planned countries' use figures have been low, there has been a marked increase in recent years. This is because energy use in DCs and CPEs has been shaped by attention to rapid industrial growth with primary emphasis on heavy energy-intensive industries and the need to supplant the inefficient traditional forms of energy. Figure 4.2-3 has a pie chart indicating the distribution of man-made greenhouse gases by different regions of the world. In spite of the observed high growth rates for DCs and CPEs, however, their energy use per capita is still very low when compared to that of industrialized countries. For example, in 1980, per capita energy use of DCs and CPEs was still substantially below levels achieved by industrialized countries in 1925[3]. At the same time it is important to bear in mind that the projected average annual rates of growth in energy use reflect a simplistic assumption that DCs would need to maintain an annual economic growth target of about 4-5 percent in order to sustain their ever increasing populations.

As a result of the extreme global imbalance in the sharing of energy, all nations have not contributed proportionately to the global emissions of trace gases. Because CO_2 is the principal gas expected to contribute to warming and other changes in the global climate, its emission from energy use has been studied the most. The global pattern of CO_2 emissions roughly compares with the energy use pattern. The global share of CO_2 emissions for ICs has decreased from about 71 percent in 1950 to 49 percent in 1980. On the other hand, the global share of CO_2 emissions for DCs has increased two-fold in 30 years, from about 6 percent in 1950 to about 12 percent in 1980. Future emissions of CO_2 from fossil fuel combustion have been calculated by a variety of increasingly sophisticated methods and various scenarios have been explored[4]. Although these scenarios are valuable for demonstrating plausibility, they are fraught with a very large range of uncertainties which limits their use for policy decisions[5].

The effect of traditional energy use, especially biomass burning and land clearance for agriculture, on the regional pattern of trace gas emissions has, until recently, received only limited attention. Some studies pointed out that the net contribution of deforestation to CO_2 emissions is negligible. This view has been strongly contested and recent studies suggest that forest clearance in the tropics could be a net source of CO_2 to the atmosphere that is of comparable or even larger magnitude to the emissions from fossil-fuel burning[6]. Combustion of the tropical biomass (forests, savannas and croplands) is now identified as a primary source.

A more disturbing fact is the recent inventories of trace gas budgets which show that the amount of these gases released to the atmosphere from biomass burning in the Amazon Basin, the savannas of Brazilian Cerrado and African rainforests and savannas is comparable to the amount released to the atmosphere from fossil fuel combustion in industrialized regions[7]. In spite of large uncertainties and biases in the computation of global emissions from biomass burning[8], these recent findings raise new questions about the contribution of non-fossil sources of energy to the "greenhouse effect". Because developing countries and some CPEs (e.g. China) depend substantially on deforestation and firewood for sources of energy, their contribution to global emissions of GHGs is more significant than their share of global fossil-fuel combustion would suggest.

Table 4.2-1: Global Distribution of Energy Use, 1980[a]

	Population[a]	Non-Commercial		Oil		Natural Gas		Coal		Hydro- and Nuclear		Total	Total Energy Use
		Per Capital Energy Use											
	(million)	Watts	%	Watts	%	Watts	%	Watts	%	Watts	%	Watts	(TW)
World	4371.5	308[b]	15	778	37	397	19	567	27	64	3	2114	9.24[c]
Industrialized Market Economies	795.1	NA[c]	--	2658	48	1323	24	1356	24	243	4	5580	4.4[h]
U.S.	227.6	220[d]	2	4093	41	3038	31	2249	23	281	3	9881	2.25[h]
Western Europe	372.6	NA[c]	—	2035	52	689	18	979	25	199	5	3902	1.45[h]
Japan	116.8	NA[c]	—	2162	67	268	8	640	20	172	5	3242	0.38[h]
Centrally Planned Europe	377.8	NA[c]	—	1559	30	1371	217	2155	42	86	2	5171	1.95[h]
Developing Market Economies	2186.2	457[c]	52	272	31	68	8	65	7	20	2	881	1.93
Brazil	123.0	371[c]	34	513	48	12	1	63	6	118	11	1077	0.13
India	662.0	190[c]	52	51	14	2	1	115	31	9	2	367	0.24
Bangladesh	88.2	95[c]	69	22	16	18	13	2	1	1	1	138	0.01
China	939.3	317[c]	36	106	12	19	2	427	49	7	1	876	0.82

Notes to Table 4.2-1:

(a) Unless otherwise indicated, data are from United Nations, 1981.
(b) This is the world average value, assuming zero non-commercial energy use in industrialized countries other than the U.S.
(c) Not available.
(d) This is estimated wood consumption as fuel by the forest products industry plus firewood consumption. Source: OTA, 1980.
(e) Souce: D.O. Hall et al., 1982.
(f) Hydroelectric and nuclear energy are counted as 3.6 MJ per kWh (electrical).
(g) Excludes non-commercial energy in industrialized countries other than the U.S.
(h) Commercial energy only.

Source: Jose Goldemberg, Thomas B. Johansson, Amulya K.N. Reddy and Robert W. Williams. *Energy for a Sustainable World.* New Delhi: Wiley Eastern Limited, 1988, p. 192.

Table 4.2-2 Share of Activities Generating CO_2 Emissions: State Contributions to Energy, Industry, Deforestation *)

Fossil Fuels (74% of CO_2 Emissions)

Oil (43% of Fossil Fuels)		Coal (42% of Fossil Fuels)		Gas (15% of Fossil Fuels)	
U.S.	23	China	20	U.S.S.R.	35
U.S.S.R.	15	U.S.	19	U.S.	27
Japan	6	U.S.S.R.	17	U.K.	4
China	3	Poland	5	Canada	3
West Germany	3	India	5	West Germany	3
Italy	3	West Germany	4	Japan	3
Mexico	3	U.K.	4	Romania	3
France	2	Japan	3	Netherlands	2
U.K.	2	East Germany	3	Italy	2
Canada	2	Czechoslovakia	2	France	2
Rest of World	38	Rest of World	18	Rest of World	16

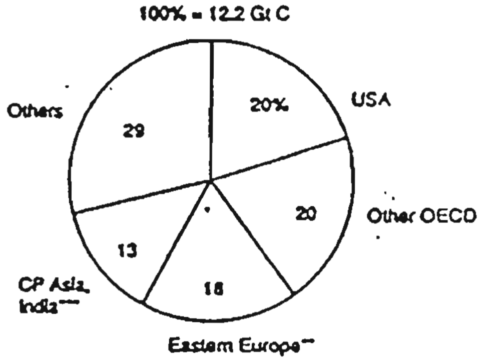
Deforestation (23% of Co_2 Emissions)		Industry (3% of CO_2 Emissions): Cement (75% of Industry)		Industry (3% of CO_2 Emissions): Gas Flaring (25% of Industry)
Brazil	20	China	16	Data Not Available
Indonesia	12	U.S.S.R.	13	
Colombia	7	U.S.	7	(Total is less than
Ivory Coast	6	Japan	7	1% of total CO_2)
Thailand	6	Italy	4	
Laos	5	India	3	
Nigeria	4	Germany	3	
Philippines	3	Brazil	2	
Burma	3	Spain	2	
Peru	3	France	2	
Rest of World	31	Rest of World	40	

*) Numbers are in percent of each activity; top 10 states.

Source: Energy and Industry Figures: Marland et al., 1989.
Deforestation Figures: Houghton et al., 1987.

Source: Nazli Choucri and Robert North. "Global Environmental Change: Toward a Framework for Decision and Policy". Presented at the Annual Meeting of the International Studies Association, Washington, D.C., April 10-14, 1990.

Figure 4.2-3: Contribution to Global Warming: Distribution of Man-Made Greenhouse Gases, 1985



* Expressed in CO_2 equivalents: higher assessment of the relative contribution of methane would raise the proportion attributed to developing nations by approximately 5% to the credit of OECD & Eastern Europe.

** Centrally-planned Europe, including USSR.

*** Centrally-planned Asia and Indian Subcontinent (mainly Bangladesh, China, India and Pakistan).

Source: MacNeill, Jim, Peter Winsemius and Taizo Yakushiji. *Beyond Interdependence: the Meshing of the World's Economy and the Earth's Ecology*. Report to the Trilateral Commission. p. 61.

CONSTRAINTS AND OPPORTUNITIES FOR LIMITING TRACE GAS EMISSIONS

The preceding section shows that when both **commercial** and **traditional** energy sources are taken into consideration, DCs and CPEs contribute significantly to global emissions of trace gases. Likewise the projected energy use figures make DCs and CPEs significant actors. Thus these countries are important actors in any international agreement designed to reduce global increases in GHGs through targeted reductions in the combustion of carbon-intensive energy sources. Because energy use is determined by the interplay of demographic, socio-economic, political, technological and environmental phenomena, it is being suggested that the international co-operation required for reducing trace gas emissions would not escape political rhetoric that characterizes the North-South economic concerns. The constraints on effective response strategies to limiting trace gas emissions from the perspective of DCs and CPEs are examined in terms of individual, social and cultural differences in the perception of climatic change problems, economic growth and developmental needs and technological consequences.

Sustainable Economic Development

Poverty is at the core of economic problems in DCs. Developing nations are extremely resentful of their poverty and are aggressive about correcting the imbalance. The solution for many countries, therefore, is rapid economic growth to support the surging population. This is expected to result in material abundance, a technologically sophisticated infrastructure, advanced productive capacity and an increase in the economic capacity of meeting basic human needs for food, water, shelter, clothing, health, employment and education.

An international conference on global warming and climatic change held in New Delhi during February 21-23, 1989 was attended by well over 150 scientists, policy makers, and government officials, mainly from nations of the Indian sub-continent. The conference focussed on the scientific evidence for, the impacts of, and policy responses to the problem of global climatic change. A comprehensive statement adopted at the end of the conference pointed out that:

> Global warming is occurring at a time when many of the world's life-support systems are already stressed by the growth of population, industrial development and need for agricultural land and the unsustainable exploitation of natural resources. These stresses are caused both by careless and short-sighted actions and as a consequence of poverty and underdevelopment. They include increasing air and water pollution, deforestation, soil erosion and salination, among others.

The statement categorically stated that the first and largest response should come from industrial nations. It also recognized that currently about 20 percent of the emissions of the principal greenhouse gas, carbon dioxide, comes from fossil fuels used in developing countries. The estimates are that by the middle of the next century, this figure could climb to well over 50 percent. However, the conference was unequivocal in pointing out that the developing country response to global warming should be carried out in a way that enhances, rather than diminishes, development prospects.

Mostafa Tolba, Executive Director of the United Nations Environment Programme, pointed out that global warming and climatic change present a window of opportunity for both the industrialized and the developing countries to address a host of priority items including trade imbalances, debt relief, technology transfer, technical assistance and financial assistance.

Mrs. Gro Harlem Brundtland, the Prime Minister of Norway, who chaired the World Commission on Environment and Development, drew from the Commission's Report *Our Common Future* in her Keynote address at the Toronto Conference in June 1988. She pointed out that there is "a need for a fresh impetus in international cooperation. Development aid and lending must be increased, and the debt crises must be resolved". She said that "the ultimate goal must be to forge an economic partnership based on equitable trade and to achieve a new era of growth, one which enhances the resource base rather than degrades it". She concluded by saying that "the mission must be to make nations return to negotiations on the global issues after years of decline in real multilateralism." It is sentiments of this nature that effectively warded off possible large-scale criticism and rhetoric from both Third World participants and from non-governmental organizations attending the Toronto Conference. The conference document stated that:

> ... countries of the industrially developed world are the main source of greenhouse gases and therefore bear the main responsibility to the world community for ensuring that measures are implemented to address the issues posed by climate change. At the same time, they must see that the developing nations of the world, whose problems are greatly aggravated by population growth, are assisted and not inhibited in improving their economies and the living conditions of their citizens. This will necessitate a wide range of measures, including significant additional energy use in those countries and compensating reductions in industrialized countries. The transition to a sustainable future will require investments in energy efficiency and non-fossil energy sources. In order to ensure that these investments occur, the global community must not only halt the current net transfer of resources from developing countries, but actually reverse it. This reversal should embrace the relevant technologies involved, taking into account the implications for industry.

The Toronto conference called upon governments to establish a *world atmosphere fund* financed in part by a levy on fossil-fuel use by industrialized countries. This recommendation in varying forms has been endorsed by every conference on this subject held around the world. The governments of Mexico and India have made proposals along these lines. Environment ministers from 68 countries subscribed to this in principle at the November 1989 Noordwijk Ministerial Conference on Atmospheric Pollution and Climate Change. The Norwegian government endorsed the idea by announcing that it will contribute a tenth of one percent of its gross domestic product to the global fund if other industrialized countries follow suit.

The only other time that environmental concerns and development needs were addressed as one package was during the early 70s. We know of the reluctance of the developing world to participate and of its subsequent endorsement of the Stockholm Conference on Human Environment in 1972. One may therefore suggest bravely that the principal reason for developing country participation in the international environmental movement has historically been more due to the perception of the possible gains and help in achieving quicker economic development from it than to any enlightened reasons that environmental protection is in their best interests or those of mankind in general. The United Nations Environment Secretariat established in 1971 to pursue the objectives of the conference succeeded in convincing the developing countries that environmental issues are not conflicting but compatible with their compelling needs. The other more important reasons given were that DCs would experience significant social and economic repercussions as a result of environmental measures taken in the industrialized world; that they should be informed and equipped to avoid the type of environmental degradation that ICs were only beginning to realize and remedy; and finally that it would be in their own interest to be party to decisions that would directly affect their interests.

Several important questions needed to be answered to obtain developing country participation. They are: How would actions taken by more industrialized nations affect them? What would be the technical assistance available? What would happen to the markets they require for their own development? What attention was likely to be given to the kind of environmental problems which directly affected them? All these questions were addressed in the *Founex Report*, a report commissioned by the Secretary-General of the United Nations Conference on Human Environment by convening a panel of 27 experts in the fields of both development and environment. It became a central document in the deliberations of the developing countries in the four regional seminars held in Bangkok, Addis-Ababa, Mexico City, and Beirut.

At the outset the Founex Report stated that the "concern for environment must not and need not detract from the commitment of the world community... to the overriding task of development of developing regions of the world" and that the developing countries should "avoid as far as feasible, the mistakes and distortions that have characterized the patterns of development of the industrialized societies". The Report made it clear that adequate safeguards and standards are necessary. However, "these standards must necessarily be those that are appropriate to the specific conditions of these countries and be capable of being observed within the resources available to them". Warning that "environmental issues may come to exercise growing influence on international economic relations", the Report stated: "... unless appropriate economic action is taken, there are a number of ways in which the developing countries could suffer rather than profit from the new emphasis on environment. The latter could have implications for aid, trade, and transfer of technology".

The points made by the Report, from the developing country perspective, and which found their place in the Declaration and Action Plan for the Human Environment adopted at the end of the 1972 Conference, affirm that additional funds will be required: 1) to subsidize research in environmental problems for developing countries; 2) to compensate for major dislocations in the exports of developing countries; 3) to cover major increases in the cost of development projects owing to higher environmental standards; and 4) to finance the restructuring of investment, production or export patterns necessitated by environmental concerns of developed countries. These recommendations resulted in the establishment of the concept of additionality and the concept of compensation. Unfortunately, in subsequent years, the United Nations system deemed it appropriate to separate economic development aspects from the environmental agenda.

The special circumstances of the developing world, however, have been recounted in all of the international environmental conferences since then. Special provisions were made to accommodate pollution control strategies that take into account their current lack of development - effectively introducing and endorsing "double standards" thus bringing them into common parlance. Assurances of technical and financial assistance and technology transfer were likewise written into the texts of several international legal instruments. But the urgency for assisting developing countries was never before stated with more seriousness. For example, Mostafa Tolba speaking at the closure of the ministerial conference on ozone layer protection in London, March 1989, stressed that in helping the Third World "we must stop talking in generalities" and that "there is a need for international mechanisms to compensate them for foregoing the use of CFCs and some of their natural resources in the interest of environmental safety". Similar sentiments were expressed by the Administrator of the USEPA at the same conference both from the official platform and at a private meeting with the delegations of India, China and Brazil.

Even the World Bank, which, until recently, was slow in according a prominent position to environmental work within the Bank, came forward with a proposal to create a new environmental lending facility. The Bank's document, *Funding for the Global Environment*, released in draft form in February 1990, recognizes that additional financial and technical assistance from industrialized countries will be crucial in helping developing countries address global environmental problems. The Bank's basic analysis of the need for increased resource transfers to limit emissions of greenhouse and ozone-depleting gases as well as to preserve biodiversity and water quality is based on another document released by the Bank (Discussion paper # 78, April 1990) called *The Greenhouse Effect: Implications for Economic Development*. This paper also makes a very persuasive case for why the development community should be concerned:

> The development community needs to outline a policy and research program for sustainable economic development which addresses the implications of possible climate effects of greenhouse gases. The greatest opportunities lie in the energy sector, which should be the primary focus of attention, notwithstanding that energy efficiency options are substantial in sectors such as agriculture and urban systems. Indeed, the opportunities for public and private energy efficiency gains are compelling and suggest that the threat of global warming can be reduced primarily by concentrating present efforts on improving the energy efficiency of the global economy.

Given the scant amount of attention (see Table 4.2-3) paid to new and renewable energy sources by both multilateral development banks and bilateral aid agencies (the statistics collected by Hoffman and Johnson[9] indicate that of the US$ 14 billion spent in the energy area, about 91% was spent on conventional power generation, about 5% on fossil-fuel recovery, and only about 3% on new and renewable energy sources) so far, the sentiments expressed above mark a clear departure. It is this renewed interest and determination to assist the Third World in their economic development that is responsible for the wave of support from developing countries. Experience with countries such as Brazil[10] supports the view that limiting CO_2 and other trace-gas emissions through reductions in energy use also limits economic growth.

Table 4.2-3: Expenditures of Multilateral and Bilateral Aid Agencies in the Energy Area (in millions of current dollars)

	Conventional Power Generation (Hydro, Nuclear, Thermal), Transmission, Distribution; Power Sector Studies	Fossil Fuels Recovery (includes studies and training)	New and Renewables (includes Geothermal, Fuelwood)	Tech. Assistance Energy Planning, Other	Total Energy Aid
MULTILATERAL AID					
1. World Bank (FY '72-Dec,'78)	5,210	305	170	—	5,686
2. Inter-American Development Bank (FY '72-FY '78)	2,596	158	4	—	2,758
3. Asian Development Bank (FY '72-FY '78)	1,183	21	0	—	1,204
4. European Development Fund (to May 1978)	141	—	9	—	150
5. UN Development Programme (to Jan. 1979)	72	23	29	13	137
6. UN Center for Natural Resources, Energy and Transport (to Jan. 1979)	3	5	4	5	17
Subtotal	9,205	512	216	18	9,952
BILATERAL AID					
1. French Aid (1976-1979)	229	16	30	5	280
2. Canadian Int'l Devel. Agency (1978/79, 1979/80)	88	0	2	1	91
3. German Aid (1970-present)	1,925	41	81	48	2,095
4. Kuwait Fund (FY '73'FY '78)	437	99	1	—	536
5. Swedish International Development Agency	?	?	?	?	?
6. Netherlands - Dutch Development Cooperation (1970-present)	119	71	7	2	198
7. UK Overseas Development Administration (1973-present)	146	1	3	—	149
8. US Aid (FY '78-=FY '80)	403	2	96	46	546
GRAND TOTALS	12,719	757	437	121	14,033
% in each sector	91	5	3	1	100

Source: T. Hoffman and B. Johnson, The World Energy Triangle, Ballinger Publishing Co., Cambridge, Massachusetts, 1981.

Source: Jose Goldemberg, Thomas B. Johansson, Amulya K.N. Reddy and Robert W. Williams, *Energy for a Sustainable World*. New Delhi: Wiley Eastern Limited, 1988, pp. 361-362.

The adoption of rapid industrialization for economic growth has brought with it a new economic problem that will make it difficult for DCs to reduce their use of pollution-intensive energy sources. The new economic problem is that of the external debt burden. A careful look at public and private long-term debt and financial flows in developing countries during 1982-88 indicates that the net transfer of resources to the tune of US$ 43 billion[11] is from developing countries to industrialized countries (see Tables 4.2-4 and 4.2-5).

In one sense the reasons for this are easy to understand. Developing nations were averaging growth rates of 6.6 percent in 1967-1973. Generally lacking in large fossil reserves, the newly industrializing countries, particularly Brazil and Argentina, depended on imported crude oil. In order to provide the resources necessary to sustain their high economic growth rates and development, the DCs resorted to foreign borrowing, which was facilitated by the explosion in international lending that followed the first major OPEC oil price increase. By 1974, the price of crude oil had quadrupled on the world market. To meet their rapid growth needs, many DCs resorted to financing their capital goods, oil and food imports while expanding aggressively their exports. In the face of rapid increases in oil prices and a world recession in the late 1970s, many developing countries sought to maintain their high growth rates through additional borrowing from commercial banks and other private financial institutions at usually high market rates of interest.

By the end of 1988, the total external debt of the DCs stood at about $1.32 trillion with much debt-servicing difficulty. For example, the Nigerian government will, in 1990, spend about 42 percent of its total annual expenditure to pay interest on its external debt. As a result of the huge accumulated external debt by DCs, pressure on their natural resources has increased sharply, in order to reduce heavy dependence on imported oil and/or expand exports to meet the financial requirements of international creditors. For example, after the second oil price rise of 1979, Brazil proposed a program to increase annual coal production from 10 million tons to 35 million tons, by 1985, in order to save on the cost of fuel oil imports. By 1984, the cement industry was to have burnt 5.6 million tons of coal to save the Brazilian economy 2.8 million tons of fuel oil[12]. Other DCs with some coal reserves may follow the Brazilian example in order to cut the cost of imported fuel oil. Despite its oil wealth, Nigeria is currently making concerted efforts towards the revitalization of the pollution-intensive coal industry to supplement oil as a source of foreign exchange - to pay part of its large external debt - and as a source of energy.

While serving a variety of social, economic and political needs, the industrial structures of the CPEs, like their counterparts in the DCs, make an inordinate and inefficient use of their primary energy when compared with the developed countries. The fact that energy prices are heavily subsidized has contributed to their inefficient use. Moreover, energy use in the CPEs is still very carbon-intensive. Coal, the major source of CO_2 emissions, is still the most dominant energy component in China's energy profile. Coal use in China has grown at an annual rate of 8 percent since the 1950s, and it now represents about 75 percent of the country's primary energy use[13]. The Soviet Union is the largest world producer of coal, and, as an important element in maintaining energy self-sufficiency and sustaining economic growth, long-term future developments will be dominated by increased coal production, in addition to an increase in reliance on oil and gas[14]. The increasing return to coal would lead to greater CO_2 emissions. In general therefore, DCs and CPEs, faced with the immediate imperative of supplying basic needs, will perceive increases in energy use

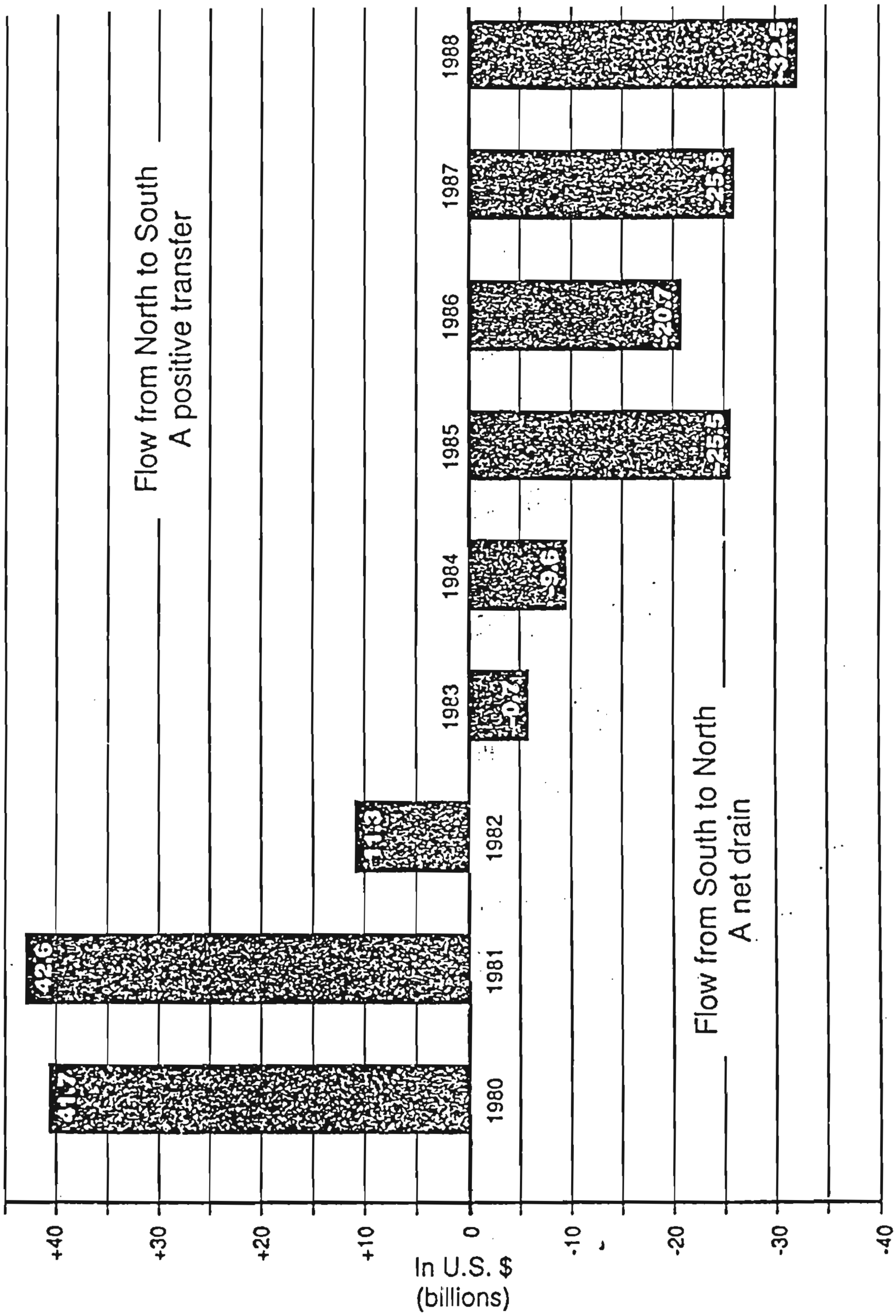
Table 4.2-4: Public and Private Long-Term Debt and Financial Flows in Developing Countries, 1982-88 (US$ billions)

Long-Term Debt and Financial Flows	1982	1983	1984	1985	1986	1987	1988
Debt Disbursed and Outstanding	563.	645.	687.	794.	894.	996.	1020.
Debt Service	98.7	92.6	101.8	112.2	116.5	124.9	131.
Principal Payments	49.7	45.4	48.6	56.4	61.5	70.9	72.
Interest Payments	48.9	47.3	53.2	55.8	54.9	54.0	59.
Net Flows	67.2	51.8	43.0	32.9	26.2	15.8	16.
Net Transfers	18.2	4.6	-10.2	-22.9	-28.7	-38.1	-43

Compiled from World Bank, "World Debt Tables, External Debt of Developing Countries", 1988-89 Edition, The World Bank, Washington, D.D.

Source: Jim MacNeill, Peter Winsemius and Taizo Yakushiji. *Beyond Interdependence: The Meshing of the World's Economy and the Earth's Ecology* (A Report to the Trilateral Commission), p. 16.

Table 4.2-5: Reversing Financial Flows for Developing Nations: Net Transfer of Resources 1980-1988



Sample of 98 nations - covers private direct investment, private loans, official flows.

Source: UN Non-Governmental Liaison Service. 1989. *An NGO Guide to Trade and Finance in the Multilateral System.* New York: UN. p. 36.

as the means of sustaining their economic growth. There will, therefore, be widespread resistance among the leadership of DCs and, to some extent, those of CPEs, to the idea of reducing global greenhouse gas emissions by reducing energy use.

Who Bears the Burden?

There is a large gap between the developed and the developing nations in their contribution to CO_2 and other trace-gas emissions in terms of their energy use. Use of energy per head in industrialized countries compared to middle-income and low-income developing countries is in the proportion of 100:10:1. One American uses as much commercial energy as 6 Yugoslavs, 9 Mexicans or Cubans, 16 Chinese, 19 Malaysian, 53 Indians, 105 Sri-Lankans, 438 Malians or 1072 Nepalese[15]. In 1974 per capita kilograms of coal equivalent, an American used 11,484 to 1,269 for Mexico, 646 for Brazil, 632 for China and 94 for Nigeria. Even if all DCs were to raise their use of world energy resources in the next two decades, their share would still be relatively small[16]. Per capita income of developed countries exceeded that of DCs by factors of about 60-100. Consequently, the price in terms of sacrificing some measure of economic growth would be much higher in DCs than in developed nations.

A fundamental question remains. Should DCs pay the price of rapid industrialization of developed nations? In other words, how is the 20 percent reduction target in CO_2 and other trace-gas emissions to be shared among nations? In view of the wide gap in energy use and stage of development between DCs and developed nations, it is doubtful if the former would willingly agree to limit the energy use, which is seen as a measure of industrial growth. From the perspective of DCs, fairness must have a role to play in energy policies and programs which seek to achieve the target reduction.

Technological and Capital Issues

Increasing reliance on alternative, cleaner sources of energy rather than the highly polluting fossil fuels to meet energy needs is one way by which atmospheric pollution by CO_2 and other trace gas emissions can be reduced. Whether the viability of alternative energy sources can meet future energy requirements in DCs and, to some extent, in CPEs, is uncertain. Some alternatives also require a staggering degree of technological know-how which DCs do not possess. In fact, DCs are almost totally dependent on the external supply of technology for developing and managing even the pollution-intensive fossil fuels. While CPEs (e.g. China and USSR) are more technologically advanced than DCs, their stage of technology is not sophisticated enough for the proper and efficient development of alternative cleaner energy sources.

In addition, a great deal of high-risk capital is needed for these alternatives, but it is rarely available in most DCs, which have a long list of other development priorities and few indigenous capital-generating sources. There is also the problem of cost competitiveness of these energy alternatives, apart from a host of environmental, safety and security problems (e.g. nuclear energy) accompanying their use. For example, the 1977 cost of $900 million for a 1,000-megawatt nuclear reactor converted to an oil equivalent of nearly $100 a barrel[17]. It is not likely that the price of production of nuclear energy would have fallen so drastically to make it comparable to the cost of importing oil. Moreover, nuclear fission comes in units too large for the present power grids of most developing nations. Hydropower is also highly capital-intensive and construction costs are usually about $600/Kw[18]. Also, although solar thermal units and photovoltaic cells can be adapted to a wide range of desired scales, neither can produce centralized electricity at costs competitive with fossil fuels[19]. In general, therefore, formidable and costly technical and capital problems stand in the way of widespread use of these energy alternatives in DCs and CPEs.

Socio-Political Issues

The problem of global warming is not likely to escape the political rhetoric that has characterized the North-South dialogue over a wide range of environmental and economic issues in the past.

On a national basis, DCs and CPEs see development as including distribution of income and social powers so that at least the basic needs of the poorest people can be met: otherwise, political instability is likely to result. A government is therefore often reluctant to take energy-saving measures that would not serve the variety of social, economic and political needs of the country. For example, it has been projected that only a ban on coal and shale oil instituted in 2000 would effectively delay a 2 °C global warming by about 25 years[20]. However, while a global ban on the use of coal will reduce greenhouse-gas emissions considerably, the Chinese might lose almost $1800 in per capita GNP[21]. This is obviously politically and economically infeasible. An attempt by the Nigerian government to reduce oil-use rates in the country by removing some of its oil subsidies met with violent protests and forced the government to soften its stand.

On the international scene, the global warming issue may be politicized by DCs' eagerness to justify unrestrained industrialization and energy use in order to reduce their high degree of poverty. Developing nations will most likely be eager to proceed with ambitious development programs that are energy intensive. To some, holding economic growth *per se* for environmental ills diverts attention away from the real causes of the problem which lie in the capitalist world's profit-motivated systems of production. To others, there is the suspicion that environmental issues are being used inadvertently by industrialized countries as a pretext for maintaining the economic status quo. The implementation of any world-wide environmental policy based on the realities of the developed nations is believed to tend to perpetuate the existing gap between developed and developing countries. Developing nations would then continue their role as "hewers of wood and drawers of water" or suppliers of cheap raw materials[22]. Politics, rather than concern about global greenhouse-gas emissions, may be responsible for the solution to global warming. Warnings about the climatic implications of global warming can be dismissed by politicians as "ecologism" and "scientific imperialism" fabricated by developed nations concerned about the survival of their affluence in the face of demands for equity[23]. Attempts to reduce global greenhouse-gas emissions may, therefore, meet with antagonism and may be regarded as interference in the internal affairs of many DCs and CPEs. For reasons of dignity and national prestige, therefore, DCs and CPEs may continue to prefer energy and capital-intensive routes to economic development because a such path is historically associated with wealth and prosperity.

DEVELOPMENT WITHOUT DESTRUCTION: A SOFT ENERGY PATH ALTERNATIVE STRATEGY

The preceding pages have shown that, because of the link between energy and development, DCs and CPEs are no longer insignificant contributors to the atmospheric build-up of greenhouse gases. However given pressing demands on these countries, there is no alternative to pursuing economic and social change so as to meet basic human needs and secure better prospects for their people. Faced with many social and economic problems of development, the issue then is that of priorities of perception.

Global warming is a transnational problem which does not respect political, social and economic systems and therefore requires North-South cooperation in developing programs that seek to achieve significant reductions in greenhouse-gas emissions. Environmental and developmental objectives should be seen as complimentary. The complementarity of environmental and developmental objectives in terms of controlling the impending global warming can be achieved by following what Lovins[24] has called the "soft energy path" strategy.

The soft energy path involves (i) improving energy efficiency whereby the same or even higher energy services can be provided by less energy; and (ii) turning to greenhouse gas-free non-fossil renewable energy sources. This two-pronged strategy relies on rapid development of what Lovins calls soft technologies which rely on "technologies that are already developed, highly economical and indistinguishable with respect to reliability and convenience from current energy systems"[25]. Soft-technology scenarios have also been demonstrated by Lovins to directly meet basic human needs, rather than supplying a costly high-technology form of energy with imported capital-intensive systems that can only enrich urban elites at the expense of rural villagers. These technologies permit, but do not require, mass production thus encouraging local manufacture by capital saving and labor-intensive methods, with equipment adapted to local needs, materials and skills. Soft technologies could therefore provide the basis for an indigenous eco-development of DCs and even CPEs. In addition, developing nations should take cognizance of the need for family planning to reduce the increasing demand for energy by their ever increasing population. The combination of population control with soft energy appears socially, economically and politically feasible to secure DC and CPE participation in international energy policies, strategies, and programs necessary to achieve a significant reduction targets for CO_2 and other trace-gas emissions, required for averting anthropogenically greenhouse gas-induced climatic changes.

CONCLUSION

By virtue of their heavy dependence on carbon-rich fossil fuels to meet their desire for rapid industrialization and economic growth, developing nations and countries with centrally-planned economies will contribute significantly to the current anthropogenically-induced high build-up of atmospheric greenhouse gases. Because of a number of social, economic and political problems, it was conjectured that to achieve a reduction target for CO_2 and other trace-gas emissions by restricting fossil-fuel use may not be very feasible for DCs and CPEs. Alternatively, opportunities for increases in energy efficiency and adoption of a "soft energy" path, not only to reduce carbon emissions, but to sustain growth, should be properly exploited by these nations. Such goals could also be translated into quantitative targets. International cooperation for transfer of soft technology and knowledge for energy efficient utilization of non-fossil renewable energy sources could prove globally beneficial. The political will to achieve such an international cooperation is all that is required.

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