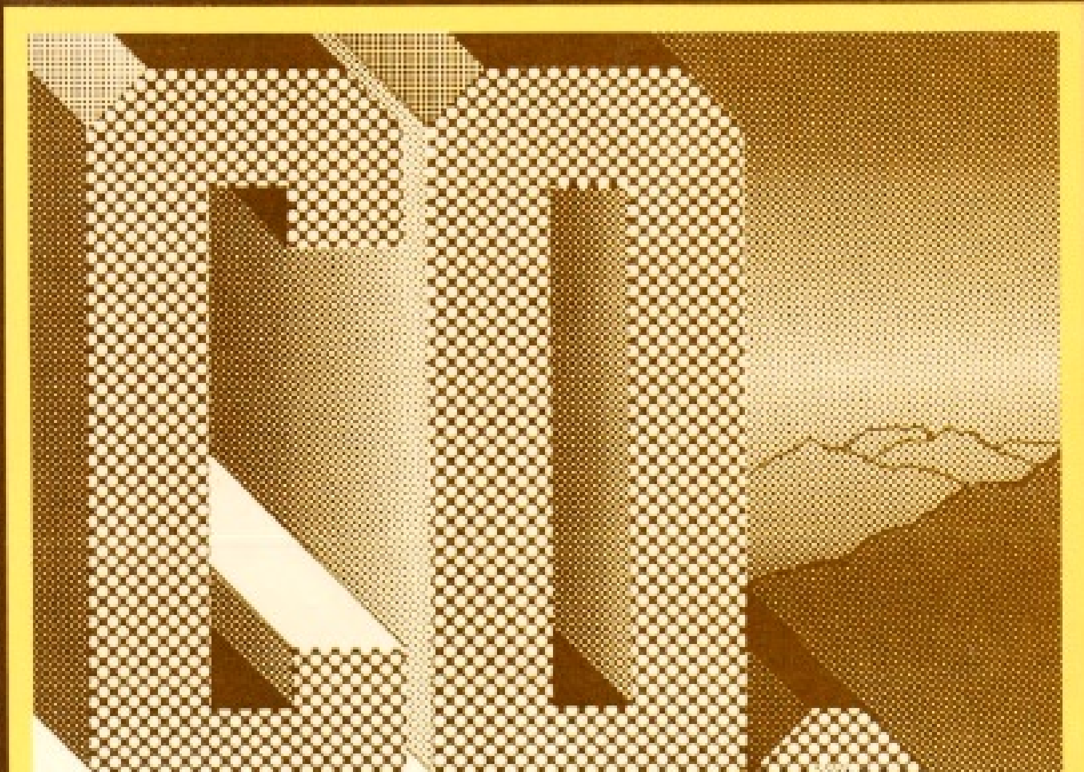
IIASA PROCEEDINGS SERIES

ENVIRONMENT

Carbon Dioxide, Climate and Society

Jill Williams, Editor



International
Institute for
Applied
Systems
Analysis

IIASA PROCEEDINGS SERIES
ENVIRONMENT

Volume 1

Carbon Dioxide, Climate and Society

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Carbon Dioxide, Climate and Society

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Editor

JILL WILLIAMS

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PREFACE

The IIASA Energy Systems Program is studying global aspects of energy systems, concentrating on a time period 15 to 50 years from now. The study therefore considers energy resources and demands, options, strategies, and constraints. One constraint on an energy system is its potential impact on climate. The IIASA Energy and Climate Subtask, which is supported by the United Nations Environment Programme (UNEP), is studying the possible impact on global climate of the three major medium- to long-term energy options: nuclear, fossil fuel, and solar energy conversion systems. A workshop was held at IIASA in February 1978, co-sponsored by the World Meteorological Organization (WMO), UNEP, and the Scientific Committee on Problems of the Environment (SCOPE), to discuss questions associated with carbon dioxide (CO_2) produced by the combustion of fossil fuels, its impact on climate and environment, and the implications of present knowledge on these questions for energy strategies. The Workshop considered three major aspects of the "the CO_2 problem". Firstly, the biogeochemical carbon cycle was discussed as a background for predicting future atmospheric concentrations of CO_2 given a knowledge of inputs. Secondly, the present state of knowledge regarding the impacts of increased atmospheric CO_2 concentrations on climate and environment was examined. Thirdly, the implications of our present knowledge (and lack of knowledge) of the first two aspects with regard to decisionmaking on energy strategies were analyzed. The material presented in the Proceedings forms the basis for a continuing study of the climate constraints of the fossil fuel option and a comparison of the options.

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INTRODUCTION

J. Williams

The IIASA Energy Systems Program is studying global aspects of energy systems, concentrating on the time period 15 to 50 years from now. This study therefore considers energy resources and demand, options, strategies, and constraints. Further details on this work are given elsewhere in these Proceedings. As a part of the Energy Systems Program the Energy and Climate Subtask is studying the climatic constraints upon large-scale energy conversion systems, in particular nuclear, fossil fuel, and solar options. This study therefore involves an evaluation of the climatic constraints associated with the CO_2 produced by combustion of fossil fuels; the Workshop on Carbon Dioxide, Climate and Society was organized as part of this effort.

The Energy and Climate Subtask is supported for a period of three years by a generous grant from the United Nations Environment Programme (UNEP), and since a substantial amount of this grant was used to organize the Workshop, UNEP is listed among the cosponsors for the meeting. We are also happy to include two further cosponsors for the meeting: the World Meteorological Organization (WMO), and the Scientific Committee on Problems of the Environment (SCOPE).

The "CO_2 problem", as it has often been called, has basically three aspects. Firstly, we are concerned with the carbon cycle, that is, a description of the sources and sinks of carbon and the transfers of carbon between the atmospheric, biospheric, and oceanic reservoirs. Only with a detailed knowledge of the biogeochemical carbon cycle can we hope to predict future levels of atmospheric CO_2 concentration.

Given that the atmospheric CO_2 concentration will reach a certain level in the future, the second aspect of the CO_2 problem is to discuss the impact of this CO_2 on climate and thus on the environment, including such areas as agriculture and the ice caps.

The third aspect is then a discussion of what the present knowledge (and lack of knowledge) about the first two points implies for decisionmaking concerning energy strategies.

The first two days of the Workshop on Carbon Dioxide, Climate and Society were spent in reviewing present knowledge on each of the above three aspects. During the second two days, three Working Groups met to discuss the problems further and to produce a list of major issues that were covered, an evaluation of our present knowledge on the three aspects of the CO_2 problem, and recommendations.

This Proceedings volume contains a virtually complete record of the Workshop. The remainder of the first part consists of introductory remarks made at the opening of the meeting by the cosponsoring organizations and a description of the IIASA Energy Systems Program as it relates to questions raised at the Workshop. Short review papers on the three aspects of the CO_2 problem are presented, followed by papers submitted for discussion in the Working Groups. Finally the reports of the Working Groups are included.

In addition to acknowledging support for the Workshop of the cosponsoring organizations, I should like to thank certain individuals who have made contributions to the production of the Proceedings. Jeanne Anderer and Barbara Lewis of IIASA have done an enormous amount of work in the editing of papers, and the assistance of Ingrid Baubinder of the IIASA Energy Systems Program in preparing the Proceedings is gratefully acknowledged. Without the dedicated work of the Documents and Publications Department and contributions from many other individuals at IIASA the prompt production of this volume would have been an impossible task.

INTRODUCTORY STATEMENTS

WELCOMING ADDRESS

R.E. Levien

It is a pleasure to welcome you on behalf of the Institute and myself to this Workshop on CO_2, Climate and Society. The Workshop has been organized jointly by IIASA, the World Meteorological Organization (WMO), the United Nations Environment Programme (UNEP), and the Scientific Committee on Problems of the Environment (SCOPE).

In order to explain how IIASA came to be interested in the problems of man's impact on the climate generally, and in the potential effects of CO_2 specifically, I would like to tell you briefly about the history and research program of the Institute, and about the way we function.

The Institute was five years old last October, though the notion of IIASA is over eleven years old. It was first proposed at the end of 1966, when US President Lyndon Johnson suggested that an Institute might be created to work on the common problems of industrialized nations by bringing together scientists from East and West, thereby serving as a bridge between different societies. In 1967, he sent McGeorge Bundy to Moscow to meet with Jermen Gvishiani, Deputy Chairman of the USSR State Committee for Science and Technology. The Soviet response was very positive. There followed five years of negotiations, during which the USA, the USSR, and ten other nations agreed to participate in the founding of such an institute.

The founders made a crucial decision: to establish the Institute not as an intergovernmental organization, like the United Nations agencies, but as a nongovernmental organization. That is what IIASA is today. Our membership consists of one scientific organization from each of the seventeen participating countries--the National Academy of Sciences in the USA, the Academy of Sciences in the USSR, and similar institutions in, now, 15 other countries. The first 12 National Member Organizations (NMOs) met in October 1972 to establish IIASA, and scientific work began in June 1973. At the time the Charter was signed, Austria offered IIASA the use of Schloss Laxenburg, which has now been renovated beautifully to meet the Institute's needs.

The 17 NMOs provide the basic funds for the Institute, the USA and the USSR NMOs each granting 1.7 million dollars in 1978, and each of the others 260,000 dollars a year: a total budget of about 7 million dollars. Each NMO has a representative on the

Council which sets the overall policy for IIASA. The research activities are the responsibility of the Director.

What are the research activities of the Institute? They are reflected in two phrases in our title: *international applied*, and *systems analysis*. *International applied* means that IIASA has as its basic function, work on real problems of international importance. We distinguish two kinds of such problems. The first we call *global*: issues that inherently cut across national boundaries and cannot be resolved by the actions of single nations. So, for example, we have the problem of global development--how, within the next 50 to 70 years, we can meet the needs of a growing population for food, clothing, housing, a safe environment, health, and so on. But rather than treat the problem as a whole, as the global modeling enthusiasts do, we study specific sectors of global development in turn. The first sector we have chosen is energy. The Energy Systems Program at IIASA, led by Wolf Häfele, is concerned with the evolution of the global energy system, particularly its smooth transition, about 15 to 50 years from now, from one based on oil and gas to one based on virtually inexhaustible energy sources--nuclear, solar, or coal. The Program has a five-year lifetime and seeks to look at the technological and economic aspects of the development of alternative energy systems. Among its concerns are the constraints that limit the choice of feasible energy strategies. One of these constraints is the potential of energy production to affect the climate through waste heat releases, changes in the earth's albedo by solar collector fields, and the production of CO_2. Work on climate impacts at IIASA was initiated with the work of Allen Murphy of the National Center for Atmospheric Research (NCAR) in the USA several years ago and has been carried forward under the leadership of Jill Williams since the middle of 1976. This effort provided the direct impetus for IIASA's organization of this Workshop.

The second global program, which began in 1977, studies the food problem in a similar context: the evolution of national food policies and their interaction through the international food markets, and the question of how well those policies will provide for the nutritional needs of a growing world population. It is evident that the Food and Agriculture Program must be concerned with climate as well. On the one hand, there is the potentially serious influence of long-term changes in climate on the food production capability of the globe, which should be taken into account in considering national and international food policies. On the other hand, there is the prospective influence of man's agricultural practices on the climate through deforestation, use of nitrogen fertilizers, and changes of albedo. We expect this interest to develop strongly in the coming years.

The second category of international problems we call *universal*. These are problems that reside within national boundaries, but that all nations face--for example the design and operation of a health care system, or an education system. While each of these is subject to national decisionmaking, all nations share these problems, and much can be learned through the exchange of information among nations. That is one of the purposes of IIASA--to facilitate exchanges of information and methodologies across national boundaries, and across social, economic, and political boundaries as well.

The second phrase in our title, *systems analysis*, means different things to different people. We take it to mean that, when studying problems of international importance, we have an obligation to study them in their full breadth--not to limit our study to the way in which a Ministry or a particular discipline might approach the question, but to include all the aspects that affect the decisions to be made. So in studying the global energy future, we are not limiting ourselves to the technology or the economics of energy, but we consider also: how many people will there be, what will their demand for energy be, what climatological and social factors are involved? And so on.

IIASA's research is organized in four Research Areas, each with its experts in particular aspects of knowledge necessary for systems studies. The Resources and Environment Area is concerned with the natural endowments of the earth, with water, minerals, with the environment, and so on, and it has specialists with skills and interests in those topics. This is the home for our climatologists and meteorologists, as well as for the water resources experts who are naturally concerned with the impact of climate change on the distribution of water supply and demand. The Human Settlements and Services Area, specializing in the human resources of the globe, has topographers, urban planners, health care specialists, and so forth. They have a latent interest in the impact of significant climate change on man's settlement patterns and living styles. The third area is Management and Technology, with specialists in organization and management matters and general technologies. Among its concerns are the management of man-made and natural disasters. Drought management, for example, may soon enter its agenda. And the System and Decision Sciences Area is concerned with the mathematical and computational tools for studying complex systems. It is developing an international computer network that offers a means for collaboration among climate modelers in different countries.

We have a residual category, as all good organizations must, that we call General Research--topics that do not fit neatly into the other Areas, some of them quite important for IIASA's work. They include a series of books on aspects of the state of the art in systems analysis.

So you can see that although the impetus for this meeting occurred in the Energy Systems Program, a concern for society's interaction with the climate pervades the Institute's entire research activity, both actually and latently.

Although I have not said much about the various studies, you can infer that this breadth of interest implies a large research program, one that is very ambitious for the resources available to the Institute. These consist of 70 scientists who salaries are paid by NMO contributions, a library with good connections to other libraries around Europe, an adequate medium-sized computer system, and an annual budget of about 7 million dollars, or 115 million Austrian Schillings. But no institution with these resources could hope to achieve the program outlined if it worked only by itself. The important aspect of IIASA is that it does not aim to be, nor does it function as, a self-contained research institution. Rather, its purpose is to be the core of an international network--the visible part of an invisible international college collaborating in the programs that have been set for us.

Around the 70 person core there are two additions within IIASA. One is the presence here of guest scholars, scientists whose salary is paid by their home institutions, who work with our staff and also serve as our link to their home institutions. For example, we have had scientists from IBM, Shell, Siemens, and Arthur Andersen. Second, we receive each year, in addition to our basic funding, about 1 million dollars of external funding. Prominent among the sources of such support has been UNEP, which has given us a major grant to work on the climate impacts of energy production--the topic of this meeting. We are grateful to them for their help. Thus in addition to our NMO-sponsored scientists, we have 10 guest scholars on average, and about 15 whose funds are provided by external resources. This makes it more feasible for us to carry out the work we want to, but even 95--or 395--is still too few for the large goals of the Institute.

The major amplification of our efforts occurs through collaborative research with particular institutions in particular countries. We have at the moment seven collaborative agreements, covering topics ranging from the development of agricultural-industrial complexes in Bulgaria, to joint work in energy, health care systems, and so on. On the topics of this meeting, we have worked closely and intensively with the British Meteorological Office and NCAR in the USA. Through each of these links we multiply the effort that IIASA and its NMOs can apply to a problem.

Beyond collaborative research, we have what we call catalyzed research--activities undertaken in other research institutions, not in close collaboration with IIASA, but stimulated by our concern for a particular problem. We have been told that our early work on CO_2 and energy has stimulated further work at other centers.

Finally, and I think most important for this meeting, there is the role of IIASA as an information exchange agent. We can, and frequently do, bring together representatives from institutions having common interests, but from many different countries. Through this mechanism of information exchange, IIASA is able to play an important role in facilitating joint work among institutions around the world. Thus, the main work of the Institute is achieved through this ever-increasing series of interlinkages between the Institute and the larger scientific community worldwide.

Again, welcome to IIASA; and now that you have been here, we hope that you will view yourselves as part of the extended IIASA community and continue your association with the Institute when you return to your home institutions. We hope to see you here many times in the future.

OPENING ADDRESS ON BEHALF OF THE SECRETARY GENERAL OF WMO

R.D. Bojkov

On behalf of the Secretary General of the World Meteorological Organization (WMO), Dr. D.A. Davis, it is a pleasure to welcome you to this Workshop. This is not the first gathering on the subject of CO_2 that has been organized with the support and participation of WMO. In December 1976, WMO organized the Scientific Workshop on Atmospheric CO_2, held in Washington, D.C., at which the United Nations Environmental Programme (UNEP), the International Council of Scientific Unions (ICSU), and IIASA were also represented. The 1976 workshop produced a valuable report (WMO, 1977) on the current state of knowledge that included recommendations for atmospheric monitoring and research aimed at improving predictions of future atmospheric CO_2 content. Based on these recommendations, the WMO Executive Committee in June 1977 approved a WMO research and monitoring project on atmospheric CO_2. A small expert group was set up and charged with advising the Executive Committee and the Secretary General on the implementation of the project. Among the participants to this Workshop are some members of this group--Dr. Kellogg, Professor Junge, and Professor Oeschger.

The WMO project calls for among other things monitoring of the CO_2 content of the atmosphere, research for predicting both the evolution of the atmospheric CO_2 content over the next 100 years and the possible impacts of these changes on climate trends and, an assessment of the consequences of a warmer lower atmosphere on, for example, glaciers and ice sheets, food production, and land use. Most activities relevant to CO_2 will be nationally sponsored. WMO will take the lead in coordinating the activities relevant to atmospheric sciences and their interaction with other fields, in close collaboration with UNEP and ICSU. To achieve the project's objective, WMO intends to:

- Collect and evaluate existing data on atmospheric CO_2 concentrations;

- Extend and improve analyses and studies of transport and circulation in and between the stratosphere, the troposphere and the hydrosphere, based on actual data, with a view to predicting atmospheric CO_2 concentrations;

- Assess the impact on the atmospheric environment of possible CO_2 increases, recognizing that this involves interdisciplinary interactions requiring input from meteorology and other fields;

- Arrange for an information exchange through reports, newsletters, and scientific meetings.

Recently, the subjects of climate change and particularly the possible effects of CO_2 on climate are being widely discussed. WMO has a long record of interest in climate, although in the past, studies on climate and man have generally concentrated on climate and its impact on man's activities. Now, more emphasis is being placed on studies of climatic change and variability and especially of man's impact on these changes. WMO is planning a World Climate Programme, and studies of the CO_2 problem will be a major priority.

Mankind is slowly realizing that it faces at least three major interrelated problems--food, energy, and population--and all are related to climate. One might think that technological improvements would minimize man's dependence on climate. However, in many respects this adaptability has been exhausted so that population increases reduce our flexibility. At the same time, technological advances carry a threat to the environment through increased emissions of CO_2, heat and rare gases, and air pollutants. All have potential effects on climate which are, in principle reversible. However "exotic" chemicals are entering the atmosphere in minute quantities which, if emitted in much greater amounts, could cause irreversible changes in the atmospheric composition and structure with possible climatic effects. At the Seventh World Meteorological Congress held in May 1975, climatic change was specified as one of six priority areas from the point of view of WMO's goal of promoting and coordinating Members' research activities.

Recognizing the potential dangers and possible long-term consequences of changes in the composition of the atmosphere, WMO initiated in the late 1960s a network of background air pollution stations. The network monitors, on a global basis, certain significant constituents of the atmosphere, including CO_2, determines the global background levels of these constituents, and documents changes in these levels with time. Ten out of 17 scheduled background air pollution stations are now in operation, and WMO is arranging for publication of the observational data. WMO, with the assistance of UNEP, is cosponsoring the central laboratory for analysis of atmospheric CO_2 in La Jolla (USA). Measures to fulfil the recommendations of the 1976 Scientific Workshop are being considered.

Continuous CO_2 measurement programs exist currently in Australia, Canada, the Federal Republic of Germany, New Zealand, Sweden, and the USA. Additional measurements are required in the equatorial belt (especially in the Pacific), the Arctic, the Atlantic, South America, Africa, and the mid-latitude regions of the South Atlantic and Indian Oceans. Careful coordination, including the possible colocation of observations, is needed between atmospheric and oceanographic monitoring programs. Very useful would be a few years of aircraft sampling.

Efforts to understand the CO_2 problem in order to provide credible predictions for different energy-use scenarios involves scholars in many disciplines: atmospheric scientists, ecologists and, perhaps most important, oceanographers and geochemists. One of the contributions of the atmospheric scientists will be to answer the following priority questions: By how much could the global temperature be increased without bringing about significant changes in the prevailing average circulation patterns? How much CO_2 can be added to the atmosphere before this temperature threshold is reached?

Worldwide industrial civilization may face a major decision over the next few decades--whether to continue reliance on fossil fuels as the principal energy source or to invest the capital research and engineering effort needed to find alternative energy sources over the next 50 years. The second alternative presents many difficulties, but the possible climatic consequences of reliance on fossil fuels for the future may be so severe as to leave no other choice.

A decision that will be made 50 years hence ordinarily would not be of much social or political concern today, but the development of the scientific and technical bases will require several decades of lead time and an unprecedented effort. No energy sources alternative to fossil fuels are currently satisfactory for universal use, and conversion to other sources will require many decades. Similarly, finding ways to reliably estimate the climatic changes that may result from the continued use of fossil fuels could very well require decades. It is hoped that the discussions at this Workshop will help in solving the problems of CO_2, climate, and society.

REFERENCE

World Meteorological Organization (1977), *Report of the Scientific Workshop on Atmospheric Carbon Dioxide*, WMO 474, Geneva.

STATEMENT ON BEHALF OF UNEP

C.C. Wallén

On behalf of the Executive Director of the United Nations Environment Programme (UNEP), Dr. Tolba, I would like to extend his greetings and wishes for a stimulating and successful meeting. UNEP closely cooperates with the Scientific Committee on Problems of the Environment (SCOPE), the World Meteorological Organization (WMO), and IIASA, and appreciates the opportunity to cosponsor this meeting with these organizations.

There have been profound changes in the relationship of man and the environment over the last century and particularly during the last years. As late as the 1930s, a feature of this relationship was how nature forced man to follow a certain pattern in his activities. During the second half of this century, the situation has changed radically to one where man has an impact on nature, which can be quite serious. There are many different pollutants in aquatic and terrestrial ecosystems that are potentially dangerous emissions into the atmosphere, some of which could result in climate changes that might threaten human and other forms of life. We recognize also a serious depletion of our natural resources.

The increasing complexity of society over the past few decades has made countries aware of their interdependence. However, it was not until the 1960s that problems of the human environment were viewed on a global basis. Following the Stockholm Conference on the Human Environment in 1972, UNEP was set up by the United Nations General Assembly. UNEP's role is basically of a catalytic and coordinating nature. Specifically, it aims to:

- Disseminate information on major environmental problems and the efforts being made to respond to them, in order to identify gaps, set objectives, and establish priorities;
- Formulate programs for action by the United Nations system or by other international organizations;
- Undertake those tasks recommended for financial support by the Environment Fund.

UNEP does not carry out special projects but functions as a funding agency; however, it also participates in the program development and in the establishment of priorities for the environmental program.

"Outer limits" has been selected by UNEP for special attention. Outer limits refers to the concept that the biosphere has only a limited tolerance for the demands placed upon it by man's activities. When these limits are transgressed, human welfare--even life itself--is threatened. No social or economic endeavor can safely ignore the restraints posed by such outer limits. Examples globally include the problems of global climatic change and threats to the ozone layer. UNEP has helped to coordinate the world's research activities in relation to the threats to the ozone layer and is therefore also interested in helping to plan worldwide research and monitoring activities related to the CO_2 problem. The representatives of UNEP to this Workshop are eager to learn about recent scientific developments for solving this problem.

So far, UNEP has cooperated extensively with WMO to develop an international approach to studying the problems of climate and climate variability. In 1976 UNEP and WMO organized a workshop on CO_2 where the Secretary General of WMO pointed out that since some scientists would not agree entirely with all the statements made in the report, it should be regarded as an interim document. It will be interesting to see how far the participants at this Workshop have come toward reaching a consensus with regard to both the CO_2 problem and to how cooperation among IIASA, WMO, SCOPE, and UNEP should be organized to achieve a better understanding of this problem.

INTRODUCTORY REMARKS FROM SCOPE

T.F. Malone*

It is a pleasure to bring greetings to this Workshop from Professor Bruno Straub, President of the International Council of Scientific Unions (ICSU), and Professor Gilbert White, President of the Scientific Committee on Problems of the Environment (SCOPE). We are pleased to be cosponsors with the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) at this important event arranged by IIASA. It promises to be a superb example of international cooperation among different organizations, and we applaud IIASA's initiative in proposing the Workshop.

ICSU is an international nongovernmental scientific organization comprising 18 Scientific Unions that span the range of natural sciences, and 65 National Members. To cover the multidisciplinary activities that include the interests of several unions, ICSU has established a number of scientific committees, of which SCOPE, founded in 1969, is one. Currently, representatives of 32 member countries and 15 unions and scientific committees participate in the work of SCOPE, which directs particular attention to the needs of developing countries.

SCOPE's mandate is to assemble, review, and assess information on man-made environmental changes and their effects on man; to assess and evaluate methodologies for measuring environmental parameters; to provide information on current research; and, by recruiting the best available constructive thinkers, to be a source of advice for research centers and organizations engaged in studies of the environment.

Following completion of the report, *Environmental Issues* (Holdgate and White, 1977), SCOPE decided to make biogeochemical cycling of carbon, phosphorus, nitrogen, and sulfur a special project. The long-term objective of the carbon project is to provide decisionmakers at the global, regional, and national level with appropriate scientific knowledge for developing practical strategies for optimizing man's interaction with the carbon cycle. Currently, no such strategies can be satisfactorily developed because of insufficient knowledge, particularly with respect to the quantitative aspects of the carbon cycle. Acquiring such knowledge calls for a major international and interdisciplinary effort that cannot be expected to arise spontaneously in the

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*Formerly Secretary General of SCOPE.

world's scientific community with the required degree of coordination, especially when one takes into account that the carbon cycle closely interacts with other biogeochemical cycles. The initiative of an international body such as SCOPE is therefore required. Sponsorship by a UN body such as UNEP is of vital importance for obtaining support from Member States and for ensuring full access to the results of the project for all countries, especially those that are underprivileged and could profit most from them. Moreover, the carbon cycle (and associated cycles) is likely to be a useful element in UNEP's Earthwatch System, correlating as it does a number of diverse parameters that are vitally important to the functioning of the earth's life-support system.

An immediate objective of the project is to set up a Coordinating Unit for the Carbon Cycle (CUCC). The CUCC will consist of a subunit in Hamburg led by Professor E.T. Degens, and a subunit in Stockholm led by Professor B. Bolin; these subunits are responsible for the scientific activities of the project. They will actively collaborate with an auxiliary unit in Brussels, led by Professor P. Duvigneaud, specializing in biogeochemical cartography, and with an auxiliary unit in Essen, led by Professor K.M. Meyer-Abich, specializing in the assessment of the socioeconomic implications of the cycle.

The purposes of the CUCC are:

- To collect information and data worldwide, on the global carbon cycle, especially with respect to fluxes, pools, sources, and sinks; to assess and synthesize the data for use in designing a global carbon cycle model, biogeochemical maps, etc.

- To supply data to potential users, e.g., climate modelers, the SCOPE community, research organizations, and national and international governmental organizations.

- To interpret data in terms of socioeconomic consequences, e.g., agricultural production capacity and energy policies.

- To maintain links with the scientific community through preparation of a second SCOPE publication on the carbon cycle, presentation of results at scientific meetings, participation of SCOPE and ICSU experts at international meetings, stimulation of research on the carbon cycle, i.e., by giving scientific guidance to scientists visiting the CUCC and by providing training opportunities to scientists, individually or in groups.

- To focus attention on the terrestrial biotic compartment by developing more refined models, interacting with groups surveying changes in terrestrial biomass and soil carbon, organizing specific meetings, and publishing the results of these efforts.

- To bring expertise to bear on the hydrosphere, including the role of shallow seas, in order to evaluate its importance in a global model and stimulate other work as appropriate.

- To liaise with other complementary SCOPE programs, especially those on the nitrogen, sulfur, and phosphorus cycles, and with other bodies within and outside ICSU, in order to develop the optimum scientific evaluation of major environmental problems.

- To secure to the extent possible the collaboration of scientists and institutes from developing countries, with the aim of obtaining data from tropical regions and stimulating research. Project results of importance to these countries will be made available to them.

Although the CUCC is to be embedded in research institutes, the project itself does not comprise a research component other than the assessment and synthesis of collected data.

Currently the question of interaction between atmospheric CO_2 and climate is a very critical one that greatly affects future energy strategies. Nevertheless, SCOPE has decided not to place the main emphasis of the CUCC on climate problems because this would endanger a broad and balanced approach to the carbon cycle as a whole. Responsibility for advancing international collaboration in the field of climate research has been entrusted by ICSU to the joint organizing committee for the Global Atmospheric Research Program (GARP). Thus, the CUCC will deal with modeling the carbon cycle and assisting climate modelers by providing data on the global fluxes and pools of CO_2 and other relevant compounds. Similarly, activities on the sulfur cycle and the phosphorus cycle are being undertaken. The national SCOPE Committees of the USSR and Sweden have proposed to UNEP that the sulfur cycle project be continued, and the Austrian SCOPE Committee is preparing a draft proposal with regard to the phosphorus cycle.

The study of the carbon cycle requires a major cooperative effort, and SCOPE looks forward to working together with the sponsors of the Workshop and with scientists worldwide on resolving the CO_2 climate problem.

REFERENCE

Holdgate, M.W., and G.F. White, eds. (1977), *Environmental Issues*, SCOPE Report No. 10, Wiley, New York.

A PERSPECTIVE ON ENERGY SYSTEMS AND CARBON DIOXIDE

W. Häfele

The IIASA Energy Systems Program is studying global aspects of energy systems, concentrating on the time period 15 to 50 years from now. It considers energy resources and demand and from this basis the future options and their systems implications can be identified. Interest then focuses on the transition from today's conditions to one option or a combination of options, with consideration of the constraints on such a transition.

The world primary energy consumption in 1975 was about 7.5 TW years per year or, in short, 7.5 TW. The share of oil and gas in this total is about 5.5 TW, with oil from the Middle East amounting to 1.5 TW. The significance of the latter point source of energy supply will be emphasized below. During the 1960s the energy price was US \$0.5/10^6Btu (~\$3/barrel) and the present price is \$2/10^6Btu (~\$12/barrel). For the short-to-medium term future, estimates for the energy price made by WAES (1977), IEA (1977), and WEC (1977) are in the range \$3-4/10^6Btu (~\$18-24/barrel) and the energy price of alternative sources (e.g., coal gasification or hydrogen) are in the range of \$4-5/10^6Btu (~\$24-30/barrel).

Figure 1 shows the time phases which can be regarded with respect to energy systems, together with the characteristics of these time phases. Three time phases are distinguished: continuation of present trends which might be termed "muddling through" until the year 2000; a transition period between 2000 and 2030; and a post-transition period beyond the year 2030.

An important consideration which must be made with respect to these time phases is the period taken for primary energy carriers to gain or lose their market shares, referred to as the market penetration period. Figure 2 shows in a logarithmic plot the contributions of various energy sources to the global energy supply during the past 100 years. The substitution of the various sources follows a regular logistic pattern, which is well known in market theory. On the basis of such a market penetration concept it is possible to extrapolate past trends and to discuss the introduction of alternative energy sources and their likely position in the market as a function of time. It can be calculated that the time period for gaining or losing a 50% market share was, for the globe, 160 years for wood, 170 years for coal, 78 years for oil, and 90 years for gas. For the United States the equivalent time periods were shorter, but still in the range of 60 years. The observed limited flexibility

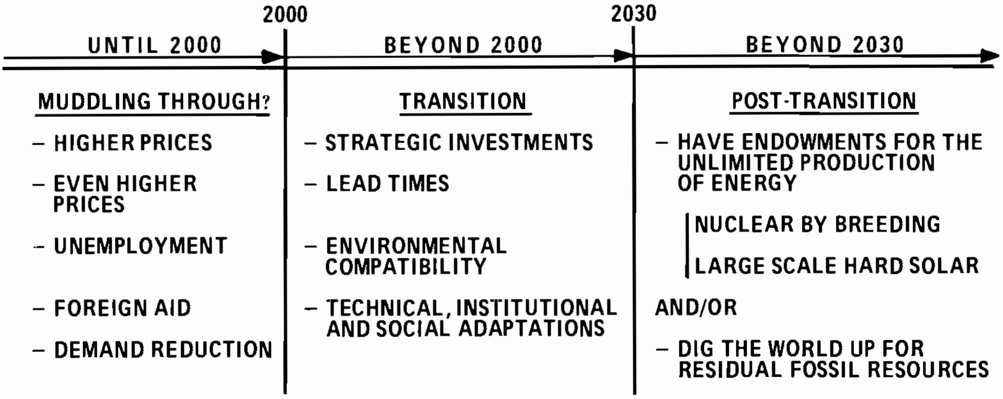


Figure 1. Time phases of energy.

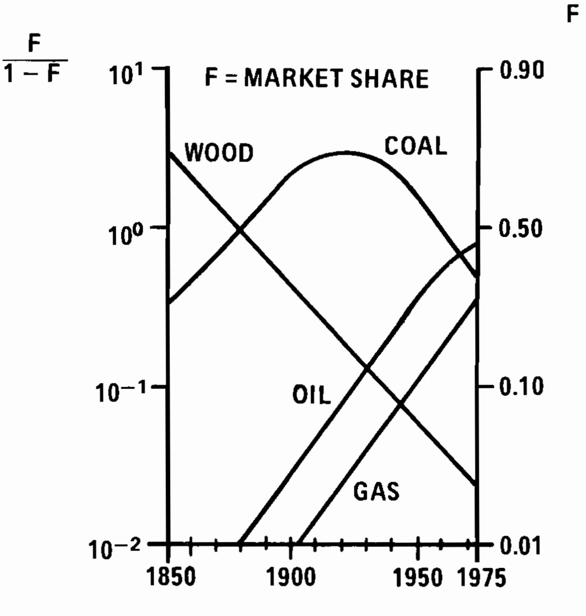


Figure 2. Energy market penetrations: World.

After: Marchetti, IIASA

of the global energy system in shifting to new energy sources must therefore be considered with respect to the time phases for energy systems shown in Figure 1.

Before we can make an assessment of the various alternative energy sources which could and must be introduced, it is necessary to outline the development of energy demand. Energy growth is stimulated by world population growth, the development of less developed countries and continued industrialization in developed countries. The most important stimulus for energy growth will result from efforts to reduce the differences between developed and developing countries. Figure 3 illustrates the unequal distribution of energy consumption per capita between countries. More than 70% of the world population lives with less than 2 kW per capita and more than 80 countries have a consumption as low as 0.2 kW/cap, with only 6% of the world population enjoying consumption levels greater than 7 kW/cap. Energy consumption is highly correlated to economic output and substantial improvement of economic conditions in the developing world will significantly increase the present global energy consumption level of 1.9 kW/cap.

The IIASA Energy Systems Program has made an estimate of future minimum energy demand based on considerations as those in the above paragraph. As shown in Figure 4, the world was disaggregated into seven regions roughly corresponding to: North America, the Soviet Union and Eastern European countries, Western Europe with Japan, Latin and South America, South East Asia and Africa, the Middle East and China. Population figures

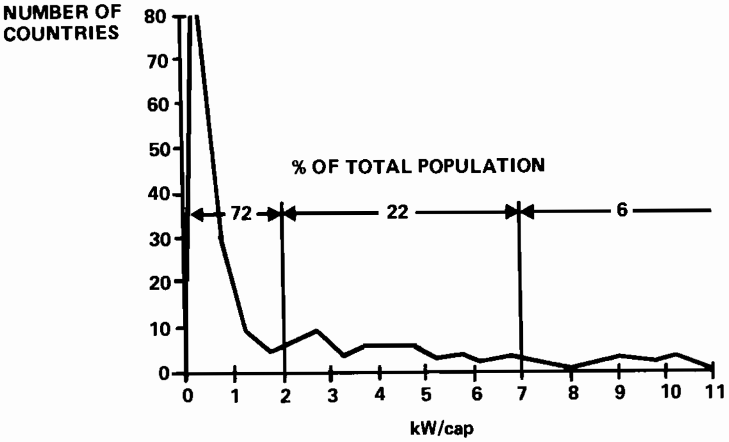
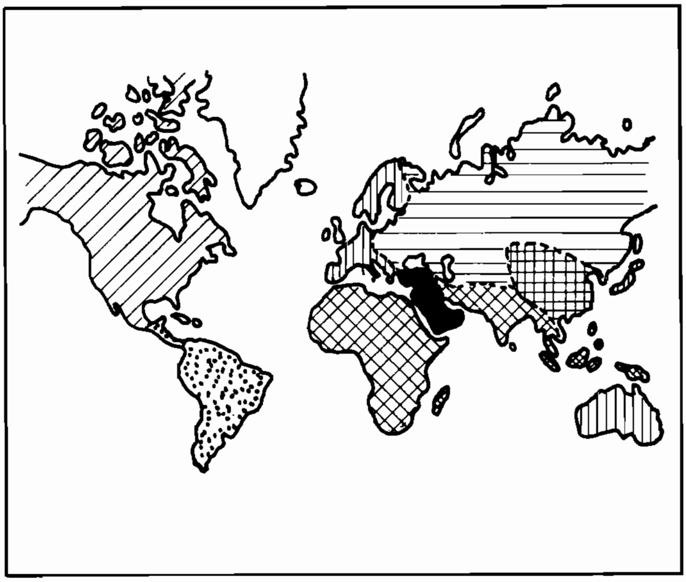


Figure 3. Distribution of per capita energy consumption, 1971.

After: Charpentier, IIASA

were taken from Keyfitz (1977), with a total world population projected for 2030 not larger than 8 billion people. Per capita energy demand growth rates in developed regions were assumed to decline steadily, coming close to saturation in 50 years from now. For developing regions higher growth rates and later saturation were assumed. The 16.5 kW/cap projection for North America implies a high degree of conservation, bearing in mind that the present US level is already at 11 kW/cap. This reference demand scenario gives a global energy demand of 35 TW and an average per capita level of 4.4 kW in 2030. These figures refer to an energy input to the economy equivalent in quality to that of the present primary energy spectrum. Changes in this quality, which are inevitable when alternative energy sources are introduced, will be discussed with regard to the supply technologies below. The cumulated overall world energy demand by 2030 is approximately 1000 TW years for this reference scenario.

The size of the available fossil energy resources to supply energy for the above scenario is a complex problem in itself and a theme of an ever continuing debate. Figure 5 relates the economically recoverable reserves of fossil energy and the cumulated consumption of the above minimum energy demand scenario. Only a fraction of the 35 TW in 2030 can be supplied in the form of conventional oil, gas, and coal. The geological



Region		Pop. 10^6	kW/ cap	TW
I	▨	310	16.5	5.0
II	▤	460	11.6	5.3
III	▥	780	10.5	8.2
IV	░	720	3.3	2.4
V	▩	3700	1.4	5.2
VI	■	300	4.8	1.4
VII	▦	1800	4.6	8.3
				~35

Population: 8–10^9, Energy: 35TW or 4.4 kW/cap

Figure 4. Reference demand scenario, World, 2030.

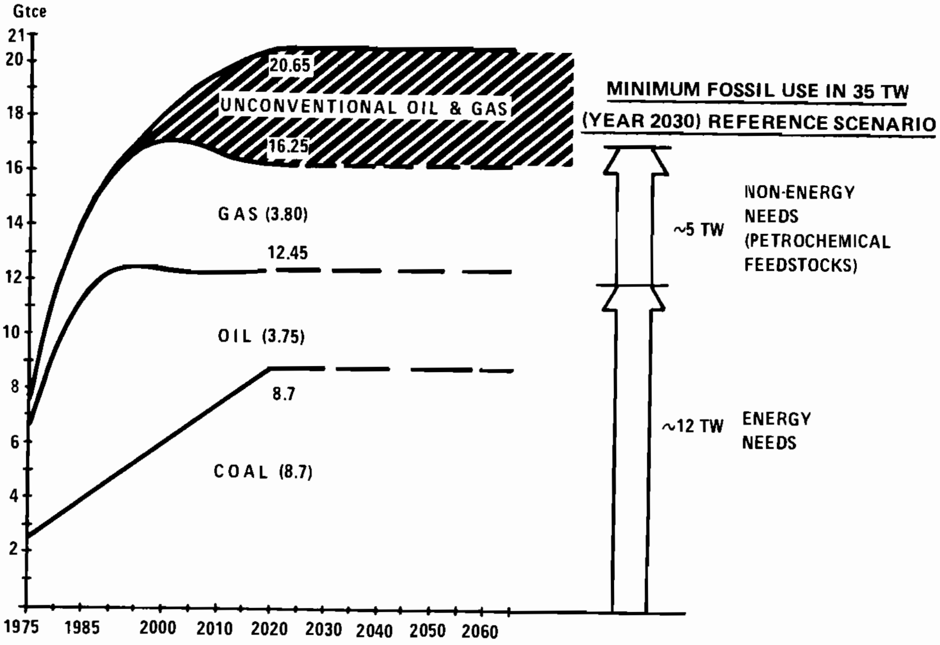


Figure 5. Total fossil fuels: possible production and lifetimes.

resources of fossil energy are much larger but are not recoverable under forseeable technological and economic conditions. A further constraint on the large-scale use of fossil fuel energy is represented by the CO_2 problem. Box models of the carbon cycle (e.g., Machta and Telegadas 1974) show the sizes of the carbon (C) reservoirs to be of the order of 600×10^9t C for the atmosphere, 1100×10^9t C for the ocean mixed layer and 29800×10^9t C for the deep ocean. The net transfer rate between the atmosphere and mixed layer of the ocean is $\sim2\times10^9$t C/year and between the mixed layer and deep ocean is $\sim0.1\times10^9$t C/year. These reservoirs and transfer rates can be compared with the fact that in combusting 4300 TW years of coal, which is a hypothetical figure based on the assumption that 50% of the geological resources of coal could be recovered, a transfer of 4500×10^9t C in the form of CO_2 would have to be accomplished from the atmosphere, through the mixed layer of the ocean and into the deep ocean. These numbers suggest that a costly direct disposal of CO_2 into the deep sea might have to be envisaged if fossil fuel could be developed as a significant source of energy beyond the year 2030. Such a scheme, using an energy island for the fossil "fuel cycle" and disposal of CO_2 into the ocean in the vicinity of the Straits of Gibraltar is illustrated in Figure 6 and has been described by Marchetti (1977).

The difficulties which obviously pile up for an adequate future energy supply on a global level are fundamental. In the light of these difficulties and in view of the long time horizon,

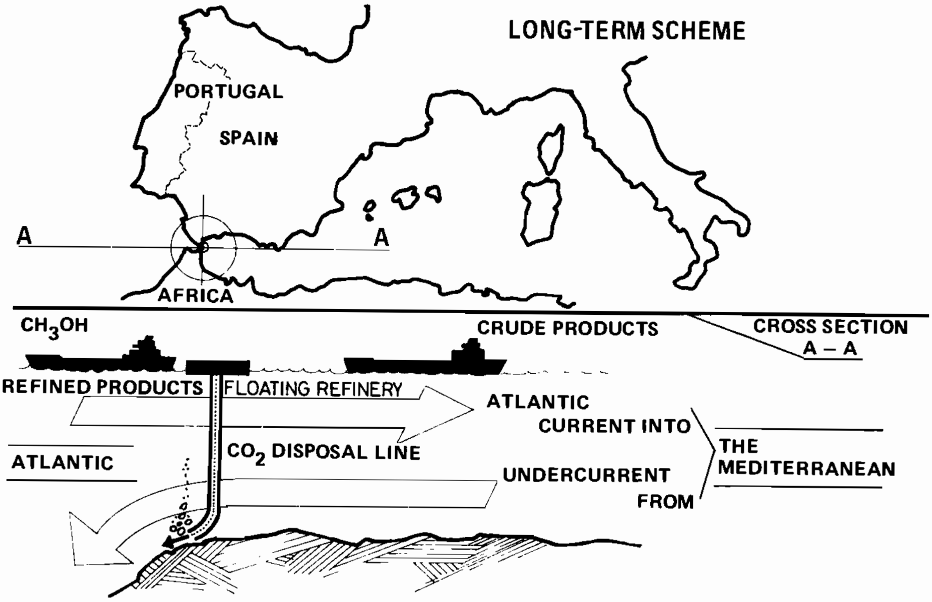


Figure 6. Long-term scheme.

Source: Marchetti (1977)

it is appropriate to have a closer look at energy demand in order to learn more about the specific problems of the transition phase. To start with, we can consider an unusual suggestion, namely "to supply energy without consuming energy": the negentropy city of Marchetti (1975). The main elements of this scheme are outlined in Figure 7. The negentropy city could be built, at least in principle, with today's technical components and would provide all the services, mechanical power, heating and cooling, etc. of our present energy systems without tapping any energy source at all. The different steps shown in Figure 7 can be explained by starting with the use of the temperature differences in tropical oceans. A kind of steam engine produces mechanical power, A, by extracting heat, Q_1, from the surface layer at temperature, T_1, discharging a smaller amount of heat, Q_2, to deeper ocean layers at temperature T_2. Instead of using the mechanical power to drive a generator and to transport electricity to the consumer, compressed air is produced. The compression heat, which equals A, is discharged to the deeper ocean layer at temperature T_2.

On balance, no energy has been taken from the ocean. The net result is a simple mixing: the oceanic temperature difference has been reduced or, scientifically speaking, the entropy

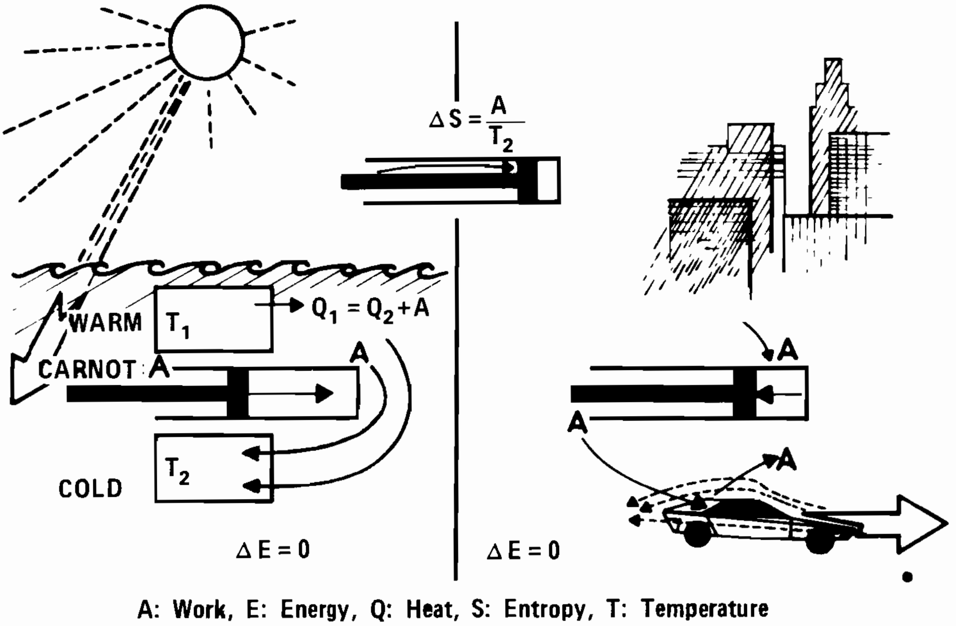


Figure 7. Negentropy City.

After: Marchetti (1975)

of the ocean has been increased. In turn a certain amount of compressed air at ambient temperature has been obtained, which does not contain more energy than before compression. No energy was taken from the ocean so that the energy of the compressed air can not have increased, but the capability of the compressed air to do work, expressed quantitatively by the reduced entropy content of the compressed air, ΔS, has changed. As it is easier to operate with a quantity that is used up instead of one that is increased in a process yielding useful output, we can refer to the negative complement of entropy, i.e. negentropy. Compressed air carrying negentropy can be stored and transported to the place where it is to be used, for instance to propel a car. There the above process is used in reverse, exchanging heat with ambient air in a closed cycle. Using this principle it would be possible to heat homes (e.g., by combining a compressed air expansion engine and a heat pump), or to perform all the other services delivered by today's energy technology.

This "Gedankenexperiment" is an extreme case. As a supply alternative the scheme would not entail classical environmental problems. There is no waste heat and there are no chemical pollutants, but other problems appear. The low negentropy density in the oceans and low negentropy carrying capacity of compressed air translate, however, into enormous material requirements for the technological devices designed to handle the "working fluids": ocean water, compressed air, and ambient air. This "Gedankenexperiment" demonstrates the fact that it is not energy which a civilization needs, it is negentropy.

Figure 8 details the various steps of conversion and transformation of energy along its way to those places where economic values are produced. Primary energy, derived in bulk quantities from natural deposits, is gradually adapted to the specific needs of final consumers. The energy sector of the economy has specialized in converting primary energy into secondary energy, a group of energy forms (e.g., light fuel oil, gasoline, electricity, hot water) with well defined specifications. Secondary energy is transported, transformed to

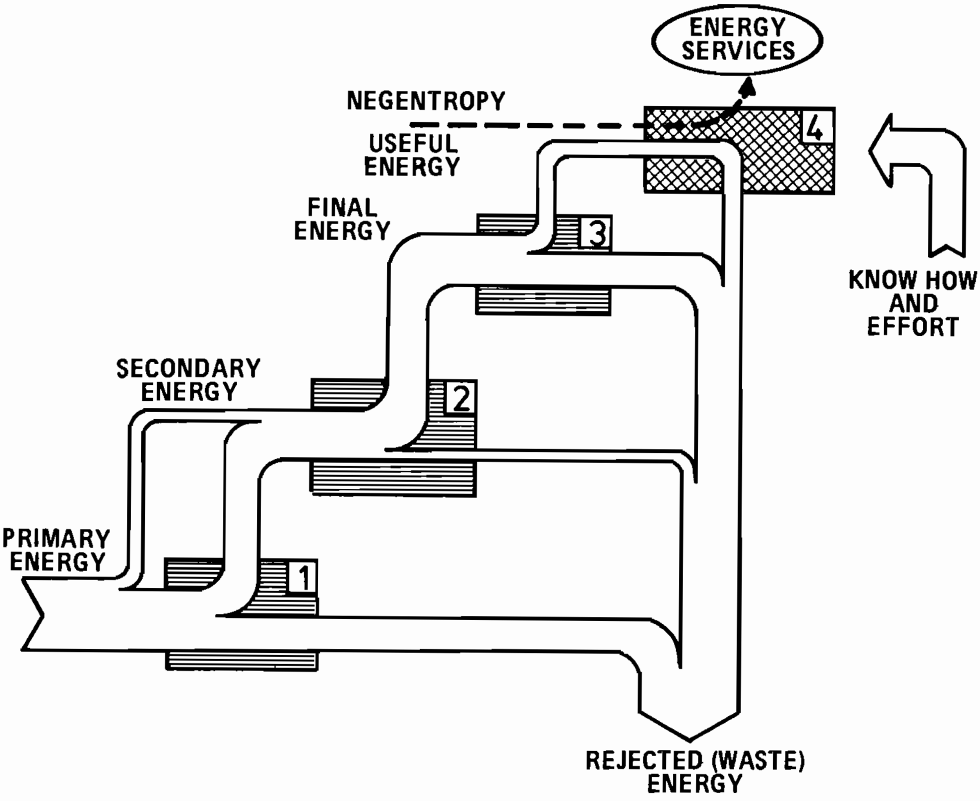


Figure 8. Energy flow and demand for energy services.

appropriate power levels and distributed to the final consumers. More than one third of the heating value of the primary energy is invested in the process of upgrading and supplying energy in modern economies. Substantial further "losses" occur at the consumer's end when final energy is converted into useful energy by operating productive tools and devices, e.g., a light bulb, an automobile engine or a stove. It is important to note that useful energy is not an economic value as such but is rather used to provide a particular service. Such a service requires at the same time input of capital and labor and constitutes the economic result, traditionally measured in monetary units, contributing to the gross national product.

For all energy services the useful energy is not really *consumed*, since in almost all cases the energy is returned to the environment as heat. There is a strict conservation law in physics for energy but there is no such law for negentropy. The above "Gedankenexperiment" suggests that the only quality which is consumed in economic processes is negentropy. It is possible to interpret energy as a proxy variable for negentropy derived from natural resources which enters productive processes in an economy. Energy is proportional to information or negentropy as long as the spectrum of final energy forms, or, more precisely, the technical energy infrastructure, does not change. Only on the level of information can total energy, capital and labor substitute for each other in the classical economic production functions.

It is with respect to the above specialization in the system that we have to look for the introduction of large-scale sources of energy which are not resource constrained. Nuclear and solar energy systems can not provide a material energy carrier, which can easily be stored, shipped over global distances and finally be distributed in small quantities to the end user at reasonable costs. All these properties are inherent features of fossil fuel energy, specifically of oil. Figure 9 shows how the concept of negentropy can be applied to the adaptation of nuclear and solar energy sources involving the upgrading of fossil fuels. This requires capital (a stock of negentropy). An input of undiluted energy (nuclear or concentrated solar) then gives a refined and clean, transportable fossil secondary energy, for example methanol. The largest single market for secondary energy, i.e., the market for liquid fuels, will suffer most from a future shortage of the primary energy source, oil. A direct substitution of oil by nuclear and solar energy is required and it appears that coal could provide the missing link.

Coal would provide the carbon for methanol synthesis. The heating value of a methanol (CH_3OH) molecule is twice as high as that of a single C atom, so the C atom in methanol *carries* with it an equal amount of energy in the form of attached hydrogen atoms. As long as the C atom is not recycled it is used as a lost (upon consumption) storage material.

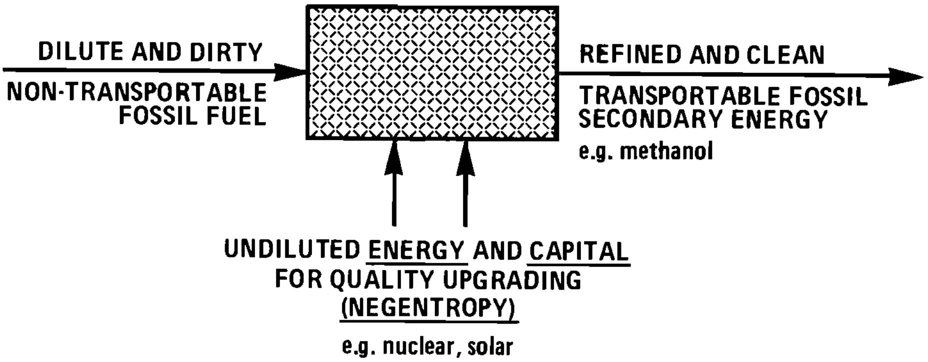


Figure 9. Using energy and capital for upgrading residual fossil fuel.

If the necessary energy to synthesize methanol is taken from other sources, namely nuclear reactors or solar concentrating devices, one ton of coal could roughly provide for a supply of two tons of coal equivalent of methanol. In view of the resource limitations of coal and the CO_2 constraints such an efficient use of the carbon atom appears mandatory. It is also possible that as long as methanol is expected to be the final product other sources of carbon than coal, including atmospheric CO_2, could be used.

In an ideal process without losses, as illustrated in Figure 10, 54 kcal of energy would have to be supplied from either nuclear or solar energy to produce one mole of CH_3OH. This requirement more than triples as shown in Figure 11 if the supply of carbon is derived from CO_2. The point here is that additional hydrogen has to be provided. If coal is available we see that 3/2 H_2 are required for one mole of CH_3OH, while twice as much, 3 H_2, is required when CO_2 provides carbon input. This is independent, of course, of whether the CO_2 comes from dense sources or from the atmosphere. If we want to take the CO_2 from the atmosphere, a theoretical total of 4.7 kcal/mol would be sufficient, but taking into account the usual losses about 30 kcal/mol would be required, which is only roughly 15% of the energy required to produce methanol from CO_2. Taking CO_2 from the atmosphere for recycling purposes and thereby for purposes of climate control is thus not too expensive. In terms of capital costs $80-100/kW methanol would be required. This is not too much compared with the capital cost of providing the 200 kcal/mol of energy in the form of H_2 which is anyway required and is perhaps $1000/kW methanol.

$$\begin{array}{l}
\underbrace{(C + 1/2H_2)}_{\text{COAL}} + 1/2O_2 = CO + 1/2H_2 + \overset{\overset{\Delta H}{\downarrow}}{26.4}\,\text{kcal} \\
(CO + 1/2H_2) + \underline{3/2}H_2 = CH_3OH_{(g)} + 21.7\,\text{kcal} \\
3/2H_2O_{(l)} \qquad\qquad = 3/2H_2 + 3/4O_2 - 102\,\text{kcal} \\
\hline
C + 1/2H_2 + 3/2H_2O = CH_3OH_{(g)} + 1/4O_2 - 54\,\text{kcal}
\end{array}$$

Figure 10. Methanol production from coal.

$$\begin{array}{l}
CO_2 + 3H_2 = CH_3OH_{(g)} + H_2O_{(g)} + 11.8\,\text{kcal} \\
\underline{3}H_2O_{(l)} = 3H_2 + 3/2O_2 - 204\,\text{kcal} \\
\hline
CO_2 + 2H_2O = CH_3OH + 3/2O_2 - 192\,\text{kcal} \\
CO_2 \text{ from air} = \frac{4.7}{\mu}\,\text{kcal} \approx 30\,\text{kcal}
\end{array}$$

Figure 11. Methanol production from CO_2.

We now introduce a supply scenario for the year 2030, where 35 TW are meant to substitute for oil, or its equivalent as a primary energy source. The underlying idea of the 35 TW supply scenario is that each primary energy contribution (except solar) should be stretched to its upper and, possibly, unrealistic limit. Solar, the most expensive contribution, is then added as a complement to the 35 TW. The scenario is illustrated in Figure 12. 5 TW are assumed for direct uses of conventional oil, gas, and coal with an additional input of 7 TW of carbon for methanol production. Further details of the derivation of the scenario are given by Häfele and Sassin (1977).

As indicated before, however, for the upgrading of residual fossil fuels, using methanol production, energy *and capital* have to be invested in substantial quantities. Capital, needed to

OIL, GAS, COAL		5 (th)	DIRECT FOSSIL
LOCALIZED RENEWABLE SOURCES (BIOGAS, WIND, SOFT SOLAR)		3 (th)	FOSSIL REPLACEMENT
HYDROPOWER	0.7 TW (e) ≙	2 (th)	FOSSIL REPLACEMENT
LWR	3 TW (e) ≙	10 (th)	FOSSIL REPLACEMENT
METHANOL (NUCLEAR & COAL)		10 (meth)	OIL REPLACEMENT
METHANOL (HARD SOLAR & COAL)		5 (meth)	OIL REPLACEMENT
		35 TW	
TOTAL FOSSIL CONSUMPTION		12 TW + 5 TW (nonenergy) = 17 TW	

(e) electric, (th) primary thermal, (meth) methanol

Figure 12. Reference supply scenario (TW), World, 2030.

Source: Häfele and Sassin (1977)

secure a long-term adequate energy supply, must be considered as the main economic substitute for presently used scarce natural energy resources. It is therefore important to check capital formation capabilities of the global economy. Figure 13 gives the capital cost estimates in today's (constant) dollars for the energy sector illustrated in Figure 12. The total required energy stock is $\$40\times10^{12}$. It is then relevant to ask what economic growth would support a buildup of a capital stock of this magnitude in the energy sector until 2030. The gross world product before the oil crisis was about $\$3.6\times10^{12}$ per year. The present state of the economy--to the extent that it is of interest here--can crudely be characterized by two ratios: the capital output ratio (i.e., the number of years for the gross national product to equal the economic value of the capital stock of the economy) and the share of the capital stock for energy purposes (i.e., the fixed capital required to supply final energy to the consumer). The former is estimated to be approximately 2.5 years today, and the latter to be close to 25%. Such an economy permits a consumption rate of roughly 60% of the GNP, with the other 40% being used for investment and certain public expenses, e.g., defense. Persistence of such values for these ratios can be considered as "business as usual".

If we assume "business as usual" to be the case, a gross world product of $\$64\times10^{12}$ per year would be needed by the year 2030, or--compared with today--a growth factor of 18; but we are talking about an energy growth factor of 4 (7.5 TW to 35 TW), and this is inconsistent. We can not, therefore, expand on capital stock by "business as usual"; energy stocks have to have a larger share of the capital stock, and this can

($75)

	ENERGY SUPPLY	CAPITAL INVESTMENTS				
			FOR PRODUCTION		FOR TRANSMISSION & DISTRIBUTION	
	TW		$/kW	10^{12} $	$/kW	10^{12} $
OIL, GAS, COAL	5 (th)		200 (th)	1	80 (th)	0.4
LOCALIZED RENEWABLE SOURCES	3 (th)	BIOGAS	100 (th)	2.1	20 (th)	0.42
		SOFT SOLAR	1000 (th)		200 (th)*	
		WIND	1000 (th)		200 (th)*	
HYDROPOWER	2 (th)		1000 (e)	0.7	700 (e)	0.5
LWR	3 (e)		700 (e)	2.1	700 (e)	2.1
NUCLEAR METHANOL	10 (th)		1500 (meth)	14	80 (th)	0.8
SOLAR METHANOL	5 (th)		3000 (meth)	15	80 (th)	0.4
				36		4.6
		GRAND TOTAL			40×10^{12} $ (STOCK)	

*With storage.
(e) electric, (th) primary thermal (meth) methanol

Figure 13. Required energy capital stock, global reference scenario (35 TW), 2030.

only come from a reduced consumption share. The energy growth factor of 4 permits a 3% overall economy growth rate, which yields a gross world product of $\$17\times10^{12}$ per year, and a consistent stock for energy installations would be around $\$10\times10^{12}$ with "business as usual"; *but* $\$40\times10^{12}$ are required. A reduction of the share of GNP going into consumption from 60 to 52.5% would allow accumulation of the required excess capital for energy stock of $\$30\times10^{12}$ but this means *immediate* action. If this reduction is only started in 15 years time, the necessary cut in consumption rate is much more severe--from 60 to 45.5%. Politically, institutionally,and socially this poses extreme problems, which can only be eased by starting strategic capital formation as early as possible.

From all of the above analysis it can be concluded that the fundamental characteristic of the transition phase will be a substitution of capital for presently used cheap resources of oil and gas. The upgrading of still existing dirty and dilute fossil energy translates within the reference scenario into an accumulation of an additional $\$30\times10^{12}$ within the next 50 years.

The extreme case of anticipating a complete recycling of CO_2, one of the aspects of the CO_2 question to be explored at this Workshop, could be interpreted to have essentially a similar order of magnitude. Very roughly speaking we might conclude by making the observation that when facing the CO_2 issue we are talking of a potential $\$10^{13}$ question.

REFERENCES

Häfele, W., and W. Sassin (1977), *A Future Energy Scenario*, Tenth World Energy Conference, Istanbul, Turkey, 19-23 September.

IEA (1977), *World Energy Outlook*, OECD, Paris.

Keyfitz, N. (1977), *Population of the World and its Regions*, internal paper, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Machta, L., and K. Telegadas (1974), Inadvertent Large-Scale Weather Modification, in W.N. Hess, ed., *Weather and Climate Modification*, Wiley, New York.

Marchetti, C. (1975), Primary Energy Substitution Models: On the Interaction Between Energy and Society, *Chem. Econ. Eng. Rev.*, 7/8, 87, 9-15.

Marchetti, C. (1977), On Geoengineering and the CO_2 Problem, *Climatic Change*, 1, 59-68.

WAES (1977), *ENERGY: Global Prospects 1985-2000*, Report of the Workshop on Alternative Energy Strategies, McGraw-Hill, New York.

WEC (1977), *Report on World Energy Demand 1985-2020*, World Energy Conference, London.

THE GLOBAL CARBON CYCLE

B. Bolin, E.T. Degens, S. Kempe, and P. Ketner

In order to assess the global sinks and sources of carbon and the interaction mechanisms between various carbon pools, the Scientific Committee on Problems of the Environment (SCOPE), a committee of the International Council of Scientific Unions (ICSU), arranged a workshop at Hamburg/Ratzeburg, FRG from March 21 to 26, 1977. The meeting was attended by 66 scientists from 22 countries. Special attention was given to having a balanced representation of the scientific community from developing and industrialized countries, because previous meetings of this type tended to have an overpresentation of problems associated with developed countries.

The meeting was financially supported by SCOPE, the United Nations Environment Programme (UNEP), the German Research Council, the University of Hamburg, and Shell.

No formal lectures were presented during the workshop. In the informal discussions, attention was focused on significant issues in the field of carbon. The three national SCOPE committees of the Netherlands, Sweden, and the FRG had prepared a four volume set of data and review articles which was presented to the workshop for consideration along with an extensive literature survey and a workshop library.

Five work groups were set up to prepare brief reviews on specific problems, and to outline future actions.

- Group 1: Atmosphere, CO_2 Source Analysis, CO_2 Level Forecasts, Transport Kinetics (Chairman, B. Bolin; Rapporteur, H.D. Freyer).
- Group 2: Primary Production and the C-Budget of the Sea (Chairman, G.M. Woodwell; Rapporteur, C.G.N. de Vooys).
- Group 3: The Geologic Carbon Cycle (Chairman, R. Wollast; Rapporteurs, A. Björkström, S. Kempe).
- Group 4: Terrestrial Net Primary Production and Phytomass (Chairman, S.C. Pandeya; Rapporteur, G.L. Ajtay).
- Group 5: Soil Microbiology and Organic Geochemistry of Soils and Sediments (Chairman, A. Nissenbaum; Rapporteur, T. Bramryd).

A graph showing the principal terrestrial sinks and sources of carbon (Figure 1) was prepared to assist in the presentation and discussion of data during the workshop. Arrows connecting the five black boxes depict the main exchange routes. Each individual box was subsequently filled with information in the form shown for the rock subcycle (Figure 2).

As a followup to the workshop, we prepared a 500 page book on the *Global Carbon Cycle*, which will be published by Wiley in late 1978 as SCOPE Report 13. The list of contents is given below.

1. The Global Biogeochemical Carbon Cycle (B. Bolin, E.T. Degens, P. Duvigneaud, and S. Kempe).
2. Primordial Synthesis of Organic Matter (E.T. Degens).
3. Variations of the Atmospheric CO_2-Content (H.D. Freyer).
4. Atmospheric Cycles of Trace Gases Containing Carbon (H.D. Freyer).
5. Terrestrial Primary Production and Phytomass (P. Ketner, G.L. Ajtay, and P. Duvigneaud).
6. The Biogeochemical Cycles of Carbon in Terrestrial Ecosystems as Affected by Man (T. Bramryd).
7. Exchanges of Carbon Between Land Biota and Atmosphere, Induced by Man (U. Hampicke).
8. Possible Effects of Increased CO_2 on Photosynthesis (J. Goudriaan and G.L. Ajtay).
9. The Carbonate System of the Ocean (K. Wagener).
10. Primary Production in Aquatic Environments (C.G.N. de Vooys).
11. Organic Carbon in the Ocean: Nature and Cycling (K. Mopper and E.T. Degens).
12. Carbon in the Fresh Water Cycle (S. Kempe).
13. Carbon in the Rock Cycle (S. Kempe).
14. Potential Use of Satellites for Assessing Pools and Fluxes of the Carbon Cycle (K.-H. Szekielda).
15. A Model of the CO_2 Interaction Between Atmosphere, Oceans and Land Biota (A. Björkström).

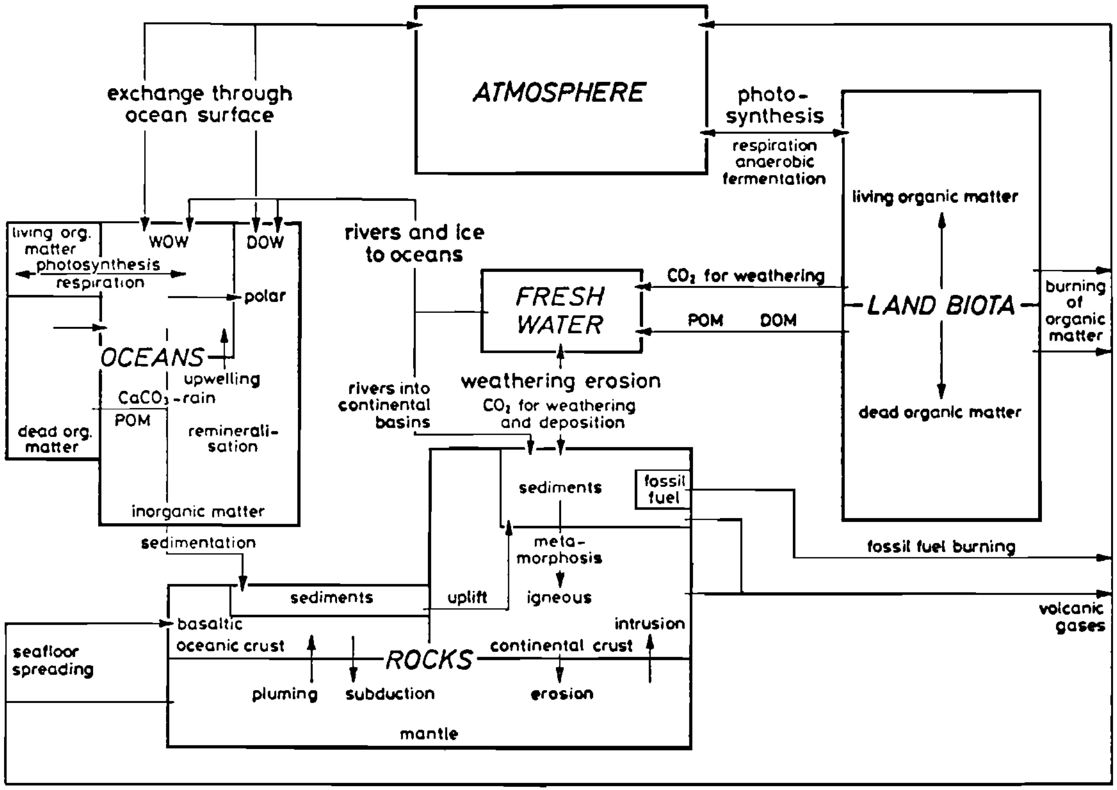


Figure 1. Terrestrial carbon pools schematically shown as 5 black boxes; arrows connecting the boxes indicate the direction of the carbon flux.

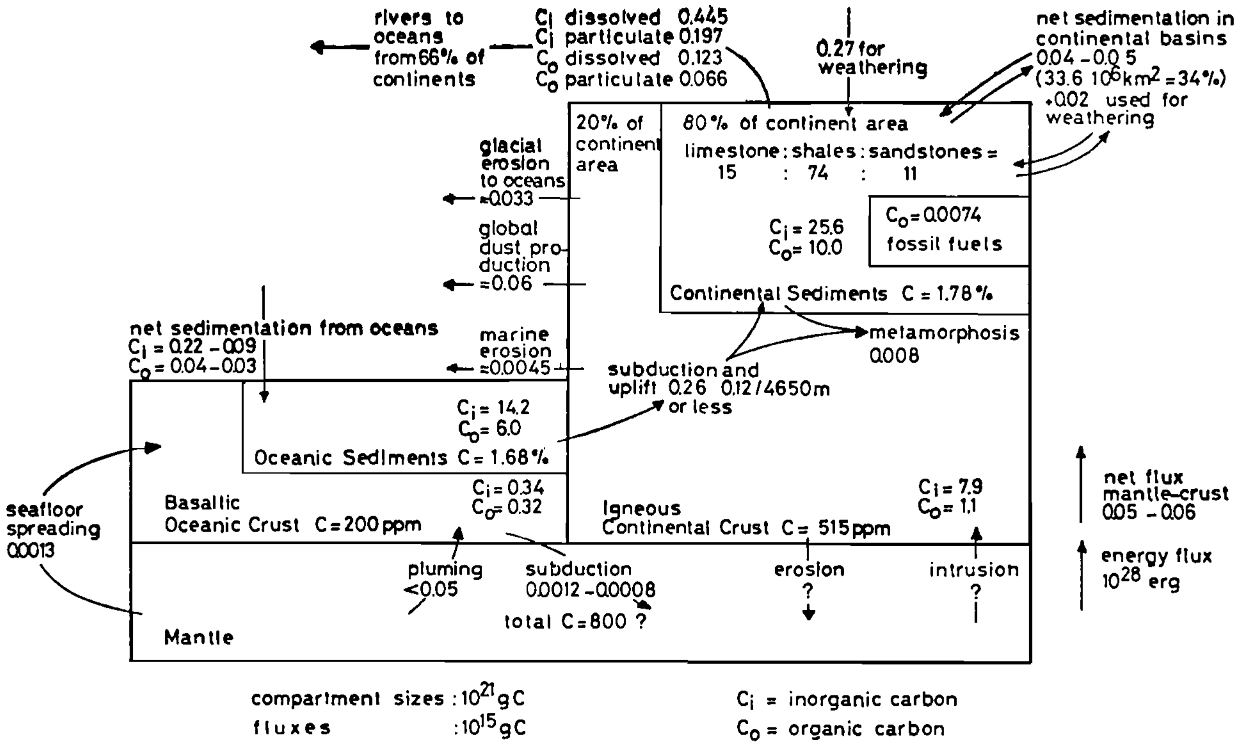


Figure 2. Carbon inventory of crustal rocks and mantle; fluxes are given in 10^{15} g C/a and the compartment sizes in 10^{21} g C.

THE CARBON CYCLE

MODELING THE GLOBAL CARBON CYCLE*

B. Bolin

Since many models of the carbon cycle have been developed, adding another model is useful only if specific purposes for doing so are also defined. At this stage of our knowlege it seems important to formulate a model with the following characteristics:

- The model should be simple in structure, but should permit the inclusion of a detailed treatment as knowledge about processes is increased and/or more data for verification become available.

- Simplifications of reality needed for designing reasonably simple models should be developed from more complete knowledge about the behavior of available subsystems.

- The carbon cycle depends on other biogeochemical cycles, e.g., on phosphorus and nitrogen which are in the sea and on land, and on oxygen and calcium which are in the sea. This fact offers further possibilities for model verification.

- The uncertainties of the model predictions should be assessed and the results should not be given merely as one likely scenario; thus many sensitivity studies are required.

Obviously we are not yet able to present a comprehensive model of this kind; however, the following synthesis may be a step in this direction. The presentation will be based mainly on computations carried out by Björkström (1978) with reference to previous works by Broecker et al. (1971), Keeling (1973), Oeschger et al. (1975), Keeling and Bacastow (1977), and Revelle and Munk (1977).

A critical evaluation will be given of how the ocean circulation has been modeled. The relative importance of penetrative convection to the deep sea, and the turbulent exchange with intermediate water and detritus flux will be analyzed by considering the distribution of ^{14}C, oxygen, calcium, and to some

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*Summary of a review paper presented at the Workshop.

extent phosphorus in the sea. The role of ocean sediments in the carbon cycle in a situation with increasing CO_2 emissions has been treated by Broecker and his colleagues. The incorporation of the most important processes into a model for the global carbon cycle will be examined.

Possible changes in the amount of carbon in land biota and soils will be considered. The modeling of the ecosystems on land for the proper treatment of their role in the global carbon cycle requires an analysis of response times of the various subsystems. The dynamics of soil types and their response to changing vegetation caused, for example, by climatic changes are of interest in this context. The uncertainty of the response of the ecosystems on land to man's intervention is considerable and its implication will be discussed.

The presentation will lead to the following tentative conclusions:

1) In addition to the 140×10^{15} g C that so far has been emitted into the atmosphere due to fossil fuel combustion, between 40×10^{15} and 120×10^{15} g C seems to have been added to the atmosphere by deforestation and by the expanding use of land for agriculture.

2) At least about 70×10^{15} g C has remained in the atmosphere, possibly as much as twice this amount, which in the latter case means a preindustrial atmospheric concentration of CO_2 as low as about 260 ppm.

3) The deep water of the oceans (below 1000 m) has played a small role as a sink for the emissions to the atmosphere due to man's activities. Probably less than 5%, and most likely less than 10% of the excess CO_2 has gone into the deep sea.

4) The intermediate water masses of the oceans (100 to 1000 m depth) probably have served as a considerably more significant sink than the deep water, but their precise role is still unclear.

5) It seems likely that some, possibly a considerable, increase of land biomass in the remaining world forests has occurred, the magnitude of which has not yet been determined precisely.

6) The implication of the above conclusions is that an approximate account of the CO_2 released into the atmosphere by man can be determined, which probably implies an airborne fraction less than 50%, even though this conclusion is uncertain.

7) Projections for future increases of the atmospheric concentration of CO_2 due to man's activities might therefore be somewhat less spectacular than those foreseen by Keeling and Bacastow (1977). The prime reason for this tentative conclusion is that the oceans and the bottom sediments might serve as more effective sinks than so far has seemed possible. Still the continued burning of fossil fuels and the exhausting of presently known reserves will lead to a manifold increase in the atmospheric CO_2 concentration; this expectation certainly warrants serious consideration with regard to possible climatic changes.

REFERENCES

Björkström, A. (1978), A Model of the Interaction Between Atmosphere, Oceans and Land Biota, in E. Degens and S. Kempe, eds., *SCOPE Report No. 13*, Wiley, New York-London (forthcoming).

Broecker, W.S., Y.-H. Li, and T.-H. Peng (1971), Carbon Dioxide, Man's Unseen Artifact, in D.W. Hood, ed., *Impingement of Man on the Oceans*, Wiley, New York.

Keeling, C.D. (1973), The Carbon Dioxide Cycle: Reservoir Models to Depict the Exchange of Atmospheric Carbon Dioxide with the Oceans and Land Plants, in S.I. Rasool, ed., *Chemistry of the Lower Atmosphere*, Plenum, New York-London.

Keeling, C.D., and R.B. Bacastow (1977), Impact of Industrial Gases on Climate, in *Energy and Climate*, National Academy of Sciences, Washington, DC.

Oeschger, H., H. Siegenthaler, U. Schotterer, and A. Gugelmann (1975), Box Diffusion Model to Study Carbon Dioxide Exchange in Nature, *Tellus*, 27, 168-192.

Revelle, R., and W. Munk (1977), The Carbon Dioxide Cycle and the Biosphere, in *Energy and Climate*, National Academy of Sciences, Washington, DC.

THE DYNAMICS OF THE CARBON CYCLE AS REVEALED BY ISOTOPE STUDIES

H. Oeschger and U. Siegenthaler

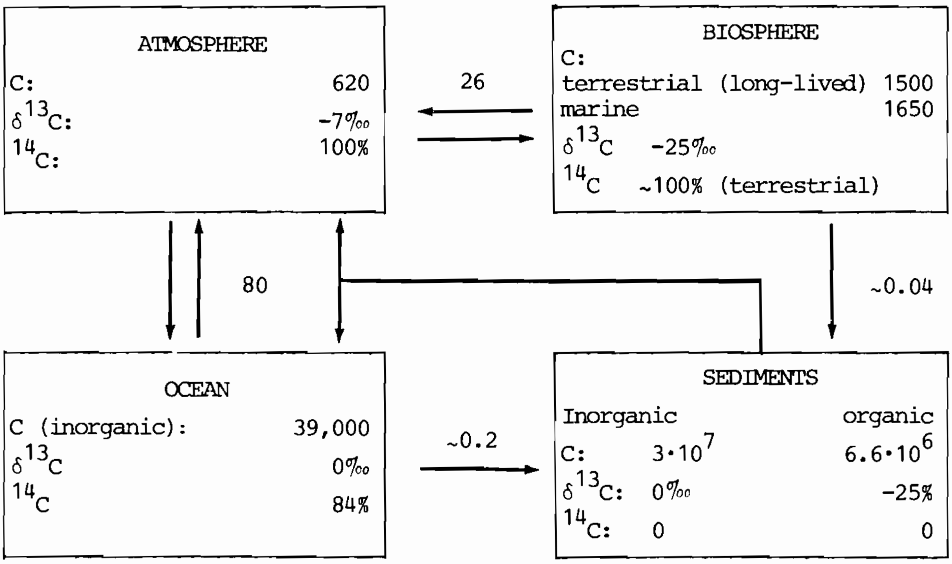
A growing number of scientists have become involved in the discussion of the CO_2 increase due to fossil fuel combustion and its possible effects on climate. During the last year strong emphasis has been given to the role of the biosphere where uncertainties are greatest. At a Dahlem Conference in 1976 [1] doubts were expressed about the reliability of existing modeling procedures. The aim of this paper therefore is to review the state of knowledge on the CO_2 exchange, mainly basing on carbon isotope studies in the different reservoirs.

THE CO_2 CYCLE AND ITS ISOTOPIC LABELLING

Figure 1 shows the main carbon reservoirs, atmosphere, biosphere, ocean and sediments, and the exchange fluxes between them. The numbers for the amounts of carbon and the exchange fluxes correspond in general to those given by Baes et al. [2].

Organic and inorganic carbon get into the sediments and return to the atmosphere or ocean by degassing of the lithosphere and by weathering. The turnover times of these slow cycles are long compared to the time scales of $\sim 10^2$ years which are of interest when discussing the CO_2 problem, since the fluxes into or out of the sediments are the equivalent of 10^{-3} to 10^{-4} atmospheric CO_2 masses per year. The fast cycles concern the exchange of the atmosphere with the biosphere and the ocean; the fluxes are of the order of 0.1 atmospheric CO_2 mass per year and therefore of relevance for the fate of excess CO_2.

Information on the time scales of the exchange processes and the mixing of the ocean can be obtained from the radioactive isotope ^{14}C (half life 5730 years) which is produced by cosmic radiation in the atmosphere. Measurements of ocean water samples taken before the large nuclear weapon tests of 1961/62 and corrected for the dilution effect by fossil CO_2 (see below) showed that the preindustrial, prenuclear ^{14}C activity of surface water was 95%, that of the average deep ocean 84% of the atmospheric ^{14}C concentration. The lower ^{14}C activity in the ocean is due to radioactive decay and enables an estimate to be made of the average time elapsed since the CO_2 in a given ocean layer left the atmosphere.



Note: The amounts of carbon are in 10^{15} g C, and fluxes in 10^{15} g C/a. The isotope values given are average concentrations. The exchange flux biosphere-atmosphere refers to the long-lived terrestrial biota only. The ^{14}C concentrations indicated are corrected for isotope fractionation to a common $\delta^{13}C = -25‰$. The actual uncorrected atmospheric and oceanic ^{14}C concentrations are 103.6% and about 88%, respectively, of modern wood ^{14}C.

Figure 1. Terrestrial carbon reservoirs.

THE STEADY-STATE ^{14}C INVENTORY AND INFERENCES ON EXCHANGE RATES

At steady state, ^{14}C production by the cosmic radiation and a decay of terrestrial ^{14}C must balance. The average present ^{14}C production rate has been calculated to be (2.2 ± 0.4) ^{14}C-atoms per cm^2 and sec [3]. From the carbon amounts and ^{14}C concentrations in the different reservoirs listed in Figure 1, the mean global rate of decay is 1.70 atoms $cm^{-2}sec^{-1}$. Sedimentation carries away another 0.08 ^{14}C atoms $cm^{-2}sec^{-1}$. (Damon et al. [4] calculate a decay rate of 1.99 atoms $cm^{-2}sec^{-1}$ including sedimentation. The difference is mainly due to their higher values for average ^{14}C activity in the deep ocean, for sedimentation, and for dead organic matter in the sea.) Thus, decay plus sedimentation agree with the computed production within its error limit which supports the present concept of carbon exchange as represented by Figure 1.

There is a permanent CO_2 exchange between atmosphere and ocean. At steady state, the two fluxes, atmosphere to ocean and ocean to atmosphere, are equal, and there is no net CO_2 transfer. There is, however, a net flux of $^{14}CO_2$ from the atmosphere to the ocean because of the ^{14}C gradient between the two reservoirs. This allows us to compute the size of the CO_2 exchange flux, F. Denoting by A_a, A_m, and A_{oc} the average $^{14}C/C$ ratios in the atmosphere, the mixed layer and the total ocean respectively, the conditions that decay in the ocean must be balanced by an influx from the atmosphere, which reads as follows (λ = decay constant of ^{14}C, 1/8260 years; N_{oc} = total inorganic and organic carbon content of the ocean; S = sedimentation rate):

$$\lambda A_{oc} N_{oc} + S \cdot A_m = A_a F - A_m F$$

or

$$F = \frac{\lambda A_{oc} N_{oc} + S\ A_m}{A_a - A_m}$$

With the numbers given in Figure 2 we get $F = 88 \cdot 10^{15}$ g/a or 20 moles per m^2 of ocean surface per year. This corresponds to a mean residence time of 7.0 years in the atmosphere before a CO_2 molecule is transferred into the mixed layer of the ocean. The uncertainty of F is ±20% because $A_m = 95 \pm 1\%$. The average $^{14}C/C$ ratio for the whole ocean of 84% corresponds to a ^{14}C age of about 1000 years relative to surface water, which gives the order of magnitude of the oceanic turnover time.

These estimates of the oceanic turnover time and of the CO_2 exchange flux with the atmosphere are obtained from simple considerations and do not depend on a specific model for the CO_2 cycle. On the other hand, any CO_2 model must correctly reproduce the essential features of the steady-state ^{14}C distribution, otherwise it cannot be expected to yield reliable predictions.

The average turnover time of the long-lived terrestrial biomass is of the order of 60 years--short compared to the half-life of ^{14}C. This makes ^{14}C dating not very favorable for getting information on biospheric fluxes. Nevertheless, ^{14}C can provide information on subreservoirs with long turnover times (humus), and bomb-produced ^{14}C also on short-term processes [5]. The main problem is the heterogeneity of the biosphere which makes it impossible to extrapolate from a few case studies to the global system.

The marine biota, although important for the oceanic cycles of carbon and many other elements, are of negligible importance for the CO_2 problem, because the amount of carbon in the living marine biomass corresponds to only 1/600 of the atmospheric CO_2, or 20% of the present annual fossil CO_2 production.

MODELS FOR THE GLOBAL CO_2 EXCHANGE

In models for the CO_2 cycle used for discussing the CO_2 increase the sedimentary reservoir is mostly omitted because the sedimentary fluxes are slow compared to the time scale of interest, i.e., a few 100 years. The atmosphere, which is internally mixed within about one year, can be modeled by a well-mixed box. Different ways of modeling the ocean have been used. Several CO_2 prognoses have been made based on models in which the ocean is subdivided into two well-mixed boxes (2B-models), a surface (or mixed layer) box and a deep-sea box. Thus, Bacastow and Keeling [6] treated the size of the mixed layer as an adjustable parameter and chose depths of 120 m and 240 m for different computing runs. However, the average thickness of the mixed layer is defined physically and is 70 to 80 m [7]. A major drawback of 2B-models is the artificial introduction of a sharp boundary between surface and deep ocean, while there is in reality a continuous transition. For this reason Oeschger et. al. [8] developed a box-diffusion (BD) model in which below a 75 m deep mixed layer there is an eddy-diffusive deep-sea reservoir in which concentrations change continuously and the fluxes are proportional to the concentration gradients. A detailed discussion of this BD-model and a comparison with the 2B-model are presented in [8,9]. In both types of models, the internal mixing rate of the ocean--described in 2B-models by the exchange coefficient k_{md} (dimension a^{-1}) between mixed layer and deep ocean box, and in BD-models by the eddy diffusivity K (m^2/a) in the deep-sea reservoir--is determined from the preindustrial ^{14}C distribution.

The main difference between the two ways of modeling is in the flux from mixed layer to deep sea. For a disturbance increasing exponentially as $e^{t/\tau}$, and if we consider the deep sea as infinitely deep (which is a reasonable approximation if $\tau <<$ mixing time of the ocean), this flux is in the BD-model proportional to $\sqrt{K/\tau}$, while in the 2B-model it is proportional to $k_{md}h_m$ (where h_m equals the mixed layer depth).

Thus, in the BD-model the flux increases with decreasing e-folding time τ, because the gradients are steeper, while in the 2B-model the flux is independent of τ. The effective depth of penetration into a diffusive deep-sea is $\sqrt{K \cdot \tau}$ or, for the CO_2 increase ($\tau \simeq 30$ years) and $K = 4000$ m^2/a, about 350 m.

In the 2B-model, an effective mixed layer depth is chosen such that the model simulates the observed atmospheric CO_2 increase. While in BD-models the flux to the deep-sea reservoirs changes with the characteristic time scale τ of the studied phenomenon, in 2B-models the effective mixed layer depth has to be adjusted to τ. A particular 2B-model will provide realistic CO_2 fluxes from surface to deep ocean for the present rate of CO_2 increase, but it may no longer do so when the CO_2 production is, for example, slowed down.

The biosphere is the most heterogeneous of the major carbon reservoirs, and it is not surprising that only few data with considerable scatter are available about its size, structure, and fluxes. Therefore, the basis is lacking for modeling the biosphere in a sophisticated way. It is simulated by two well-mixed boxes corresponding to long-lived and short-lived biota [7] or, when short-lived plants are not considered because of their minor mass, by one box only [9].

Part of the plants react to a higher CO_2 concentration by a stronger productivity, so that the biosphere might act as a sink for additional CO_2. This phenomenon can be described by a biota growth factor, essentially giving the ratio between the relative changes of productivity and CO_2 concentration. Values between 0 and 0.6 have been used for the biota growth factor [6,8,9].

OBSERVED CHANGES OF THE CONCENTRATION OF ATMOSPHERIC CO_2 AND ITS ISOTOPIC COMPOSITION

A model for the exchange of the three carbon isotopes should be able, besides the steady state distribution, to simulate responses to disturbances of the system. Natural and anthropogenic processes lead to atmospheric variations. Such observed disturbances are discussed below (see also Table 1).

^{14}C Fluctuations Observed in Tree-Rings

Trees preserve a record of the $^{14}C/^{12}C$ ratio in the lower atmosphere at the time of their formation. ^{14}C measurements on tree-rings covering the last approximately 8000 years, the age of which was determined by dendrochronology, show two kinds of fluctuations. From 7000 b.p. (before present) to 2000 BP the average atmospheric ^{14}C activity decreased by about 10%. Superimposed on the general trend are secular variations (wriggles) of the order of 1 to 2% [10]. Both effects can be explained either by variations in the ^{14}C production rate or by variations in the carbon exchange system. At periods of high (low) terrestrial and/or solar magnetism, shielding of the effects of the galactic component of cosmic radiation leads to relatively low (high) isotope production in the atmosphere. Paleomagnetic data indicate that 7000 years ago the value of the earth's geomagnetic dipole was only one half that of 2000 years ago and estimates show that this increase in the magnetic field strength could well have resulted in the observed decrease in the atmospheric $^{14}C/^{12}C$ ratio.

Table 1. Natural and anthropogenic influences on CO_2, $^{13}C/^{12}C$, $^{14}C/^{12}C$.

Phenomenon	Effects in atmosphere
<u>Variation of ^{14}C production</u>	^{14}C variations:
Modulation of cosmic radiation (solar and terrestrial magnetism)	Solar magnetism ± 1-2% Terrestrial magnetism ± 10%
Artificial ^{14}C production (nuclear weapon and industry)	Excess in Northern Hemisphere 1963: + 100%; 1977: + 30-40%
<u>Variations of reservoir sizes and exchange fluxes</u>	
Changes in biomass/climate and deforestation	$\delta^{13}C$ change $\lesssim$ 1‰?
Temperature influence on CO_2 solubility and ocean circulation	Secular ^{14}C variations?
Ocean level variations (CO_2 capacity of ocean)	Long-term ^{14}C variations?
<u>Variation of total CO_2 in the atmosphere - ocean - biosphere system</u>	
Volcanism	?
Change in sedimentation and weathering rates	?
Use of fossil fuel	CO_2: + 10% in 1970 $\delta^{13}C$: - 0.5 to 1‰ in 1970 ^{14}C: - 2% in 1950

Some of the remaining deviations (wriggles) may be due to over-interpretation of measurements with statistical errors of a size comparable to that of the effects to be looked for. It has been shown that periods of high solar activity (and therefore strong shielding of galactic cosmic radiation) coincide with low atmospheric $^{14}C/^{12}C$ ratios, suggesting that these fluctuations reflect ^{14}C production rate variations [11]. Since the ^{14}C wriggles and anomalies in the sunspot record coincide with periods of climatic fluctuations [12], variations in the carbon exchange between the atmosphere and the ocean may well have contributed to the observed phenomenon.

CO_2 Increase and Decrease of $^{14}C/^{12}C$ (Suess Effect) and $^{13}C/^{12}C$ in the Atmosphere

Careful monitoring of the atmospheric CO_2 level was only started in 1957 by C.D. Keeling at Mauna Loa, Hawaii, and at the South pole [13]. For the period 1958-1974 the observed CO_2 increase corresponds to 53% of the fossil CO_2 produced during that period. CO_2 modelers today generally assume that about the same fraction, i.e., 50 to 60% of the CO_2 totally introduced into the atmosphere, has remained there [2].

CO_2 originating from fossil fuel combustion contains no ^{14}C and therefore leads to a decrease in the atmospheric $^{14}C/^{12}C$ ratio (Suess effect). In 1950, before the H-bomb tests, the Suess effect was estimated to be -2 ± 0.3% [14]. At that time the cumulative fossil CO_2 production was approximately 10% of the preindustrial atmospheric CO_2 and the corresponding atmospheric CO_2 increase 5 to 6%. One would at first expect ^{14}C dilution to be of the same size as the CO_2 increase but of an opposite sign. However, the system's responses are not the same for the CO_2 concentration and for isotopic ratios.

Atmospheric CO_2 is in direct exchange only with dissolved gaseous CO_2 in the sea which makes up only a small fraction of the dissolved inorganic carbon, the major part being bicarbonate (HCO_3^-) and carbonate (CO_3^{--}) ions. If the atmospheric CO_2 pressure is increased by p%, the concentration of dissolved CO_2 gas also increases by p% (assuming equilibrium), but total CO_2 ($CO_2 + HCO_3^- + CO_3^{--}$) increases by p/ξ% only due to shifts in the chemical equilibria. The buffer factor ξ is about 10 for current conditions [14], but increases with increasing CO_2 pressure [6]. Thus, if the fossil CO_2 were distributed only between the atmosphere and the mixed layer (which contains approximately the same amount of total CO_2 as the atmosphere), about 9/10 of the excess CO_2 would remain in the atmosphere and 1/10 would go into the mixed layer, while the changes in the isotope ratios, $^{14}C/^{12}C$ and $^{13}C/^{12}C$, would be equal in both reservoirs at equilibrium. This explains why the relative atmospheric CO_2 increase is larger than the Suess effect. This implies, by the way, that the absolute amount of ^{14}C in the atmosphere increased due to the input of ^{14}C-free CO_2, because the increase of the back flux of CO_2 from the ocean was larger than the decrease in its $^{14}C/C$ ratio, so that there was an enhanced ^{14}C flux from the mixed layer to the atmosphere.

A comparison of the CO_2 increase and the Suess effect helps to confirm the estimates on the value for the worldwide buffer effect. A model discussion [8] shows that a value of -2% in 1950 for the Suess effect is in agreement with a buffer factor of about 10, corresponding to the theoretical value.

Some authors have supposed that the net biospheric flux into the atmosphere might be as high as the fossil flux (Woodwell and Houghton [15]). Siegenthaler and Oeschger [9] discussed whether such a high biospheric CO_2 input might be compatible with current ideas on the CO_2 system. Assuming that the biospheric CO_2 release was always equal to the fossil flux, the atmospheric CO_2 increase would have been, according to BD-model computations, much faster than that observed since 1958. A total CO_2 production function twice the fossil production would be compatible with the observed increase for the last 20 years if

- either the biosphere would have taken up one half the excess CO_2 (deforestation compensated by increased biota growth);
- or the buffer factor had an effective value of 3 instead of 10;
- or the excess CO_2 were mixed very fast into the deep sea and the ocean were saturated to an effective depth of 1300 m, while 380 m are obtained by means of the BD-model calibrated with the steady-state oceanic ^{14}C distribution.

However, deforestation was not necessarily always proportional to fossil CO_2 production but may have been large in the past and small now. As discussed by Siegenthaler et al. in these Proceedings, even considerable total biospheric CO_2 releases would not have caused a steeper CO_2 growth since 1958 than observed if they had occurred 50 to 100 years ago. In that case, the preindustrial CO_2 level must have been significantly below the value of about 290 ppm generally accepted at present.

Since the average ^{14}C concentration of the biota is not much lower than that of atmospheric CO_2, the $^{14}C/^{12}C$ ratio is not measurably affected by deforestation. Both, fossil and biospheric CO_2 have a $\delta^{13}C$ about 18‰ lower than the atmosphere (Figure 1). Measurements on dated tree-rings can be used for determining the ^{13}C decrease caused by the CO_2 input [16,17]. A model discussion of the ^{13}C decrease is given by Siegenthaler et al. in these Proceedings.

Response to the Bomb ^{14}C Input

A large amount of ^{14}C was introduced into the atmosphere by the hydrogen bomb tests in 1961/62, leading to a temporal ^{14}C excess of 100% in the northern hemisphere. Data on the dispersal of the artificial ^{14}C in the atmosphere and the ocean offer an additional test for models of the CO_2 exchange. The increase in the surface ocean computed with the BD-model [8] satisfactorily agrees with experimental values. For the Atlantic Ocean between 35°S and 45°N, an average ^{14}C level of 112.7% was observed in 1972 compared to a prenuclear bomb value of 94.3% [17]. This compares well with the BD-model prediction of 112.3% for 1970 for the average ocean [8]. Based on the bomb ^{14}C distribution in the Atlantic Ocean, Stuiver, too, concludes that the division of excess CO_2 between the atmosphere and the ocean is nearly equal [17].

Seasonal Variations

Seasonal variations in CO_2 concentrations have been observed at Mauna Loa as well as at the South Pole [13]. At Mauna Loa there is a CO_2 maximum in spring and a minimum in early autumn, the difference between maxima and minima being about 5 ppm or 1.7% of the average concentration. Three effects can be made responsible for the seasonal variations:

- Vegetational cycles with a net flux into the biosphere in spring and summer and a net flux into the atmosphere in fall and winter. This is probably the dominant cause [18]. Since the $^{13}C/^{12}C$ ratio of the biosphere is significantly lower than in the atmosphere, the CO_2 variations are accompanied by ^{13}C variations, i.e., an increase of ^{13}C during the growing season and a decrease when CO_2, lower in ^{13}C, is flowing back into the atmosphere [19].

- Hemispherical cycles in the net flux into the ocean due to temperature-induced variations of the CO_2 partial pressure in the ocean and of sea ice cover. Since the CO_2 pressure is higher in warmer water, the temperature dependence of solubility alone would lead to a CO_2 maximum in summer.

- A seasonal cycle in the combustion of fossil fuel due to winterly heating.

The different characteristics of continents and oceans as sources or sinks for CO_2 will be reflected in a varying concentration in an air mass circulating around the globe, accompanied by corresponding ^{13}C variations. This should be more pronounced in the northern than in the southern hemisphere because of the unequal distribution of CO_2 sources and biomass among the two hemispheres.

PARTITIONING OF EXCESS CO_2 AMONG THE CARBON RESERVOIRS

As stated above the atmospheric CO_2 increase from 1958 to 1974 corresponds to 53% of the fossil input in this time span. The BD-model, with a buffer factor of 10 and a biota growth factor of 0.2, predicts for 1970 a partitioning of the total excess CO_2 of 56:9:35% in the atmosphere, the biosphere, and the ocean, respectively (numerical computation with CO_2 production as given in [20]). Since the size of the biota growth factor is not well known, we have plotted in Figure 2 its influence on the partitioning of the excess CO_2, as calculated analytically for a CO_2 production increasing exponentially with a time constant of 35 years. The ratio between oceanic and atmospheric fraction is 0.66, independent of the biota behavior in this linear model.

According to the model calculations for an e-folding time of 35 years, 60% of the totally produced CO_2 remains in the atmosphere if the size of the biosphere is constant. However, the observations indicate that this fraction is smaller than 60%, so that, according to the model, there must have been a net growth of the biosphere.

From Figure 2 we could, in principle, find the size of the biota growth factor by inserting the appropriate value for the airborne fraction of the excess CO_2. The resulting growth

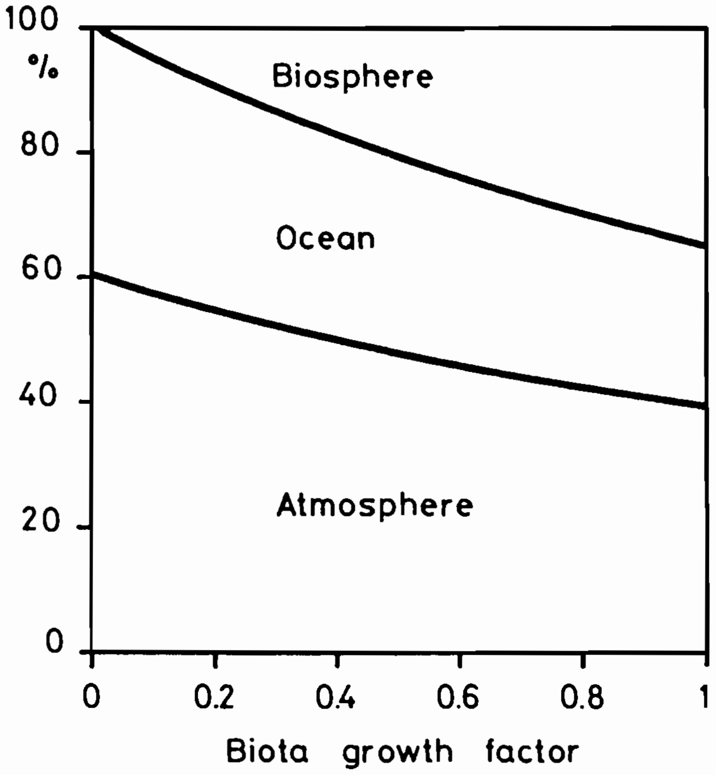


Figure 2. Partitioning of excess CO_2 as a function of the biota growth factor to the box-diffusion model, treating the biosphere as a well-mixed box. An exponentially rising CO_2 production is assumed, with an e-folding time of 35 years; buffer factor = 10.

factor would, however, be affected with a large uncertainty since relatively small errors in model parameters or in the airborne fraction lead to a considerable error in the result.

PREDICTIONS OF FUTURE ATMOSPHERIC CO_2 LEVELS

Prognoses of future atmospheric CO_2 levels depend primarily on the underlying fossil energy scenarios. We have presented and discussed CO_2 predictions for different assumptions elsewhere [9] and will give here a short summary only.

First, we must be aware of the ocean's limited capacity for the uptake of additional CO_2. While the ocean contains about 60 times as much carbon as the atmosphere, it can take up at maximum, i.e. at steady state, six times as much of the excess CO_2 as the atmosphere because of the buffer factor of about ten. Therefore, even at a steady state which is reached only after many centuries, about one seventh of the total produced CO_2 remains in the atmosphere. Because the buffer factor increases with the larger CO_2 concentration, this figure is even a lower limit for the amount remaining forever in the atmosphere. Thus, if man would burn all exploitable fossil fuel (assumed equivalent to 11.5 times the preindustrial atmosperic CO_2 burden), the new steady-state atmospheric concentration would be about four times its preindustrial size (assuming constant biomass).

For the transient atmospheric CO_2 levels, we first consider the case of a constant CO_2 production at the rate of 1970. An essential point is that no new equilibrium is reached. The fraction of cumulative CO_2 residing in the atmosphere will in 2070 still be between 38 and 59% (depending on the model used), compared to 51 to 62% in 1970. If all economically exploitable fossil fuel (11.5 × preindustrial atmospheric CO_2) is burned according to a logistic function of time (Figure 3), the CO_2 concentration would have doubled in 2020 and the maximum atmospheric CO_2 level, 5 to 10 times the preindustrial value, would be reached 40 to 80 years after the production peak, occurring around 2060.

If the atmospheric CO_2 level should not exceed 150% of the preindustrial value, a CO_2 production function as shown in Figure 4 is obtained. The CO_2 emission rate could increase, until 2010, to about 1.5 times that of 1970. Afterwards it should level off and decrease again to 1970 values in the middle of the next century. In 150 to 250 years from now the yearly fossil fuel consumption could still be 25 to 40% of the current value.

In the long run, when water with an enhanced CO_2 pressure will have mixed down to large depths or if the CO_2 content of surface waters has risen dramatically, dissolution of carbonate sediments may start. This will lead to a growing alkalinity and a considerably larger capacity of the sea water for excess CO_2 [21]. This process is, however, extremely slow and will become active only on the time scale of thousands of years.

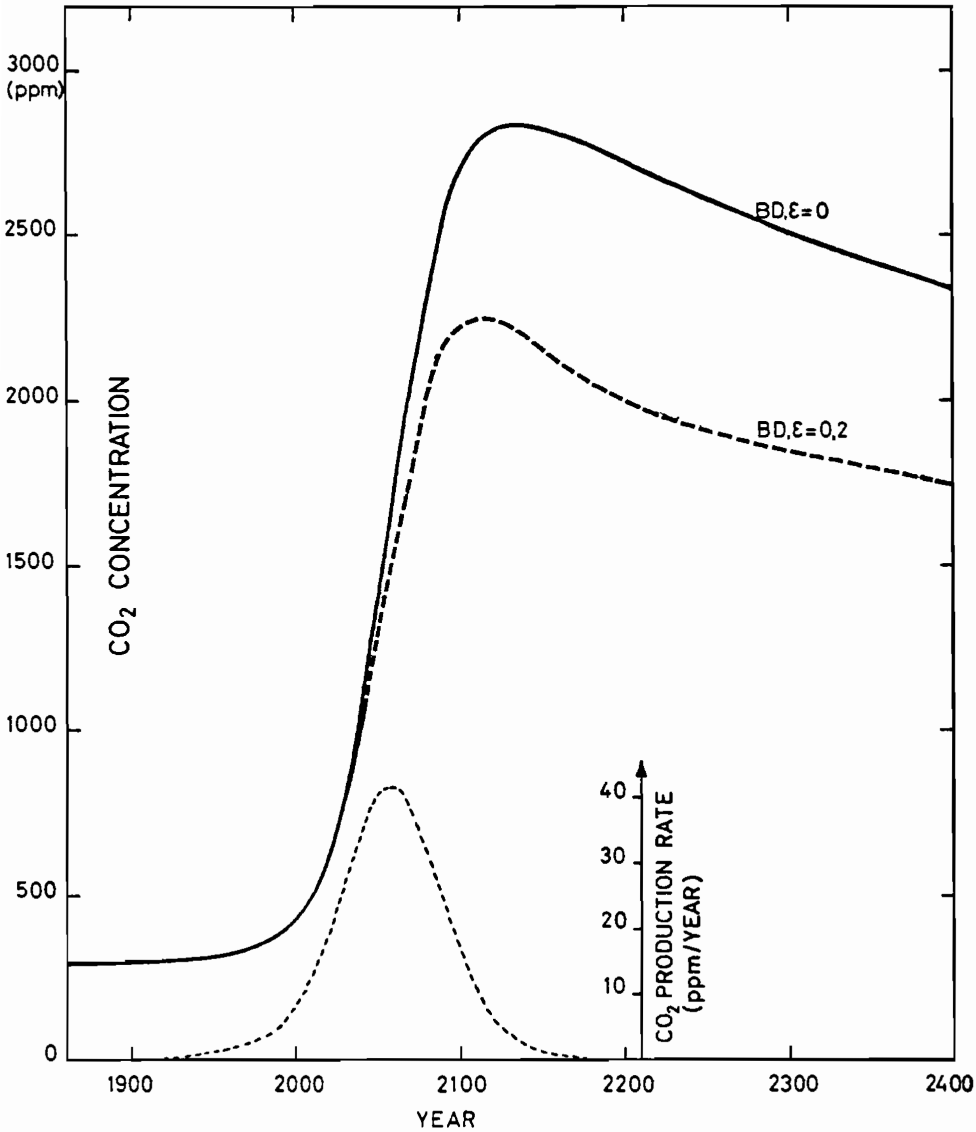


Figure 3. Prediction for the case that all recoverable fossil fuel is burnt. Lowermost curve: assumed CO_2 production rate. The concentration curve for a biota growth factor $\epsilon = 0.2$ is dashed because it would predict a large biota growth that does not seem probable.

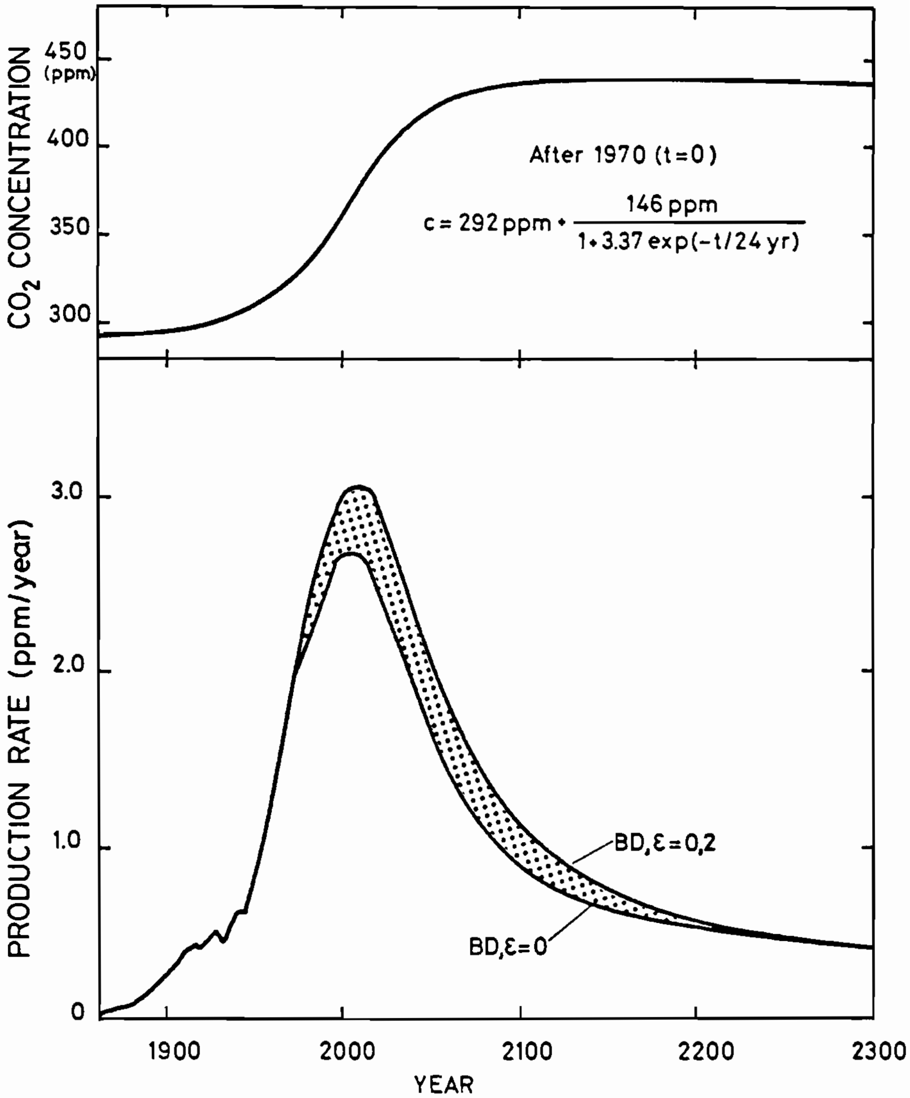


Figure 4. CO_2 production rates, as observed until 1970 and as permitted after 1970, for an increase of the atmospheric excess in a prescribed way (top curve) to a maximum of 50% of the preindustrial atmospheric level.
ϵ = biota growth factor.

FUTURE RESEARCH

On the occasion of several workshops and symposia recommendations have been made regarding future research which should help to improve our knowledge on the CO_2 exchange in nature. In the following we would like to draw attention to research related to isotope studies. Investigations of the present behavior of the CO_2 system should be accompanied by the attempt to reconstruct its history and natural variations.

A grid of monitoring stations for total atmospheric CO_2, $^{13}C/^{12}C$ and perhaps also $^{14}C/^{12}C$, should be established based on models of atmospheric circulation and mixing. Sampling locations and sequences should be selected such that data representative for larger regions can be obtained. Monitoring should not be restricted to CO_2 alone. The measurement of other atmospheric constituents may help to distinguish between phenomena due to changes in atmospheric circulation and those typical for CO_2 alone.

Efforts should be made to extend our knowledge on the CO_2 system back in time prior to 1958. Valuable information on the history of atmospheric $^{13}C/^{12}C$ and $^{14}C/^{12}C$ can be obtained from studies of tree-rings, peat, and carbonates. The data should be interpreted in terms of fluctuations of reservoir size and exchange fluxes.

Direct information on the CO_2 partial pressure and its variations in the past can, in principle, be obtained from CO_2 studies on ice cores, since it is one of the parameters determining the CO_2 content of natural ice. The values obtained so far, however, show large fluctuations and other parameters seem to dominate the enclosure mechanism [22]. Efforts to overcome these difficulties include:

- Extraction of the air in the bubbles without melting the ice for determination of CO_2/N_2 ratios. Comparison with the CO_2 content of the ice lattice.
- Comparison of CO_2 contents of ice with other parameters as fabrics, $^{18}O/^{16}O$, chemistry, etc.
- Laboratory experiments and model calculations to determine the mechanism of CO_2 enclosure in ice and its dependence on environmental parameters.

The general impression is that the necessary advancement of the knowledge on the CO_2 system will only be obtained by concerted interdisciplinary efforts which go far beyond those of the past years.

REFERENCES

[1] Stumm, W., ed., *Global Chemical Cycles and Their Alteration by Man*, Abakon Verlagsgesellschaft, Berlin, 1977.

[2] Baes, C.F., H.E. Goeller, J.S. Olson, and R.M. Rotty, *The Global CO_2 Problem*, ORNL-5194, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1976.

[3] Lingenfelter, R.E., and R. Ramaty, Astrophysical and Geophysical Variations in C14 Production, in I.U. Olsson, ed., *Radiocarbon Variations and Absolute Chronology*, Almqvist and Wiksell, Stockholm, 1970.

[4] Damon, P.E., J.C. Lerman, and A. Long, Temporal Fluctuations of Atmospheric ^{14}C: Causal Factors and Implications, *Ann. Rev. Earth Plan. Sci.* (in press).

[5] Rafter, T.A., and J.D. Stout, Radiocarbon Measurements as an Index of the Rate of Turnover of Organic Matter in Forest and Grassland Ecosystems in New Zealand, in I.U. Olsson, ed., *Radiocarbon Variations and Absolute Chronology*, Almqvist and Wiksell, Stockholm, 1970.

[6] Bacastow, R., and C.D. Keeling, Changes from AD 1700 to 2070 as Deduced from a Geochemical Model, in G.M. Woodwell and E.V. Pecan, eds., *Carbon and the Biosphere*, CONF-720510, U.S. Atomic Energy Commission, Springfield, Virginia, 1973.

[7] Bathen, K.H., On the Seasonal Changes in the Depth of the Mixed Layer in the North Pacific Ocean, *J. Geophys. Res.*, 77 (1970), 7138-7150.

[8] Oeschger, H., U. Siegenthaler, U. Schotterer, and A. Gugelmann, Box Diffusion Model to Study Carbon Dioxide Exchange in Nature, *Tellus*, 27 (1975), 168-192.

[9] Siegenthaler, U., and H. Oeschger, Predicting Future CO_2 Levels, *Science*, 199 (1978), 388-395.

[10] Suess, H.E., Secular Variations of the Cosmic Ray Produced Carbon-14 in the Atmosphere and Their Interpretation, *J. Geophys. Res.*, 70 (1965), 5937-5952.

[11] Stuiver, M., Carbon-14 Content of 18th and 19th Century Wood: Variations Correlated with Sunspot Activity, *Science*, 149 (1965), 533-535.

[12] Eddy, J.A., Climate and the Changing Sun, *Climatic Change*, 1 (1977), 173-190.

[13] Keeling, C.D., R.B. Bacastow, A.E. Bainbridge, C.A. Ekdahl, P.R. Guenther, L.S. Waterman, and J.F.S. Chin, Atmospheric Carbon Dioxide Variations at Mauna-Loa Observatory, Hawaii, *Tellus*, 28 (1976), 538-551; Keeling, C.D., J.A. Adams, C.A. Ekdahl, and P.R. Guenther, Atmospheric Carbon Dioxide Variations at South Pole, *Tellus*, 28 (1976), 552-564.

[14] Broecker, W.S., Y.-H. Li, and T.-H. Peng, Carbon Dioxide, Man's Unseen Artifact, in D.W. Hood, ed., *Impingement of Man on the Oceans*, Wiley-Interscience, New York, 1971.

[15] Woodwell, G.M., and R.D. Houghton, Biotic Influence on the World Carbon Budget, in [1].

[16] Freyer, H.D., and L. Wiesberg, Anthropogenic Carbon-13 Decrease in Atmospheric Carbon Dioxide as Recorded in Modern Wood, in *Isotope Ratios as Pollutant Source and Behaviour Indicators*, IAEA-SM-191/10, International Atomic Energy Agency, Vienna, 1975.

[17] Stuiver, M., Atmospheric CO_2 Increases Related to Carbon Reservoir Changes, *Science* (in press).

[18] Machta, L., The Role of the Oceans and Biosphere in the Carbon Dioxide Cycle, in D. Dyrssen and D. Jagner, eds., *The Changing Chemistry of the Oceans*, Almqvist and Wiksell, Stockholm, 1972.

[19] Keeling, C.D., The Concentration and Isotopic Abundancies of Carbon Dioxide in the Atmosphere, *Tellus*, 12 (1960) 200-203; Esser, N., Institut für Umweltphysik, Heidelberg, unpublished results.

[20] Keeling, C.D., Industrial Production of Carbon Dioxide from Fossil Fuels and Limestone, *Tellus*, 25 (1973), 174-198.

[21] Bolin, B., and E. Eriksson, Changes in the Carbon Dioxide of the Atmosphere and Sea Due to Fossil Fuel Combustion, in B. Bolin, ed., *The Atmosphere and the Sea in Motion*, Rockefeller Inst. Press, New York, 1959.

[22] Stauffer, B., and W. Berner, CO_2 in Natural Ice, *Journal of Glaciology* (in press).

BIOTIC INTERACTIONS WITH ATMOSPHERIC CO_2

G.M. Woodwell

C.D. Keeling and his colleagues at the Scripps Institution of Oceanography have shown beyond question that the CO_2-content of the atmosphere is increasing at a rate that has ranged over the past 20 years between about 0.5 and 1.0 ppm/a (Keeling and Bacastow, 1977). These studies have been supplemented by other well known sampling programs confirming the change such as those reported by Bischoff (1973) and by Pearman and Garratt (1973). The increase in atmospheric CO_2 has been commonly assumed to be due to the combustion of fossil fuels which release about 5×10^{15} g C annually into the atmosphere (Keeling, 1973; Rotty, 1977). Data on the increase of atmospheric CO_2 and the release of CO_2 from combustion of fossil fuels are the best known segments of the world carbon cycle. Other important segments are difficult to measure owing to their complexity; thus only estimates can be made when completing a world budget. It is the interpretation of these other segments that is currently in question, especially the role of the biota and the oceans. I shall address the role of the biota in this brief paper.

The annual oscillation in the CO_2 content of the atmosphere measured at Mauna Loa, Hawaii, USA is about 5 ppm, with a peak concentration in late winter and a minimum in late summer. The pattern is reversed in the southern hemisphere, and seems to follow the seasonal pulse of carbon storage by terrestrial plant communities of the temperate zone. Forests seem to be especially important because they occupy a large area and have a seasonal pulse of metabolism large enough to affect the CO_2 content of the atmosphere by measurable amounts.

The observation raises additional questions about the role of the biota in the world carbon budget. First, could there be a change in the size of the carbon pool held within the terrestrial biota that would affect the long-term trend in the CO_2 content in the atmosphere? The change in the biota could be either toward increased storage or toward a net release due to the harvest of forests. In models of the world carbon balance, the biota is commonly assumed to be a sink for atmospheric carbon (Keeling and Bacastow, 1977; Siegenthaler and Oeschger, 1978). Second, could there be biotic transfers of carbon within the oceans, resulting in the storage of carbon in addition to that normally accounted for in studies of the large organic and inorganic pools?

Each of these questions is linked to complex subsidiary questions for which simple measures are unavailable. Nevertheless, we can make limited progress in refining the challenge.

The pools of carbon that are in short-term exchange with one another include the atmospheric pool, commonly estimated as about 700×10^{15} g C; the terrestrial biota, estimated by Whittaker and Likens (1973, 1975) for the early 1950s as about 827×10^{15} g; the total carbon held within the mixed layer of the oceans, possibly 600×10^{15} g; and the terrestrial humus and the carbon held in the oceans below the thermocline, both of which are usually thought to be in somewhat slower exchanges with the atmosphere. These various pools have been summarized recently in diagrams by Woodwell et al. (1978), Woodwell (1978), and Stuiver (1978). The fossil fuel carbon is an additional source of carbon for the atmosphere.

There is an additional pool of stored carbon on land. The terrestrial humus includes the organic litter on the surface of the soil and the diffuse organic matter in addition to live roots in soils. The total amount has been estimated variously in recent years as between 700 and 3000×10^{15} g C (Schlesinger, 1978; summarized by Woodwell et al., 1978). A change in this pool could also be large enough to affect the CO_2 content of the atmosphere.

The most important single observation is that the CO_2 content of the atmosphere is increasing. The increase is about 2.3×10^{15} g C annually, considerably less than the release from fossil fuel combustion. There appears to be a net transfer to the oceans into the inorganic carbon pools, but the net transfer seems to be considerably less than the total release from fossil fuels, possibly as low as the amount accumulating in the atmosphere. (For recent summaries see Stuiver, 1978, and Siegenthaler and Oeschger, 1978.)

The increase in atmospheric CO_2 results from a series of complicated exchanges among these pools. While we would like to define the exchanges quantitatively, construct a model and predict the future course of the CO_2 content of air, making such predictions is tenuous owing to insufficient data about major sources and sinks for atmospheric CO_2. The major question at present concerns the *size* of the total release of carbon into the atmosphere. A careful review of the changes in the terrestrial biota shows that there is probably a net release from this source alone of more than 5×10^{15} g annually. The release is from the harvest and transformation of forests into other types of vegetation that fix and store much less carbon. History confirms the trend. The spread of modern civilization with the intensification of the use of all resources has led to the progressive reduction of forests worldwide (Darby, 1956; Eckholm, 1976).

In addition, there is a release of organic matter from the decay of the humus held within forest soils. Woodwell et al. (1978) estimated the annual release at 2.0 × 10^{15} g, and the total release from the biota and humus as 7.8 × 10^{15} g or 50% greater than the fossil fuel release. The range of uncertainty attached to this estimate was from 2 to 18 × 10^{15} g.

The possibility that the increase in atmospheric CO_2 has stimulated photosynthesis and caused increase carbon storage in the remaining vegetation cannot be dismissed casually. E. Lemon (1978) reviewed the issue and concluded that any stimulation would be very small. Field research on the topic is difficult and the topic should receive intensive review.

The suggestion that the releases of CO_2 into the atmosphere may be considerably larger than have been assumed in recent analyses means that there must be additional sinks for atmospheric carbon. The major sink is the oceans, where the largest sink is the oceanic depths. The question is whether additional carbon beyond that introduced through a mixing of the surface and abyssal water can be transferred to the depths.

The mechanism for such a transfer exists; the question is whether the mechanism is important. Again, there is no simple answer; a thoroughly satisfactory answer may require several years' active research on carbon transfers within the ocean. Although the mass of plants and animals in the oceans is small in proportion to the other pools of carbon in active exchange with the atmosphere (as recognized by Siegenthaler and Oeschger (1978) in their recent model), the total carbon participating in the metabolism of the oceanic biota is very large indeed. Net photosynthesis is thought to be about 24 × 10^{15} g C annually (Whittaker and Likens, 1973, 1975). While this figure is open to interpretation, it is probably not wrong by more than a ± 50% at the greatest, and the net fixation of carbon in the oceans would remain significant in either case.

This fixed carbon is transferred almost immediately to small animals and from that point enters the decay chain. A substantial fraction of it is excreted in the form of fecal pellets that fall through the water at rates considerably higher than plankton and thereby enter the upper layers of the oceanic depths. There the pellets may be caught in other biotic transformations; they may decay further to release the carbon into the inorganic carbon pool or into the large pool of humic materials in the oceanic waters. To be significant in the world budget, the quantity of carbon transferred in this way would not have to be large in proportion to the size of the pools involved. A transfer of less than 10 × 10^{15} g would obviously resolve the major questions about an additional sink for carbon and would be very difficult to detect as a fraction of either the very large pools of carbon held within the inorganic carbon pool of the oceanic deep ($40{,}000 \times 10^{15}$ g), of the 1000 to 3000×10^{15} g held within the humus of the oceans as dissolved organic matter.

The data in support of such an hypothesis are limited, but the broad pattern is reasonable. There is a discrepancy in the world carbon balance as currently calculated. The largest additional sink is in the oceans if the mechanism for the transfer of carbon exists. To date we have tended to ignore biotic transfers, relying instead on the C^{14} data from oceanic waters that seem to show the age of these waters as several thousand years. Such analyses of carbon, however, offer average ages; they do not reveal details of the age structure of different segments of the carbon pools. It is now reasonable to seek additional information about the biotically active segments of these large pools to discover whether there is a series of exchanges of new carbon previously overlooked.

Recent studies of the rates of sedimentation across the thermocline lend support to the hypothesis that the role of the biota in the oceanic transfers may be larger than previously assumed. Rowe and Staresinic (1977) have shown that such a route of transfer is indeed significant. The details of biotic circulation in the oceans are only now being explored.

The interpretations of the carbon balance of the atmosphere made over the past several years seem to have been based on an underestimate of both the role of the terrestrial biota and humus as a source of CO_2 and the potential role of the oceanic biota in moving fixed carbon into the depths. Neither of these roles has been established in a thoroughly convincing way; both require considerable additional research and review. The potential role of the CO_2 content of the atmosphere in controlling climate makes this an important topic quite apart from the intrinsic importance of the world carbon budget as a topic of intellectual interest and practical importance.

REFERENCES

Bischoff, W. (1973), Carbon Dioxide Concentration in the Upper Troposphere and Lower Stratosphere, III, *Tellus*, 25, 305.

Darby, H.C. (1956), The Clearing of the Woodland in Europe, in William L. Thomas, ed., *Man's Role in Changing the Face of the Earth*, Vol. 1., University of Chicago Press, Chicago.

Eckholm, E. (1976), *Losing Ground*, Norton, New York.

Keeling, C.D., and R.B. Bacastow (1977), Impact of Industrial Gases on Climate, in *Energy and Climate*, National Academy of Sciences, Washington, DC.

Lemon, E (1978), *Symposium Series in Oceanography*, Office of Naval Research, Washington, DC (in press).

Pearman, G.I., and J.R. Garratt (1973), Space and Time Variations of Tropospheric Carbon Dioxide in the Southern Hemisphere, *Tellus*, 25, 309.

Rotty, R. (1977), *Present and Future Production of CO_2 from Fossil Fuels - A Global Appraisal*, paper prepared for the Energy Research and Development Workshop on Significant Environmental Concerns, Miami, Florida, March 7-11.

Rowe, G.T., and N. Staresinic (1978), Sources of Organic Matter to the Deep-Sea Benthos, *AMBIO* (in press).

Schlesinger, W. (1977), Carbon Balance in Terrestrial Detritus, in Richard Johnston, Peter Frank, and Charles Michener, eds., *Annual Review of Ecology and Systematics*, Vol. 8, Annual Reviews Inc., Palo Alto, California.

Siegenthaler, U., and H. Oeschger (1978), Predicting Future Atmospheric Carbon Dioxide Levels, *Science*, 199, 388.

Stuiver, M. (1978), Atmospheric CO_2 and Carbon Reservoir Changes, *Science*, 199, 253-260.

Whittaker, R.G., and G.E. Likens (1973), Carbon and the Biota, in G.M. Woodwell and E.V. Pecan, eds., *Carbon and the Biosphere*, CONF-720510, U.S. Atomic Energy Commission, Springfield, Virginia.

Whittaker, R.H., and G.E. Likens (1975), The Biosphere and Man, in H. Lieth and R.H. Whittaker, eds., *Primary Productivity of the Biosphere*, Springer, New York.

Woodwell, G.M. (1978), The Carbon Dioxide Question, *Sci. Am.*, 238, 34-43.

Woodwell, G.M., R.H. Whittaker, W.A. Reiners, G.E. Likens, C.C. Delwiche, and D.B. Botkin (1978), The Biota and the World Carbon Budget, *Science*, 199, 141-146.

PRELIMINARY EVALUATION OF PAST CO_2 INCREASE AS DERIVED FROM ^{13}C MEASUREMENTS IN TREE RINGS

H.D. Freyer

INTRODUCTION

Owing to the long-term increase of atmospheric CO_2, its carbon isotope ratio changes with time. Emitted CO_2 from the combustion of fossil fuels as well as CO_2 released by man's modifications of land biota and soils (respiration CO_2) are marked with respect to atmospheric background CO_2 by a $\delta^{13}C$ deficit of about 18 ‰ (PDB scale). Both fossil and nonfossil respiration CO_2 can be distinguished not by their ^{13}C, but by their ^{14}C values. The ^{14}C content of atmospheric CO_2 corresponds nearly to that of nonfossil CO_2; in fossil CO_2, however, the ^{14}C isotope had decayed. Therefore, a decrease in the $^{14}C/^{12}C$ ratio reflects the fossil fuel production of CO_2, whereas a decrease in the $^{13}C/^{12}C$ ratio is due to both fossil fuel combustion and alteration of land biota.

Atmospheric CO_2 variations of the past can be recognized by carbon isotope studies of fixed atmospheric CO_2 in the form of wood in tree rings. The dilution of the atmospheric $^{14}CO_2$ content by fossil CO_2 (the so-called Suess effect) was first proposed and measured in tree rings by Suess (1955). Later results were summarized by Damon et al. (1973). Measurements of $^{13}C/^{12}C$ ratios in tree rings have been reported by different groups and recently summarized by Stuiver (1977). The author has used his own data and those of Freyer and Wiesberg (1974a,b) and Rebello and Wagener (1976) for estimating the past biospheric CO_2 source.

In this paper additional ^{13}C data (in the cellulose fraction) from different trees of the northern hemisphere are presented, covering the last 150 years. These data were taken for preliminary model evaluation of the past atmospheric CO_2 increase and total anthropogenic CO_2 production since industrialization. The results will be published elsewhere in detail (Freyer, 1978b, 1978c; Freyer and de Silva, 1978).

^{13}C RECORD IN NORTHERN HEMISPHERIC TREES DURING THE LAST 150 YEARS

The trees (mostly oak and pine species) were selected from at least three different regions in the northern hemisphere (French Atlantic coast; North Carolina, USA; Eifel, FRG), partly because of the claim that trees in these regions are exposed to a well-mixed atmosphere.

Former measurements (Freyer and Wiesberg, 1974b) have shown that even if the trees are selected carefully, the scatter of relative ^{13}C isotope values obtained from individual trees is by far larger than the reproducibility of measurements or the natural fluctuations within one tree ring. This scatter is possibly due to local and physiological factors; some factors of major (record of respiration CO_2, pollution effect) or minor significance (temperature effect) that have been discerned will be reported elsewhere. Therefore, a relatively large number of trees were analyzed to get a representative record.

Measurements within twentieth century wood were made on 26 trees. For the ^{13}C record in nineteenth century wood, measurements on only three trees are available--including the Douglas fir analyzed by Stuiver (1977)--which agree with one another very well. For comparison of individual measurements, the ^{13}C variations over the time record of a tree have been calculated as deviations from the tree-specific isotopic value within the periods 1890-1920 and 1930-1950 for nineteenth and twentieth century trees, respectively. The ^{13}C record of the nineteenth century trees is illustrated in Figure 1; it is connected with the mean record obtained from the other 26 trees for the 1920-1974 time interval. Anomalous isotopic values (due to the record of respiration CO_2 in the youth stage of forest trees and the pollution effects on some Eifel trees) have been omitted.

The oldest tree in this investigation, a Black Forest pine, exhibits relatively constant ^{13}C values within the first half of the nineteenth century. It has been verified from additional trees that since the beginning of industrialization the ^{13}C values have decreased, so far by about 2% in total. A qualitative decrease in ^{13}C values has to be expected because of increasing atmospheric CO_2 levels, but other effects become evident that disagree with the present model conception (e.g., Machta, 1973) of exponentially increasing CO_2 levels of the past. During the first time interval, between 1860 and 1920, the ^{13}C values decreased at a rate that could not have been caused even by complete retention of all fossil CO_2 introduced into the atmosphere. For the interval between 1940 and 1960, the input of fossil CO_2

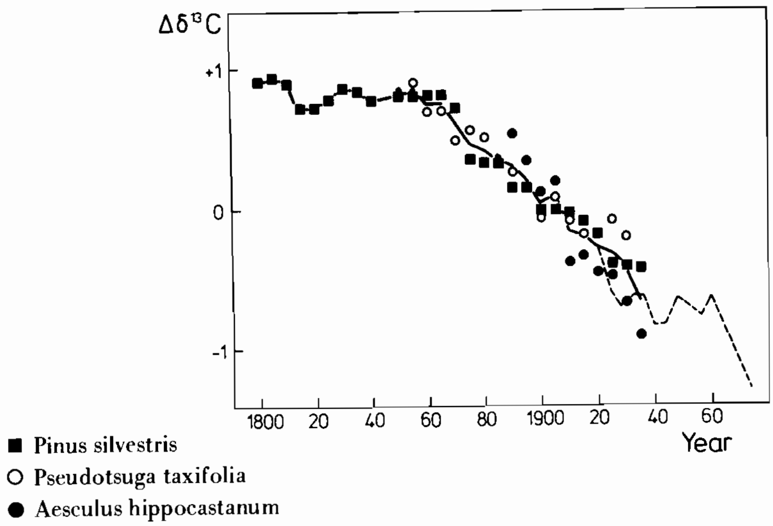


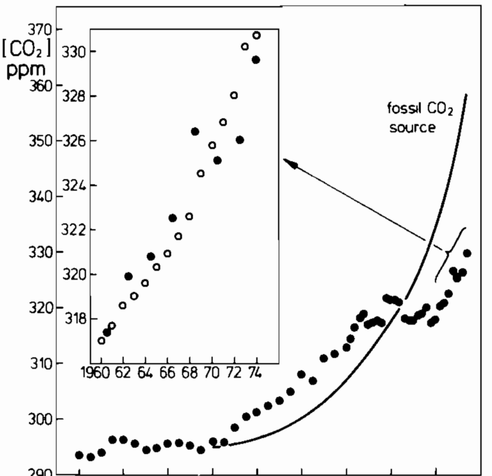
Figure 1. ^{13}C variations from tree ring measurements (measurements Stuiver, 1977) represented as mean deviations from the average 1890–1920 value of each tree; the ^{13}C record of these trees is connected with the record for 1920-1974 (broken line) obtained from 26 other trees.

into the atmosphere has been increasing; however this effect cannot be recognized in the observed ^{13}C fluctuations, even when disturbances of the record are supposed. Only the decreasing ^{13}C values within the 1960–1974 interval agree, above all qualitatively, with direct measurements of atmospheric CO_2 levels.

PRELIMINARY EVALUATION OF PAST ATMOSPHERIC CO_2 INCREASE AND TOTAL ANTHROPOGENIC CO_2 PRODUCTION SINCE INDUSTRIALIZATION

Variations in δ^{13}C with concentration in atmospheric CO_2 samples have recently been summarized by Freyer (1978a) from measurements of Keeling (1958, 1961), Esser (1975), Freyer and Wiesberg (1975), and Freyer (1978c). A linear fit between δ^{13}C values and the reciprocal of CO_2 concentrations ($[CO_2]$ expressed in ppm CO_2 of dry air) has been obtained with a correlation coefficient $r = 0.99$ in the following form: $\delta^{13}C\ (PDB) = 5640\ (1/[CO_2]) - 24.89$. This equation has been used for calculation of the δ^{13}C shift resulting from the Mauna Loa CO_2 data (Keeling et al., 1976; Baes et al., 1976). It has been found that this shift for the 1960–1974 period agrees very well with the δ^{13}C shift obtained from tree ring data. Considering that the atmospheric CO_2 measurements at Mauna Loa and $\delta^{13}C$ tree ring data were made in separate geographical regions, any agreement between the two sets of data is surprising. The linear equation has been calculated only for short-term atmospheric CO_2 variations; application to long-term increasing CO_2 levels has been neither estimated nor experimentally checked. The coefficients, possibly, can alter because isotope exchange reactions of CO_2, at least between atmosphere and ocean, have to be considered for long-term CO_2 variations.

Nevertheless, for preliminary interpretation of our tree ring measurements the unaltered fit has been used. The $\Delta\delta^{13}C$ data of Figure 1 were adjusted to the average isotopic content of atmospheric CO_2 in 1960/1961 ($\delta^{13}C = -7.12$‰PDB) and the obtained $\delta^{13}C$ values converted into atmospheric CO_2 concentrations, which are given in Figure 2. The total increase of atmospheric CO_2 concentrations with a preindustrial value of 295 ± 1 ppm seems to be reasonable. Therefore, alterations of the above linear fit may be only small. In Figure 2 the cumulative function of the fossil fuel CO_2 input (after Keeling, 1973, and Rotty, 1973, 1977) into the atmosphere is also marked, illustrating that



● Evaluated

○ Direct measurements at Mauna Loa (Keeling et al., 1976; Baes et al., 1976) for 1960-1974

Figure 2. Atmospheric CO_2 levels for the 1800-1974, evaluated from model interpretation of ^{13}C tree ring data.

atmospheric CO_2 concentrations within the 1860-1940 interval have to be considerably higher than expected. These concentrations could not have been caused by the fossil fuel input; an additional CO_2 input from the biosphere has to be assumed. For the 1960-1974 interval the calculated atmospheric CO_2 concentrations correspond to direct measurements.

The variability of calculated atmospheric CO_2 concentrations in the 1930-1960 interval is uncertain. Temperature fluctuations are a disturbing factor for the ^{13}C record in tree rings, but the direct temperature effect is at most of the order of 0.1 to 0.3‰ variation in $\delta^{13}C$ per °C; moreover, the sign of this effect has been described oppositely as both positive and negative (Pearman et al., 1976; Freyer and de Silva, 1978). Nevertheless, a direct ^{13}C response may have some consequences. A maximum of mean annual temperatures in the northern hemisphere exists in 1940 with about 0.5°C above the 1920 temperature level (Wilson and Matthews, 1971). The temperature fluctuations of the tree stations are somewhat different (Freyer and de Silva, 1978). For preliminary interpretation of results, the direct temperature ^{13}C response has not been considered because of the uncertainty of the effect. In addition to the direct response, temperature fluctuations will influence the global exchange behavior of CO_2 between atmosphere and ocean.

Using similar mass and isotope balances for ^{14}C and ^{13}C, the airborne CO_2 fraction referring to the total CO_2 input into the atmosphere has been calculated from atmospheric CO_2 levels given in Figure 2, production data of fossil CO_2, and ^{14}C measurements. The ^{14}C data were obtained from estimations of Baxter and Walton (1970) and measurements in tree rings summarized by Damon et al. (1973). It was found that the data from analyses of the two sets converge to an airborne fraction of about 36%. Assuming a time constant airborne fraction of 36%, function III of the total CO_2 input given in Figure 3 has been evaluated from atmospheric CO_2 levels. The nonfossil CO_2 input function I representing the additional biospheric source follows as the difference between III and the known fossil CO_2 input function II. Function I is, possibly, superimposed on the exchange behavior of the ocean. Eriksson (1963) has estimated that a 1°C increase in ocean temperatures increases the atmospheric partial pressure of CO_2 by about 6%. This effect may have some consequences for the shape of function I during the 1920-1940 warming and the 1940-1960 cooling interval, but definitely not to the extent demonstrated in Figure 3. In later studies corrections of the ^{13}C data in tree

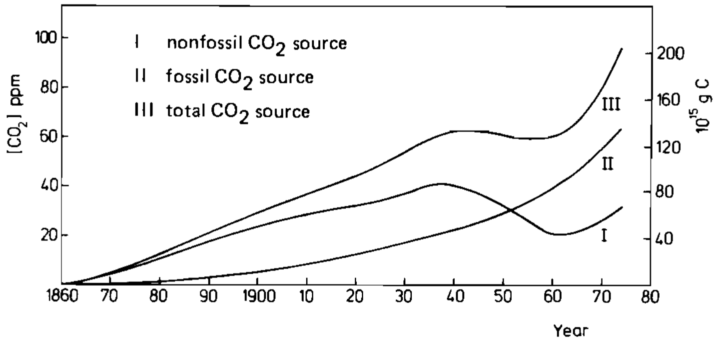


Figure 3. Cumulative function of the nonfossil, fossil, and total CO_2 input source since industrialization, as derived from model interpretation of ^{13}C ring data.

rings for a direct temperature response and the temperature-dependent mass and isotopic exchange of CO_2 between atmosphere and ocean have to be made.

CONCLUSIONS

The following figures have been evaluated from our preliminary interpretation of tree ring data, which may be altered after correction of model assumptions:

- Preindustrial atmospheric CO_2 concentration has been 295 ± 1 ppm.
- The biospheric CO_2 source from the beginning of industrialization to the middle of this century has been larger than the fossil one.
- The ratio of the cumulative input of fossil to nonfossil CO_2 into the atmosphere from the beginning of industrialization up to 1974 is 2:1 (136×10^9 t C of fossil and 70×10^9 t C of nonfossil CO_2).
- The present input rates are 5×10^9 t C/a of fossil and $3 \pm 2 \times 10^9$ t C/a of nonfossil CO_2, based on an airborne fraction of (58 ± 14)% (Freyer, 1978a) and 36% for fossil and total CO_2 input, respectively.

The biospheric source data are in the range of estimations given by other authors (Adams et al., 1977; Bolin, 1977; Hampicke, 1977; Woodwell et al., 1977) from statistics. Both Stuiver (1977) and Wagener (1978), partly using some of our ^{13}C tree ring measurements, have calculated higher cumulative biospheric CO_2 production data of 120 and 208 × 10^9 t C, respectively, with completely different models.

REFERENCES

Adams, J.A.S., M.S.M. Mantovani, and L.L. Lundell (1977), Wood Versus Fossil Fuel as a Source of Excess Carbon Dioxide in the Atmosphere: A Preliminary Report, *Science*, 196, 54-56.

Baes, C.F., H.E. Goeller, J.S. Olson, and R.M. Rotty (1976), *The Global Carbon Dioxide Problem*, Report ORNL-5194, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Baxter, M.S., and A. Walton (1970), A Theoretical Approach to the Suess Effect, *Proc. R. Soc. (London)(Series A)*, 318, 213-230.

Bolin, B. (1977), Changes of Land Biota and Their Importance for the Carbon Cycle, *Science*, 196, 613-615.

Damon, P.E., A. Long, and E.I. Wallick (1973), On the Magnitude of the 11-Year Radiocarbon Cycle, *Earth Planet. Sci. Lett.*, 20, 300-306.

Eriksson, E. (1963), Possible Fluctuations in Atmospheric Carbon Dioxide Due to Changes in the Properties of the Sea, *Journal of Geophysical Research*, 68, 13, 3871-3876.

Esser, N. (1975), *Messung der absoluten Konzentration und des* ^{13}*C-Gehaltes von atmosphärischem* CO_2, Diplomarbeit, Inst. für Unweltphysik, Univ. Heidelberg.

Freyer, H.D. (1978a), Variations of the Atmospheric CO_2 Content, in B. Bolin, E.T. Degens, S. Kempe, and P. Ketner, eds., *The Global Carbon Cycle*, Wiley, New York.

Freyer, H.D. (1978b), *On the* ^{13}*C Record in Tree Rings, I:* ^{13}*C Variations in Northern Hemispheric Trees During the Last 150 Years*, submitted to *Tellus*.

Freyer, H.D. (1978c), *On the* ^{13}*C Record in Tree Rings, II: Registration of Microenvironmental* CO_2 *and Anomalous Pollution Effect*, to be submitted to *Tellus*.

Freyer, H.D., and M.P. de Silva (1978), *On the ^{13}C Record in Tree Rings, III: Temperature Implications*, to be submitted to *Tellus*.

Freyer, H.D., and L. Wiesberg (1974a), Dendrochronology and ^{13}C Content in Atmospheric CO_2, *Nature*, 252, 757.

Freyer, H.D., and L. Wiesberg (1974b), Anthropogenic Carbon-13 Decrease in Atmospheric Carbon Dioxide as Recorded in Modern Wood, in *Proc. FAO/IAEA-Symp. Isotope Ratios as Pollutant Source and Behaviour Indicators*, IAEA, Vienna.

Freyer, H.D., and L. Wiesberg (1975), Review on Different Attempts of Tracing Back the Increasing Atmospheric CO_2 Level to Pre-Industrial Times, in E.R. Klein, and P.D. Klein, eds., *Proc. 2nd Internat. Conf. Stable Isotopes*, USERDA CONF-751027, Oak Brook, Illinois.

Hampicke, U. (1977), Das CO_2-Risiko, *Umschau*, 77, 599-606.

Keeling, C.D. (1958), The Concentration and Isotopic Abundances of Atmospheric Carbon Dioxide in Rural Areas, *Geochim. Cosmochim. Acta*, 13, 322-334.

Keeling, C.D. (1961), The Concentration and Isotopic Abundances of Carbon Dioxide in Rural and Marine Air, *Geochim. Cosmochim. Acta*, 24, 277-298.

Keeling, C.D. (1973), Industrial Production of Carbon Dioxide from Fossil Fuels and Limestone, *Tellus*, 25, 174-198.

Keeling, C.D., R.B. Bacastow, A.E. Bainbridge, C.A. Ekdahl, P.R. Guenther, L.S. Waterman, and J.F.S. Chin (1976), Atmospheric Carbon Dioxide Variations at Mauna Loa Observatory, Hawaii, *Tellus*, 28, 538-551.

Machta, L. (1973), Prediction of CO_2 in the Atmosphere, in G.M. Woodwell, and E.V. Pecan, eds., *Carbon and the Biosphere*, CONF-720510, U.S. Atomic Energy Commission, Springfield, Virginia.

Pearman, G.I., R.J. Francey, and P.J.B. Fraser (1976), Climatic Implications of Stable Carbon Isotopes in Tree Rings, *Nature*, 260, 5554, 771-773.

Rebello, A., and K. Wagener (1976), Evaluation of ^{12}C and ^{13}C Data on Atmospheric CO_2 on the Basis of a Diffusion Model for Oceanic Mixing, in J.O. Nriagu, ed., *Environmental Biogeochemistry, Vol. 1: Carbon, Nitrogen, Phosphorus, Sulfur and Selenium*, Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan.

Rotty, R.M. (1973), Commentary On and Extension of Calculative Procedure for CO_2 Production, *Tellus*, 25, 508-517.

Rotty, R.M. (1977), *Present and Future Production of* CO_2 *from Fossil Fuels - A Global Appraisal*, preprint.

Suess, H.E. (1955), Radiocarbon Concentration in Modern Wood, *Science*, 122, 415-417.

Stuiver, M. (1978), Atmospheric CO_2 Increases Related to Carbon Reservoir Changes, *Science*, 199, 253-260.

Wagener, K. (1978), *Total Anthropogenic* CO_2 *Production During the Period 1860-1975 from C-13 Measurements*, unpublished manuscript.

Wilson, C.L., and W.H. Matthews, eds. (1971), *Inadvertent Climate Modification (SMIC)*, MIT Press, Cambridge, Massachusetts.

Woodwell, G.M., R.H. Whittaker, W.A. Reiners, G.E. Likens, C.A.S. Hall, C.C. Delwiche, and D.B. Botkin (1977), *The Biota and the World Carbon Budget*, to be submitted to *Science*.

MODEL RESPONSES OF THE ATMOSPHERIC CO_2 LEVEL AND $^{13}C/^{12}C$ RATIO TO BIOGENIC CO_2 INPUT

U. Siegenthaler, M. Heimann, and H. Oeschger

In recent contributions to the CO_2 discussion, several authors emphasized that the role of the biosphere in the global carbon cycle should be considered in more detail, and that, owing to human action, the global biomass may have decreased, giving rise to a significant CO_2 input into the atmosphere in addition to the CO_2 produced from the burning of fossil fuels. Woodwell and Houghton [1] estimated that the present biotic input might be between 0.5 and 2 to 4 times that from fossil fuel, which currently amounts to about 5×10^9 tons of carbon per year. Their estimate was speculative since they lacked appropriate data. Bolin [2] evaluated statistics from the Food and Agriculture Organization of the United Nations and from other studies, and concluded that the accumulated input of carbon from the biota is 50 ± 25% of the cumulative fossil production, and the present annual input is 10 to 35% of the present fossil CO_2 flux. Moreover the enhanced CO_2 concentration has probably induced an increased assimilation rate of a part of the biosphere. Thus there are two processes with opposite effects, and the sizes of both are known with only relatively large uncertainty.

Any CO_2 release must influence the atmospheric CO_2 concentration. The atmospheric concentration has been measured with good precision only since 1957 [3,4], while earlier measurements showed large scatter. ^{13}C analyses on tree rings should yield information on atmospheric CO_2 variations. The preindustrial atmospheric ^{13}C concentration was about -7 permil, while fossil fuel and wood currently have about -25 permil, so that CO_2 from both sources tends to lower the atmospheric $^{13}C/^{12}C$ ratio.

We have computed the responses of the atmospheric CO_2 and ^{13}C levels to a combined fossil and biogenic input by means of a box-diffusion model. The model is described in [5,6] and Oeschger and Siegenthaler in these Proceedings, and the model parameters used are those given in [6], except for the biosphere where we found that a different modeling procedure is more satisfactory when considering forest clearing (see Appendix). In addition, the isotope fractionation has been included in a similar way as in [7]. Data for the annual fossil production are taken from [8] and, for 1971-1974, from [9].

In order to demonstrate the effect of different biospheric input histories (in addition to the fossil input), we present the model responses for the following cases (see Figure 1a):

- Zero biogenic input, only fossil CO_2;
- Biogenic flux always equal to one half the fossil flux, i.e., both increase in an approximately exponential way;
- Biogenic production rate according to a Gaussian curve, with maximum in 1890 and width $\sigma = 20$ years, cumulative input from biota equal to 65×10^9 t of C, or one half the fossil input until 1974. After 1950, the biogenic production is essentially zero for case 3, which has been included for analyzing the effect of a *past* input on the *present* situation. For all three cases, no fertilizing effect of the additional CO_2 is assumed (biota growth factor $\varepsilon = 0$).

For comparing the model responses with measured atmospheric CO_2 data, it was necessary to adjust the preindustrial level for each case such that the model predicts, for 1971, the measured value of 326.5 ± 0.3 ppm. The preindustrial values thus obtained for cases 2 and 3 (276 and 280 ppm, respectively) are below the most probable range of 288-295 ppm [10], yet cannot be definitely ruled out. Figures 1b and 2 show the atmospheric CO_2 concentrations as predicted by the model. Case 2 (biogenic = one half fossil input rate) yields an approximately exponential increase as does case 1 (fossil only) but steeper. Case 2 must, however, be excluded since the predicted CO_2 levels differ greatly from observed data (Figure 2). If the net biotic input rate is always a constant fraction of the fossil production, then according to the box-diffusion model it will be at maximum for about 10% of the production, even allowing for uncertainty in the model parameters.

For case 3 (biotic input centered around 1890), the increase slows down after first having been rapid; from about 1950 on, the curve is similar to case 1 which means that even a relatively large CO_2 input in the past could not be recognized from the atmospheric trend over the last 20 years. The fraction of the totally injected CO_2 residing in the atmosphere in 1974 is 53% for case 3, compared to 60% for case 1.

Figure 1c shows the computed decrease in the atmospheric $^{13}C/^{12}C$ ratio. Qualitatively, we have a similar picture for the atmosphere CO_2 increase (Figure 1b). Quantitatively, there is

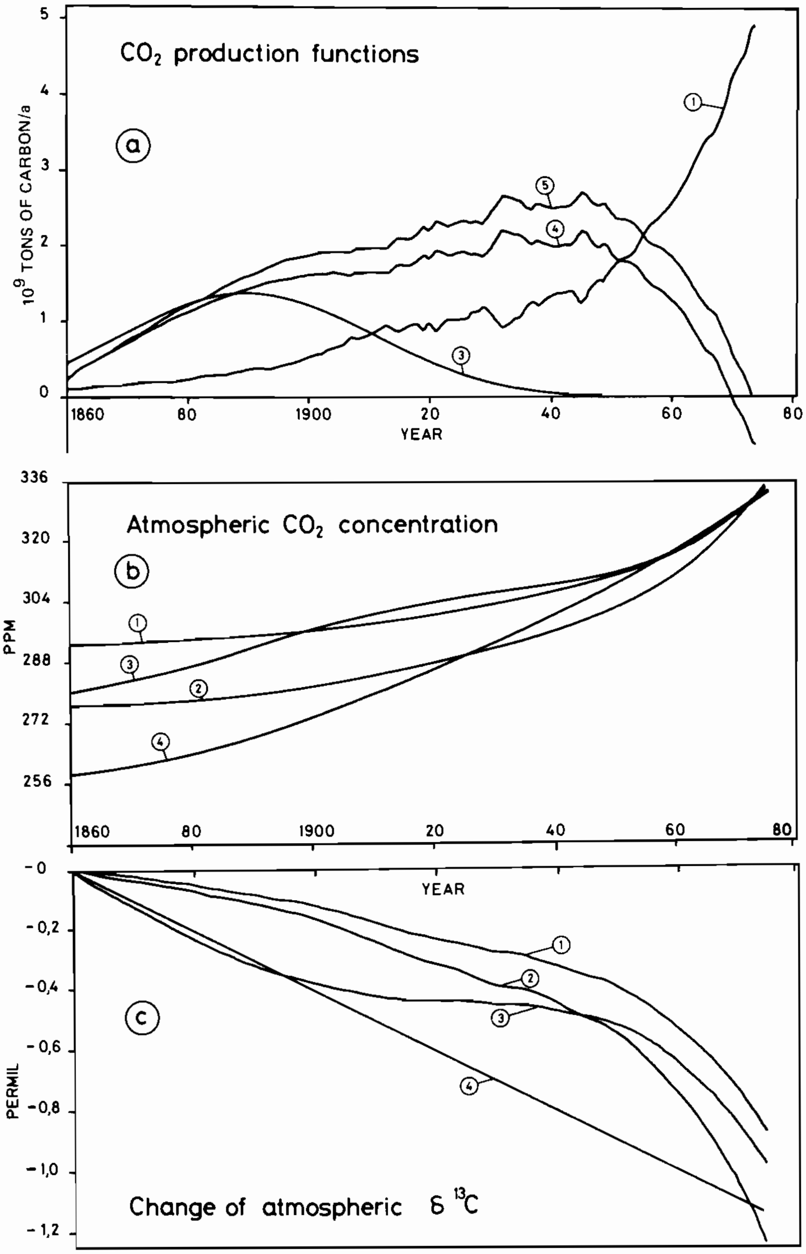


Figure 1. Model inputs and results. Case 1: Fossil CO_2 only, production rates after [8,9]. Case 2: Biospheric production rate always 50% of fossil (not shown in Figure 1a). Case 3: Biospheric input around 1890, cumulative biospheric input is 50% of fossil up to 1974. Case 4: Prescribed atmospheric $^{13}C/^{12}C$ decrease of 1‰/100 years since 1860. Case 5: same as 4. Biota growth factor for cases 1 to 4 is $\epsilon = 0$, for case 5, $\epsilon = 0.2$. In Figure 1a, cases 3 to 5 show biospheric part of input only.

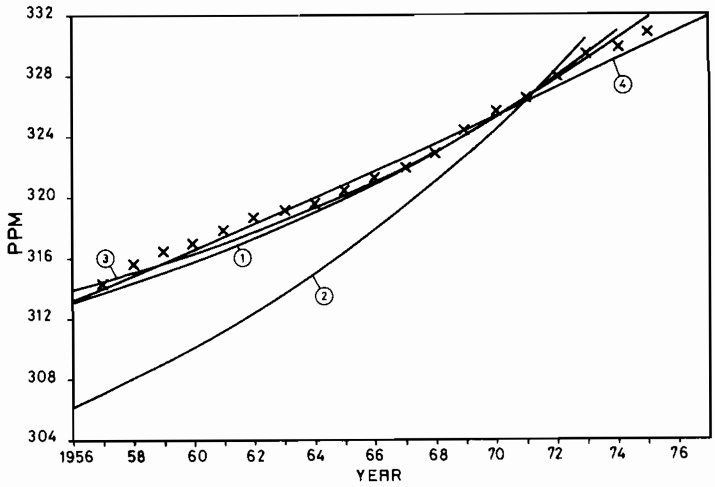


Figure 2. Atmospheric CO_2 concentration. 1-4: model computations (see Figure 1); x: observed values, averages of Mauna Loa and South Pole data (from [3,4] and Keeling, private communication).

an essential difference, since the $\delta^{13}C$ change is, to a first approximation, independent of the buffer factor that affects the oceanic uptake of excess CO_2. Thus while there is about an 11% increase in CO_2 until 1970 (case 1), the corresponding change in $\delta^{13}C$ of 0.7‰ results in only 4% of the 18‰ difference between $\delta^{13}C$ of fossil CO_2 and preindustrial atmospheric CO_2. This feature is analogous to the ^{14}C dilution by fossil CO_2 (the Suess effect). The $\delta^{13}C$ depression is at first quite different for cases 1 (fossil only) and 3, because of the large biospheric input in case 3. By 1950, the ^{13}C deficit has partly dispersed between atmosphere, ocean and biosphere for case 3, and the difference has decreased to about 0.1 permil.

Stuiver [11] compiled ^{13}C data on tree ring series; the available data show much scatter. ^{13}C data from three sources [11,12,13] show an approximately linear decrease of $\delta^{13}C$ between 1860 and 1970, the average rate of decrease being between about 0.6 [12] and 1.7‰/100 years [13]. We have computed the biogenic CO_2 production rate which, together with the rate for fossil CO_2, would have created a linear ^{13}C decrease from 1860 on, with a slope of −1.0‰/100 years (curve 4 in Figure 1c). The resulting functions for CO_2 production from forest burning are shown in

Figure 1a as case 4, for a biota growth factor $\varepsilon = 0$, and as case 5, for $\varepsilon = 0.2$. In both cases, the biospheric output increases rapidly until about 1900, then slowly to 1950, and then decreases rapidly to finally reach a negative value (which, of course, does not make sense) for case 4, and zero for case 5 where the forest cutting is partly compensated by enhanced productivity.

The *net* changes of biomass are very nearly the same for cases 4 and 5, and so are the computed CO_2 concentration functions, starting at a preindustrial level of 258 ppm (Figure 1b). The predicted values for 1957 to 1975 (Figure 2) are compatible with the observed data, the deviations being 1 ppm at most. The amount produced until 1974 by forest burning is 157×10^9 t for case 4 and 195×10^9 t of C for case 5, in both cases more than the 133×10^9 t of fossil carbon released.

We have also considered the case of a linear ^{13}C decrease with a rate of -1.4‰/100 years. The corresponding biotic CO_2 output (for $\varepsilon = 0$) would be higher by 1 to 2×10^8 t/a than for case 4. The resulting CO_2 concentration curve, starting at 229 ppm, is clearly not compatible with the observed data after 1957, so this case is not further discussed.

In summary, we find that not only the *amount of biospheric CO_2* is important, but, because of the time-dependent flow into the oceans, also the *time of release into the atmosphere*, i.e., the history of the biospheric CO_2 production is essential. If a large input pulse occurred only a few decades ago, it is still influencing the present CO_2 level by providing a decreasing atmospheric "baseline", since excess CO_2 is still being taken up by the ocean. The longer ago such an input occurred, the smaller is its influence on the present trend. In principle, a relatively large cumulative biospheric CO_2 production, even larger than the fossil input, would be compatible with the observations since 1957, but the production function would have had to decrease within the last 20 or 30 years to a low value now. Furthermore, the preindustrial CO_2 level would then have had to be lower than generally assumed today.

Actually, the rate of forest clearing probably did not increase quasi-exponentially, such as the fossil CO_2 did, but was high already in the last century [14], and possibly, there was even a net growth of biomass since 1900, at least in developed countries (see Wood and Botkin data in [1], Figure 1).

The above discussion depends on the validity of our box-diffusion model and its basic assumptions. These have been discussed in detail in [6]. The only sink for excess CO_2, excluding the biota, is the ocean, whose capacity for taking up CO_2 is determined by chemical equilibria for the aquatic carbonate system and can be described by a buffer factor and by the rate of vertical mixing, expressed by an eddy diffusivity in our model. Since we know from ^{14}C measurements that the turnover time of the ocean is of the order of 1000 years, vertical mixing cannot be much faster (and therefore more effective for removing excess CO_2) than assumed in our model. The buffer factor is determined by chemical equilibrium constants which are relatively well known, but since its exact size is of crucial importance, it seems desirable that the buffering action of seawater should be studied in further detail.

Besides improvements in modeling, more information about the atmospheric CO_2 and ^{13}C history is an absolute necessity, such as measurements on tree rings and other samples (layered mollusc shells, dated cereal samples, old glacier ice). However, analyses of tree rings provide only an indirect record of atmospheric $\delta^{13}C$. ^{13}C in plants is affected by various factors, e.g., climate, local conditions such as height above ground, and plant physiology--which is clearly demonstrated by the scatter between ^{13}C records from different trees (see [8] and discussion thereafter). A better understanding of these factors is needed. ^{13}C measurements of Craig [15] on a Sequoia gigantea tree, covering about 2500 years, showed variations of 1 to 2 permil, so that it seems possible that the natural preindustrial atmosphere also exhibits significant ^{13}C (and CO_2?) fluctuations.

Observations of the atmospheric ^{14}C depletion (the Suess effect) do not give information on the biosphere, since average biospheric CO_2 has nearly the same ^{14}C concentration as the atmosphere.

Most important are direct obervations of biomass area, density, age structure, etc. Since a 1% change of biomass already has a large effect, these data must be precise, which may be difficult to achieve in view of the heterogeneity of the global biosphere.

Appendix

Modeling of the Biosphere

We consider only long-lived plants, since the amount of carbon stored in the short-lived part of the biosphere is relatively small and has a short turnover time.

In our former versions of the box-diffusion model [5,6], for the change of biomass we have the following:

$$N_b = F_{ab} - F_{ba} = \text{productivity - decay}$$

with

$$F_{ab} = k_{ab}N_{ao}(1 + \varepsilon\nu_a)$$

$$F_{ba} = k_{ba}N_b$$

where

N_a, N_b: amounts of carbon in atmosphere and biosphere,

F_{ab}, F_{ba}: fluxes between atmosphere and biosphere,

ν_a: relative increase of atmospheric $CO_2 = \frac{N_a - N_{ao}}{N_{ao}}$,

k_{ab}, k_{ba}: exchange coefficients, and

ε: biosphere growth factor.

(Say, for a 10% increase of N_a, i.e. $\nu_a = 0.10$, and $\varepsilon = 0.2$, the productivity would increase by 2%.) This form of F_{ab}, depending on atmospheric CO_2 only, is no longer reasonable when including deforestation, since the productivity remains constant even for a smaller forested area and thus tries to restore the original state. F_{ab} should, therefore, primarily depend on the size of the biosphere. However, the "Ansatz" $F_{ab} = k_{ba}N_b \cdot (1 + \varepsilon\nu_a)$ (a similar one was used by Bacastow and Keeling [7]) is not very realistic because steady state ($F_{ba} = F_{ab}$) is reached only for $\nu_a = 0$, i.e., the biosphere swallows all excess CO_2 introduced into the carbon exchange system.

Therefore, we represent biomass by a product of the overgrown area, S_b, times the biomass density, D_b (t of C per m^2):

$$N_b = D_b\, S_b \quad ;$$

we assume that deforestation d (t of C per year) concerns the area only, but leaves the density unchanged:

$$D_b\, \dot{S}_b = - d \quad .$$

The fertilizing effect of CO_2 affects density only, not area:

$$D_b = f_o(1 + \varepsilon\nu_a) - k_{ba}\, D_b$$

where f_o is the preindustrial productivity per m^2. Thus we have now two differential equations for describing the changes of biomass, because we must fix two of the three variables N_b, D_b, S_b.

The fluxes into and out of the biosphere are given by

$$F_{ab} = f_o\, S_b(1 + \varepsilon\nu_a)$$

$$F_{ba} = k_{ba}\, D_b\, S_b + d \quad .$$

For ^{13}C and ^{14}C, appropriate isotope fractionation factors are introduced.

Obviously, this is still an oversimplified representation of the biosphere, but in this way it is possible to consistently and simultaneously describe deforestation and fertilization by CO_2 in a global model.

REFERENCES

[1] Woodwell, G.M., and R.D. Houghton, Biotic Influences on the World Carbon Budget, in W. Stumm, ed., *Global Chemical Cycles and Their Alterations by Man*, Abakon Verlagsgesellschaft, Berlin, 1977.

[2] Bolin, B., Changes of Land Biota and Their Importance for the Carbon Cycle, *Science*, 196 (1977), 613-615.

[3] Keeling, C.D., R.B. Bacastow, A.E. Bainbridge, C.A. Ekdahl, P.R. Guenther, L.S. Waterman, and J.F.S. Chin, Atmospheric Carbon Dioxide Variations at Mauna-Loa Observatory, Hawaii, *Tellus*, 28 (1976), 538-551.

[4] Keeling, C.D., J.A. Adams, C.A. Ekdahl, and P.R. Guenther, Atmospheric Carbon Dioxide Variations at South Pole, *Tellus*, 28 (1976), 552-564.

[5] Oeschger, H., U. Siegenthaler, U. Schotterer, and A. Gugelmann, Box Diffusion Model to Study Carbon Dioxide Exchange in Nature, *Tellus*, 27 (1975), 168-192.

[6] Siegenthaler, U., and H. Oeschger, Predicting Future CO_2 Levels, *Science*, 199 (1978), 388-395.

[7] Bacastow, R., and C.D. Keeling, Changes from A.D. 1700 to 2070 as Deduced from a Geochemical Model, in G.M. Woodwell and E.V. Pecan, eds., *Carbon and the Biosphere*, CONF-720510, United States Atomic Energy Commission, Springfield, Virginia, 1973.

[8] Keeling, C.D., Industrial Production of Carbon Dioxide From Fossil Fuels and Limestone, *Tellus*, 25 (1973), 174-198.

[9] Rotty, R.M., *Global Carbon Dioxide Production From Fossil Fuels and Cement, A.D. 1950-A.D. 2000*, IEA(M)-76-4, Institute of Energy Analysis, Oakridge, Tennessee, 1976.

[10] Callendar, G.S., On the Amount of Carbon Dioxide in the Atmosphere, *Tellus*, 10 (1958), 243-248.

[11] Stuiver, M., Atmospheric CO_2 Increases Related to Carbon Reservoir Changes, *Science*, 199 (1978), 253-260.

[12] Freyer, H.D., and L. Wiesberg, Anthropogenic Carbon-13 Decrease in Atmospheric Carbon Dioxide as Recorded in Modern Wood, in *Isotope Ratios as Pollutant Source and Behaviour Indicators*, International Atomic Energy Agency, Vienna, 1975.

[13] Nriagu, J.D., ed., *Biochemistry*, Ann Arbor Science Publication, Vol. 1, University of Michigan, Ann Arbor, 1976.

[14] Reiners, W.A., and H.E. Wright, Impact of Prehistoric and Present Fire Patterns on the Carbon Dioxide Content of the Atmosphere, in W. Stumm, ed., *Global Chemical Cycles and Their Alterations by Man*, Abakon Verlagsgesellschaft, Berlin, 1977.

[15] Craig, H., Carbon-13 Variations in Sequoia Rings and the Atmosphere, *Science*, 119 (1954), 141-143.

SOURCE FUNCTIONS FOR CO_2 IN THE ATMOSPHERE

K.-E. Zimen

In our recent publication [1] we considered the source functions for CO_2 and assessed future CO_2 levels in the atmosphere, with and without changing the biomass, using a five-box model. Meanwhile we have become aware of a number of relevant papers which have appeared or are forthcoming [2-6]. I would like, therefore, to make two remarks in addition to what we have published.

FINAL CUMULATED INPUT OF CO_2 FROM FOSSIL FUELS

For the ultimate recovery of coal, oil, and natural gas, and thus for the final input of CO_2 from fossil sources into the atmosphere (n_∞^{if}) we have used earlier [7]

$$n_\infty^{if} \simeq 600 \times 10^{15} \text{ mols} \simeq 12 \times N_o^a$$

where N_o^a is the preindustrial amount of CO_2 in the atmosphere, taken as 292 ppmv or 52.1×10^{15} mols. The same figure has recently been used by Baes et al. [8,9]. In our recent publication we have preferred a lower value of

$$n_\infty^{if} \simeq 400 \times 10^{15} \text{ mols} \simeq 8 \times N_o^a$$

This value is in agreement with the estimate by Perry and Landsberg [10], who have advanced a figure of $8.2 \times N_o^a$.

The range of possible values for the final cumulated input of CO_2 may be even larger than 8 to 12 times N_o^a, and it seems worthwhile to elaborate on this point.

Figure 1 shows a McKelvey diagram for resources explaining my nomenclature and the symbols used. Table 1 then gives the

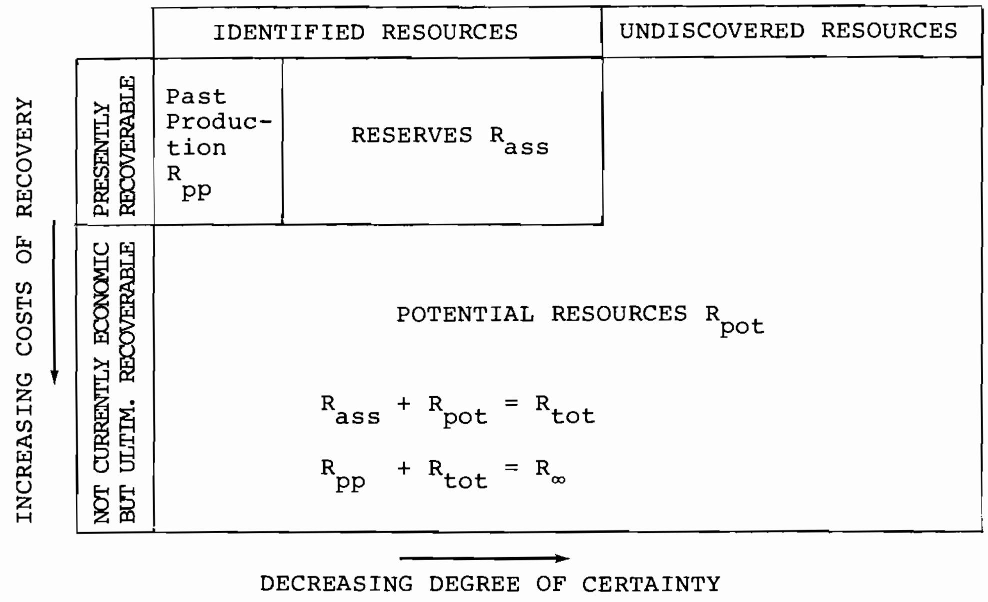


Figure 1. Simplified McKelvey diagram of resources.

Table 1. Recent estimates of global fossil resources and corresponding amounts of CO_2.

	Hubbert [11]		WEC-74 [12]		WEC-77 [12]			Probable Range	
	rxR_{∞}^{*} $10^{21}J$	CO_2 $10^{15}mol$	R_{ass} $10^{21}J$	R_{tot}	R_{pp}	R_{ass} $10^{21}J$	R_{tot}	R_{∞} $10^{21}J$	CO_2 $10^{15}mol$
	1	2	3	4	5	6	7	8	9
Solid fuels	53.2	106	15.1	150-300	3.81	18.7	297	150-300	300-600
Pet l.liquids	14.2	24	4.0	7.9 - 79	1.85	-	7.5-14.9	9 - 79	15-130
Tars & shales	2.9	5	-	11**-140***	0	-	-	11	18
Natural gas	13.1	17	1.9	4.3-43	0.93	2.5	10.6	4 - 43	5-55
Sum	83.4	152	-	168-433	6.59	-	-	174-433	338-803

*Recoverable under present conditions (r: present recovery factor).
**Total known resources.
***Includes "speculative resources" down to 0.04 1 oil per kg crude.

most recent estimates concerning the global resources of fossil fuels and the corresponding amounts of CO_2 calculated with the following "CO_2 factors" (cf. [1]):

for coal	2.00 mol C/MJ
for oil	1.68 mol C/MJ
for gas	1.29 mol C/MJ .

The figures given by Hubbert [11] refer to the resources (including past production) recoverable under present technical and economic conditions. Thus, the corresponding 150×10^{5} mols are surely a minimum value. Summing up the low estimates of different authors compiled by the World Energy Conference (WEC) one arrives at 338×10^{15} mols. Summing up the high estimates and excluding the highly speculative figure for the oil from tar sands and shales one gets instead 803×10^{15} mols. Obviously the estimates made by different experts differ widely, especially concerning the remaining resources of oil and gas (a factor of about 10), while the estimates for coal are consistent within a factor of 2 or 3. The great differences are, of course, quite understandable, because there is not only the difficulty of estimating the remaining undiscovered resources but also the ultimate recovery, which is highly dependent on the price at which the products can be sold, i.e., on the competition with other sources of primary energy.

In conclusion one can say that for the final cumulated input, any value between 200×10^{15} mols and, say 800×10^{15} mols, can be justified at present, that is 4 to 16 times the preindustrial amount of CO_2 in the atmosphere. Our choice of $n^{if}_{\infty} \simeq 8 \times N^{a}_{o}$ reflects our belief that fossil fuels probably will be replaced slowly but steadily by nuclear and eventually renewable sources of energy long before the last ton of coal has been recovered from the ground.

INPUT OF CO_2 FROM CHANGING BIOMASS

The yearly input of CO_2 into the atmosphere from the combustion of fossil fuels ($\dot{n}^{if}$) is at present [1]:

$$\dot{n}^{if}_{a.p.} \simeq 0.4 \times 10^{15} \text{ mols/y} = 0.4 \text{ Pmols/y*}$$

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*1 petamol (Pmol) = 10^{15} mols, cf. for example [13].

The input of CO_2 from reduced biomass due to deforestation and the reduction of organic matter in the soil (n^{ib}) have been treated recently by a number of authors and surveyed by Woodwell et al. [14].* The range of estimates is from 1 to 8 Gt of carbon per year (with a possible maximum of 18 Gt/y), thus

$$\dot{n}^{ib}_{a.p.} = (0.1 \ldots 0.7) \text{ Pmols/y} \simeq (0.2 \ldots 2)\, \dot{n}^{if}_{a.p.}$$

The difficulty is, that one does not know where to find the sink for this additional input of CO_2. This problem is reflected in our results. Figure 2 shows the future levels of CO_2 under three

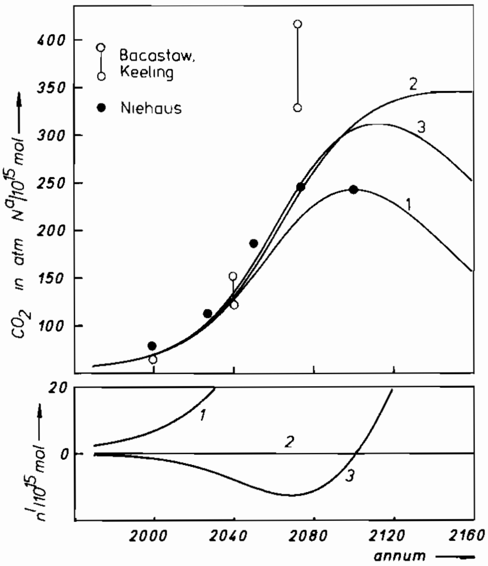

Figure 2. Future CO_2 levels in the atmosphere under status quo conditions of fossil fuel consumption, i.e. with an increase of $\alpha = 4.3\%/y$ (for lower values of α see [1]), and with the parameters of the standard box-model (cf. [1]). Curve 1: growth of biomass ($\beta = 0.44$) (cf. [15]), no deforestation ($\delta = 0$); curve 2: no change of biomass ($\beta = \delta = 0$); curve 3: net reduction of biomass ($\beta = 0.44$, $\delta = 0.32$).

Source: [1]

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*See also H.D. Freyer's contribution to these Proceedings, and Wagener [6].

different assumptions for the biological growth factor β [1] and our "deforestation factor" δ, which for small perturbations is simply defined by

$$\dot{n}^{ib} = \delta \times \dot{n}^{if} \quad .$$

At first the results of Figure 2 may be surprising, because deforestation does not change the future increase of CO_2 notably during the next 100 years or so. When the large β-value takes over, there develops a difference between curves 2 and 3. A second look, however, makes the result understandable. All models can and should be tested by trying to simulate the experimental data on the increase of CO_2 in the atmosphere, mainly from Mauna Loa, Hawaii, USA, and that is what we have done. When simulating the Mauna Loa record with a rather large deforestation factor, one has to change the parameters of the mixed surface sea in such a way that much more CO_2 is taken up by the oceans; otherwise one cannot get any fit. With a biological growth factor of $\beta = 0.44$ and the parameters of the so-called standard box-model (cf. Figure 2 in [1]), we obtained the best fit with $\delta = 0.08$, i.e.,

$$\dot{n}^{ib} = 0.08 \times \dot{n}^{if} \quad ,$$

a deforestation factor even lower than the lowest of the estimates mentioned above. Larger values for δ can only be accomodated with quite arbitrary assumptions concerning the size of the mixed surface sea and its time constants. When going to figures lower than 0.44 for the biological growth factor, not even $\delta = 0$ is sufficient for an adjustment to the Mauna Loa data.

Thus it seems that we have three possibilities:

- If we think the parameters of the standard box-model for the mixed surface sea are about right, then we have to accept a relatively high biological growth (β) through the rising partial pressure of CO_2 and a relatively low deforestation, etc. (δ).

If, however, the weight of evidence points in the direction of a higher deforestation, which seems to be the case, then one has two possibilities:

- The oceans can take up more CO_2 per unit time than follows from the present models, with the parabolic function of the buffer factor. At present neither the box-model nor the diffusion model of Oeschger et al. [16] can explain such a large uptake by the oceans.

A third possibility therefore remains:

- We have to find a new sink or sinks for the CO_2. Perhaps one of these sinks could be the carbonates on land. The sediments on the continents constitute roughly 5×10^8 km^3. The fraction of limestone in the sediments is about 8%, but with regard to the fraction on the surface exposed to the air it may be about 29% [17]. If one distributes the 5×10^8 km^3 sediments evenly all over the land area of 136×10^6 km^2, one gets a layer of 3.7 km. Let us assume, that on the average a layer of 1 m is in contact with the CO_2 in the air. (Limestones are very porous.) Then, with a density of $CaCO_3$ of 2.7 t/m^3, the amount of limestone in this surface layer is

$$\frac{0.29 \times 5 \times 10^{17}\ \text{m}^3 \times 1\ \text{m}}{3700\ \text{m}} \times \frac{2.7 \times 10^6\ \text{g}}{\text{m}^3}$$

$$\simeq 1 \times 10^{20}\ \text{g} = 1 \times 10^{18}\ \text{mols} \quad .$$

Thus the carbon reservoir in contact with the atmosphere is about 2 orders of magnitude larger than the carbon reservoirs in the atmosphere, the biosphere, and the mixed surface sea.

REFERENCES

[1] Zimen, K.E., P. Offermann, and G. Hartmann, Source Functions of CO_2 and Future CO_2 Burden in the Atmosphere, *Z. Naturforsch.*, 32a (1977), 1544.

[2] Bolin, B., Changes of Land Biota and Their Importance for the Carbon Cycle, *Science*, 196 (1977), 613.

[3] Siegenthaler, U., and H. Oeschger, Predicting Future Atmospheric CO_2 Levels, *Science*, 199 (1978), 388-395.

[4] Revelle, R., and W. Munk, The CO_2 Cycle and the Biosphere, in *Energy and Climate*, National Academy of Sciences, Washington, DC, 1977.

[5] Keeling, C.D., and R.B. Bacastow, Impact of Industrial Gases on Climate, in *Energy and Climate*, National Academy of Sciences, Washington, DC, 1977.

[6] Wagener, K., *Total Anthropogenic CO_2 Production During the Period 1860-1975 From C-13 Measurements*, unpublished.

[7] Zimen, K.E., and F.K. Altenhein, The Future Burden of Industrial CO_2 on the Atmosphere and the Oceans, *Z. Naturforsch.*, 28a (1973), 1747.

[8] Baes, C.F., Jr., H.E. Goeller, J.S. Olson, and R.M. Rotty, The Global CO_2 Problem, ORNL-5194, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1976.

[9] Baes, C.F., Jr., H.E. Goeller, J.S. Olson, and R.M. Rotty, Carbon Dioxide and Climate: The Uncontrolled Experiment, *American Scientist* , 65 (1977), 310.

[10] Perry, H., and H.H. Landsberg, Projected World Energy Consumption, in *Energy and Climate*, National Academy of Sciences, Washington, DC, 1977.

[11] Hubbert, M.K., Survey of World Energy Resources, in R.A. Karam and K.Z. Morgan, eds., *Energy and the Environment: Cost-Benefit Analysis*, Pergamon Press, Oxford, 1976.

[12] *Survey of Energy Resources: World Energy Conference 1974*, US National Committee of the WEC, New York, 1974; and *World Energy Conference*, 1977, to be published.

[13] National Bureau of Standards, *NBS Circular 1078*, Washington, DC, 1976.

[14] Woodwell, G.M., R.H. Whitaker, W.A. Reiners, G.E. Likens, C.C. Delwiche, and D.B. Botkin, The Biota and the World Carbon Budget, *Science*, 199 (1978), 141.

[15] Bacastow, R.B., and C.D. Keeling, Changes from AD 1700 to 2070 as Deduced from a Geochemical Model, in G.M. Woodwell and E.V. Pecan, eds., *Carbon and the Biosphere*, CONF-720510, U.S. Atomic Energy Commission, Springfield, Virginia, 1973.

[16] Oeschger, H., U. Siegenthaler, U. Schotterer, and A. Gugelmann, Box Diffusion Model to Study Carbon Dioxide Exchange in Nature, *Tellus*, 27 (1975), 168-192.

[17] Möller, P., personal communication.

MODELING CHARACTERISTICS OF TERRESTRIAL ORGANIC CARBON

A. Björkström

INTRODUCTION

Living and dead organic material on land together constitutes a carbon reservoir, hereafter called terrestrial organic carbon. When estimates of living biomass in the world (e.g. Whittaker and Likens, 1973; Bazilevich et al., 1971) are added to estimates of dead material in the soil (e.g. Bohn, 1976; Schlesinger, 1977), the results indicate that the reservoir of terrestrial organic carbon is between three and six times the present carbon content of the atmospheric CO_2.

In recent years, the role of terrestrial organic carbon in the changing atmospheric CO_2 balance has become a subject of increasing interest. This is not least due to the realization that the man-made releases of CO_2 of biological origin may be of the same order of magnitude as the CO_2 production from fossil fuel combustion. Also, the possibility of the terrestrial biosphere as a sink for excess CO_2 needs to be explored in a quantitative way.

As a consequence of this, there has been increasing interest in questions relating to the incorporation of the terrestrial organic carbon in mathematical models of the global carbon cycle. Obtaining accurate estimates of the size and natural rate of exchange of terrestrial organic carbon is one relevant part of this problem. However, more important is probably to gain some insight into its dynamical properties, i.e., to investigate questions such as: How does the natural biota respond to increased atmospheric CO_2 content? What percent of the carbon fixed in photosynthesis is returned to the atmosphere before x years, for various values of x?

MODELING TERRESTRIAL ORGANIC CARBON

A first attempt at modeling a flux through a geophysical system is often to treat it by "first-order" dynamics. This approach assumes the rate of outflux of a given reservoir to vary in proportion to the amount in it, and to be independent of the amount contained in the other reservoirs of the system. There are several reasons why this is a poor description of the properties of the interactions between the terrestrial organic carbon and the reservoirs connected to it.

The rate at which photosynthesis in the world proceeds is dependent on the total amount of green material in plants. To the extent that this amount varies with varying total biomass, the input rate from the atmosphere to the terrestrial organic matter is not independent of the size of the latter reservoir. Furthermore, most of the terrestrial organic carbon is in the form of dead organic material, which takes no part in the photosynthesis. It is therefore illustrative (not only for this reason) to consider living and dead material as separate reservoirs in a box model. A division of this kind was applied by Craig (1957) and we have used the same principle in our study.

Even within the reservoirs of living and dead organic carbon, respectively, different carbon atoms stay for very different lengths of time. This is not least dependent on the different turnover times of the different vegetation systems in the world. It appears instructive to be able to give account to the different characteristics in this regard between, for example tropical and boreal forests. In our experiments, we plan to do this by connecting to the atmospheric box in our model three or four pairs of reservoirs of living and dead material, representing different major biomes of the world.

In a mathematical model of the atmospheric-oceanic carbon cycle, the biota and soil were included as mentioned above. The entire model is illustrated in Figure 1. A more complete description of the model will be published elsewhere. Here we shall only mention that the gross primary production of the natural biota (i.e., the flux from the atmosphere to the biota) was assumed to vary according to the equation

$$F_{ab} = F_{abo} \cdot (1 + \beta \ln(N_a/N_{ao})) \cdot (\frac{N_b}{N_{bo}}) \qquad (1)$$

where N_a and N_b denote the amounts of carbon in the atmosphere and biota, respectively. F_{ab} is the gross primary production, and index o denotes a steady-state value. The so-called biota growth factor, β, is a measure of the potential of the biota to increase its assimilation rate as the atmospheric CO_2 content increases. The mathematical formulation of equation (1) is based on studies in glass houses. Its applicability to vegetation under natural conditions has been discussed by Keeling (1973).

RESULTS OF COMPUTER EXPERIMENTS

Sensitivity analyses indicate that the most crucial parameters when determining the partitioning of the CO_2 released until now are the preindustrial CO_2 concentration in the atmosphere and

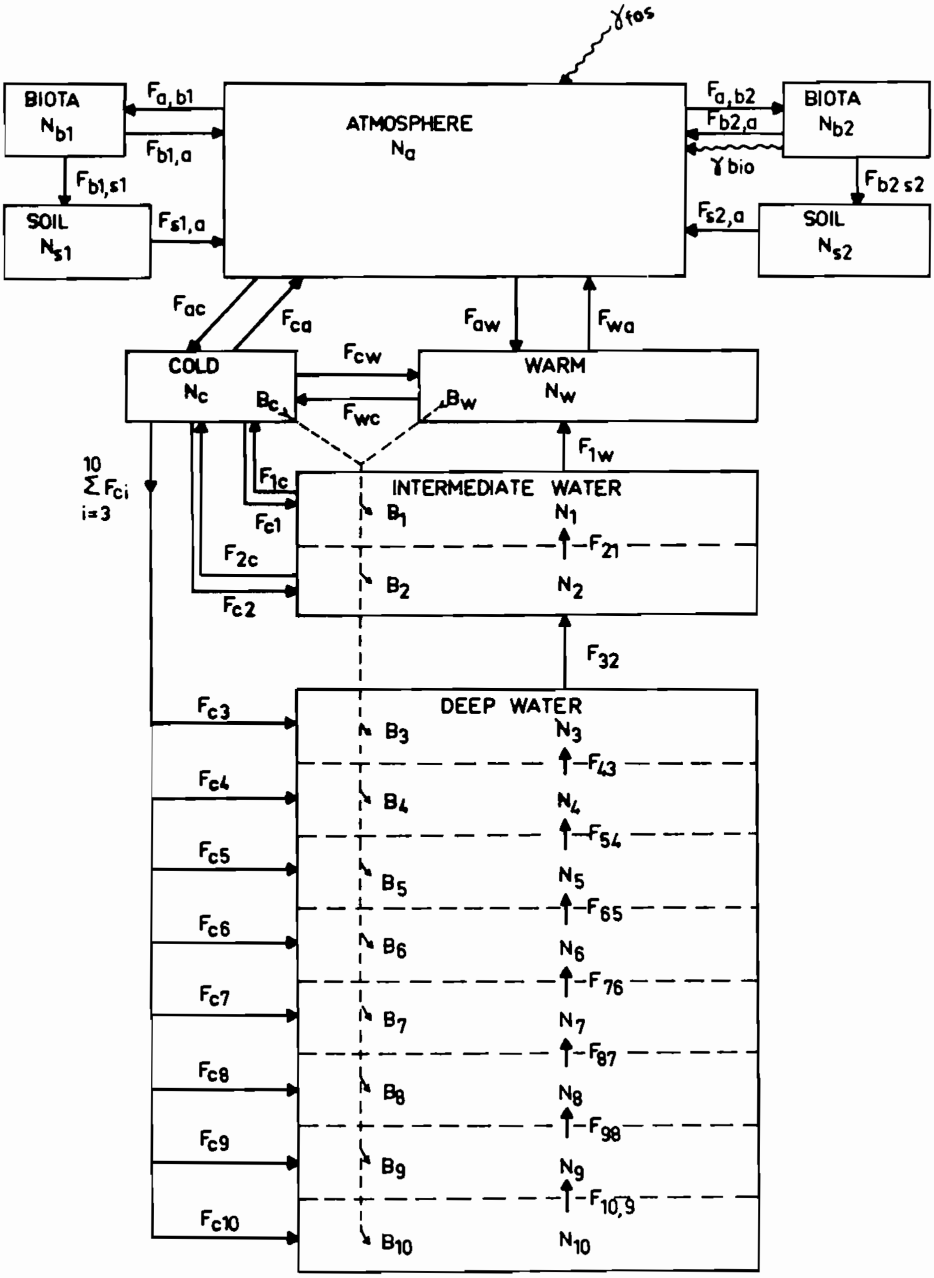

Figure 1. Model of the global carbon cycle for studying the partitioning of the CO_2 released until now between the atmosphere, the ocean, and the biota. (The reservoirs N_{b1} and N_{s1} represent living and dead organic carbon; the reservoir N_{b2} initially contains an amount of carbon which is successively transferred into the atmosphere, representing man's impact on the terrestrial organic carbon.)

the biota growth factor, β. In comparison the uncertainty introduced by the lack of precise knowledge about the oceanic exchange processes, or the biological processes in the ocean, appears to be less profound. To account for the spread in present estimates on the carbon content of the biota and soil, and in estimates on the net primary production, observations from different authors were combined to yield in one case the shortest obtainable value for the turnover time for the biota-soil system, in the other case the longest possible time. For these two cases experiments were performed with different values for β, to find what value for the preindustrial atmospheric CO_2 content was necessary to give a content of 320 ppm in 1970. The results are shown in Figures 2a and 2b. The corresponding partitioning of the excess CO_2 between the atmosphere, the biota and soil, and the ocean is shown in Figure 3.

REFERENCES

Bazilevich, N.I., L.E. Rodin, and N.N. Rozov (1971), Geographical Aspects of Biological Productivity, *Soviet Geography: Review and Translation*, 12, 5, 292-317.

Bohn, H.L. (1976), Estimate of Organic Carbon in World Soils, *Soil Sci. Soc. Amer. J.*, 40, 3, 468-470.

Craig, H. (1957), The Natural Distribution of Radiocarbon and the Exchange Time of Carbon Dioxide Between Atmosphere and Sea, *Tellus*, 9, 1-17.

Keeling, C.D. (1973), The Carbon Dioxide Cycle: Reservoir Models to Depict the Exchange of Atmospheric Carbon Dioxide with the Oceans and Land Plants, in S.I. Rasool, ed., *Chemistry of the Lower Atmosphere*, Plenum, New York-London.

Schlesinger, W.H. (1977), Carbon Balance in Terrestrial Detritus, *Ann. Rev. Ecol. Syst.*, 8, 51-81.

Whittaker, R.H., and G.E. Likens (1973), Carbon in the Biota, in G.M. Woodwell and E.V. Pecan, eds., *Carbon and the Biosphere*, CONF-720510, U.S. Atomic Energy Commission, Springfield, Virginia.

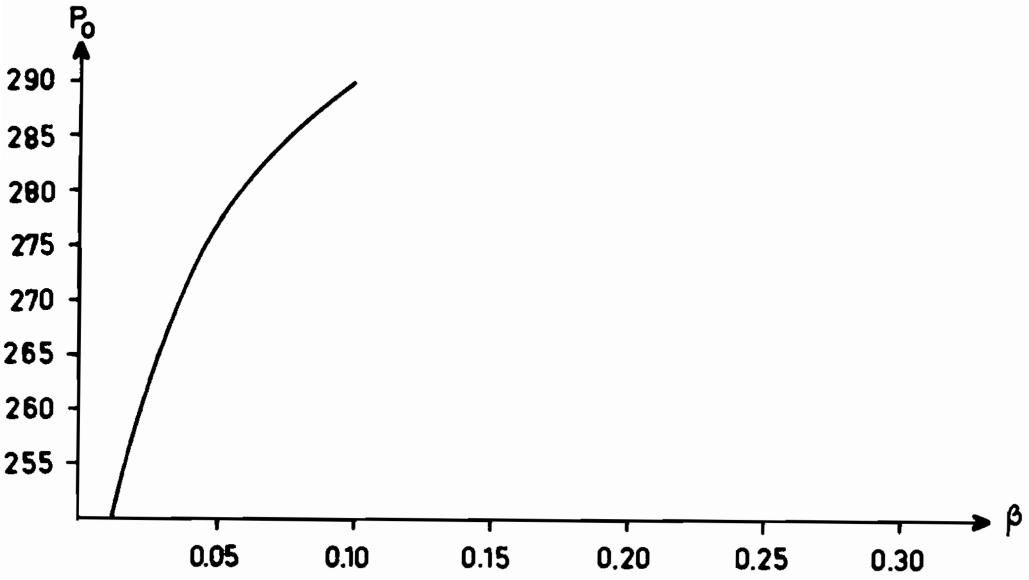

Figure 2a. Combinations of preindustrial CO_2 partial pressure, P_o, and biota growth factor β, yielding an atmospheric CO_2 pressure of 320 ppm in 1970. (The graph represents the case where the biota amounts to 560 x 10^{15} gC (less than an average estimate) and has a net primary production of 86 x 10^{15} gC/a (more than an average estimate).)

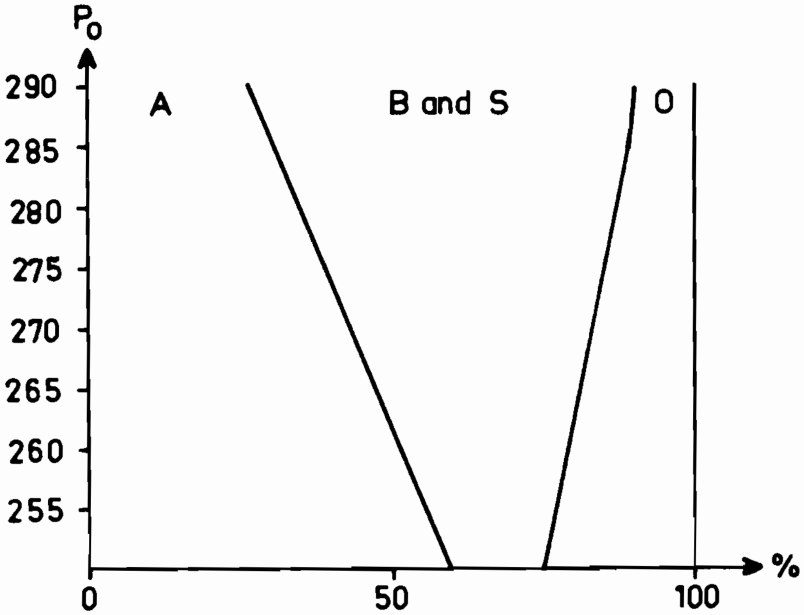

Figure 2b. Distribution of released CO_2 between atmosphere, biota, and ocean for cases corresponding to the graph in Figure 2a.

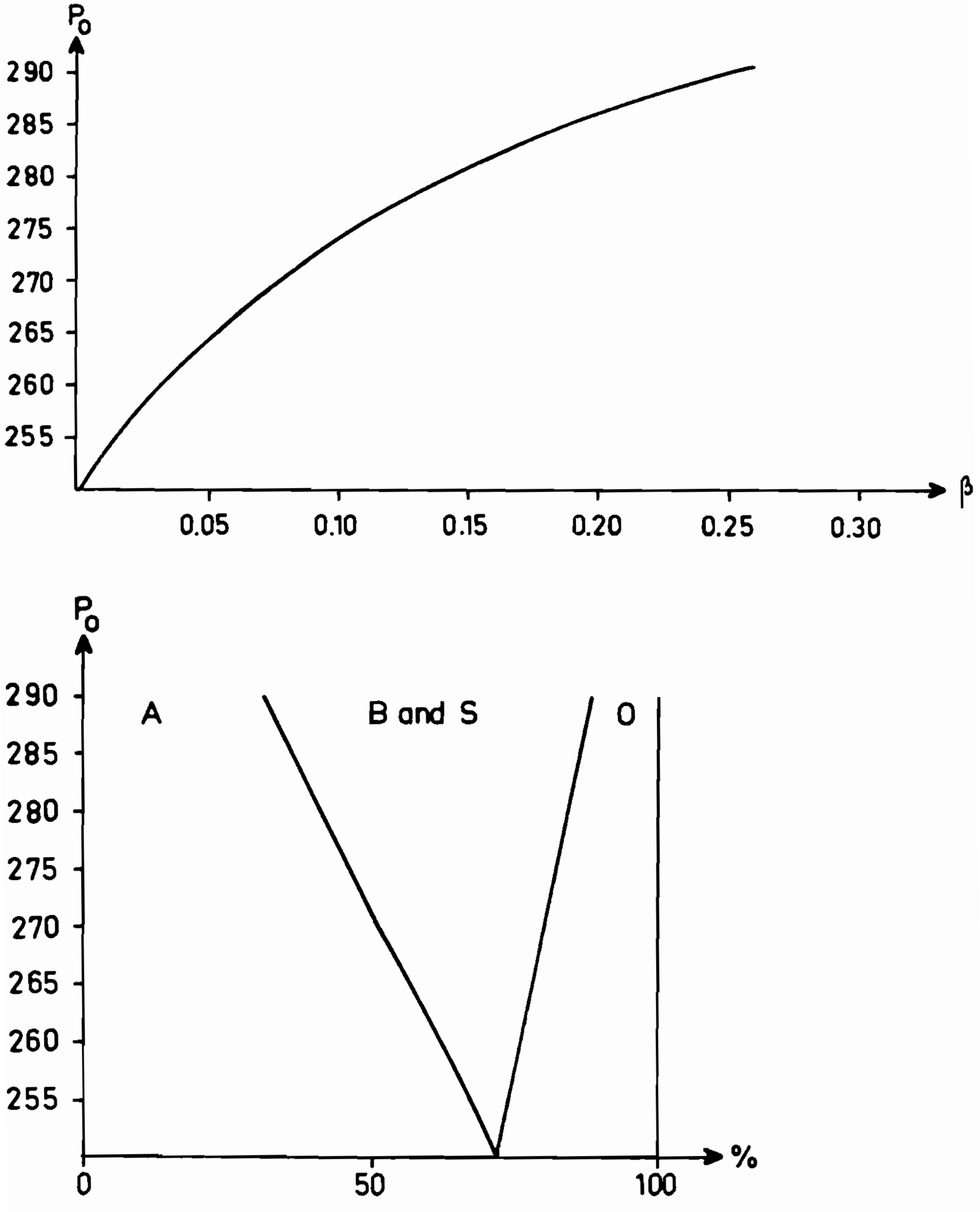

Figure 3. The case of an extremely "large and slow" biota, containing 1090 x 10^{15} gC, with an annual net primary production of 39 x 10^{15} gC/a.

VEGETATION AND CO_2 CHANGES

H. Lieth

The primary productivity of plants is a major partner for the CO_2 fluctuation in the atmosphere. The impact works both ways. The vegetation can cause major changes in the atmospheric gas composition and the CO_2 concentration may cause major alterations in the performance of the vegetation. We report here mainly about the potential of the global vegetation as a source of CO_2 concentration in the atmosphere.

Global productivity data have been assessed in several ways by Lieth and others; for a summary see Lieth and Whittaker (1975). Lieth and Box (1978), and Box (1978) have recently estimated the magnitude of gross primary productivity, net primary productivity, and dark respiration. The so-called Miami Model (Lieth 1973) was used as starting point for this calculation.

The Miami model uses nonlinear regression equations describing the correlation between net primary productivity, average annual temperature, and average annual total precipitation, respectively. About 65 data pairs were available for the construction of the two equations. These equations have the form

$$\mathrm{NPP} = \frac{3000}{1 + e^{1.315-0.119T}} \qquad (1)$$

for the correlation temperature versus net primary productivity; and

$$\mathrm{NPP} = 3000(1 - e^{-0.000664P}) \quad , \qquad (2)$$

for the correlation precipitation versus net primary productivity. The global productivity pattern was constructed on the basis of data from about 1000 meteorological stations spread over the land surfaces as evenly as possible. For details see Lieth (1975a). The map (the Miami model), which was later numerically evaluated by Box (1975), yields a total productivity value commensurate with the values in Table 1. The Miami model is in many respects the most convenient instrument for enabling us to make predictions pertinent to global heating and cooling possibilities.

Table 1. Net primary productivity (NPP) and energy fixation of major vegetation units of the world.

Source: Lieth (1975a, 1975c)

		NPP			Annual Energy Fixation		
Vegetation Unit	Area (10^6 km^2)	Range (kg/m^2 a)	Approx. mean (kg/m^2 a)	Total for Area (10^9mt)	Approx. com-bustion value (kcal/g)	Mean for m^2 (10^6 cal/ m^2)	Total for Area (10^{18} cal)
1	2	3	4	5	6	7	8
Forests	50			81.6			368.6
Tropical rainforest	17.0	1.0-3.5	2.8	47.4	4.1	11.5	195.5
Raingreen forest	7.5	1.6-2.5	1.75	13.2	4.2	7.4	55.5
Summergreen forest	7.0	0.4-2.5	1.0	7.0	4.6	4.6	32.2
Mediterranean sclerophyll forest (inclusive chaparral)	1.5	0.25-1.5	0.8	1.2	4.9	3.9	5.9
Warm temperate mixed forest	5.0	0.6-2.5	1.0	5.0	4.8	4.7	23.5
Boreal forest	12.0	0.3-1.2	0.65	7.8	4.6	3.0	36.0
Woodland	7	0.2-1.0	0.6	4.2	4.6	2.8	19.6
Dwarf and Open Scrub	26			2.6			11.0
Tundra	8.0	0.06-1.3	0.16	1.3	4.5	0.7	5.6
Desert scrub	18.0	0.01-0.25	0.07	1.3	4.5	0.3	5.4
Grassland	24			19.2			76.8
Tropical grassland (incl. grass-dominated savannah)	15.0	0.2-2.9	0.8	12.0	4.0	3.2	48.0
Temperate grassland	9.0	0.07-1.3	0.8	7.2	4.0	3.2	28.8
Desert (extreme)	24			-			0.1
Dry desert	8.5	0-0.01	0.003	-	4.5	-	0.1
Ice desert	15.5	0-0.001	-	-	-	-	-
Cultivated Land	14	0.1-4.0	0.65	9.1	4.1	2.7	37.8
Fresh Water	4			5.0			21.4
Swamps and marsh	2.0	0.8-4.0	2.0	4.0	4.2	8.4	16.8
Lake and stream	2.0	0.1-1.5	0.5	1.0	4.5	2.3	4.6

Table 1. (cont'd)

1	2	3	4	5	6	7	8
Total for Continents	149			121.7			535.3
Open ocean	332	0.002-0.4	0.13	41.5	4.9	0.6	199.2
Upwelling zones	0.4	0.4-0.6	0.5	0.2	4.9	2.5	1.0
Continental shelf	26.6	0.2-0.6	0.36	9.2	4.5	1.6	43.1
Algae beds and reefs	0.6	0.5-4.0	2.0	1.2	4.5	9.0	3.6
Estuaries	1.4	0.5-4.0	1.8	2.5	4.5	8.1	11.3
Total Marine	361	0.002-4.0	0.161	55.0			258.2
Overall Total	510			176.7			793.5

The interaction between the biosphere and the atmosphere involves more than the balance between input and output of CO_2 into the biosphere, which would be described adequately by the net primary productivity values. We have therefore constructed a correlation model for gross primary productivity, net primary productivity (NPP), and dark respiration, using the data set in the Table 2.

Table 2. Least-squares fit of NP and GP curve using saturation function.

Source: Lieth and Box (1978)

Point	Gross Primary (GP) (g/m^2)	Net Primary (NP) (g/m^2)	Y(=NP/3000)	GP LN(1-Y)
1	2150.0	1350.0	0.4500	-1285.349
2	1390.0	750.0	0.2500	-399.878
3	2230.0	1350.0	0.4500	-1333.176
4	2350.0	1350.0	0.4500	-1404.917
5	2140.0	1130.0	0.3767	-1011.521
6	7300.0	2060.0	0.6867	-8471.547
7	5250.0	1340.0	0.4467	-3106.921
8	4530.0	1870.0	0.6233	-4423.059
9	4090.0	1540.0	0.5133	-2945.518
10	3500.0	1390.0	0.4633	-2178.323
11	12320.0	2860.0	0.9533	-37757.305
12	2750.0	1530.0	0.5100	-1961.711
13	5170.0	2270.0	0.7567	-7306.863
14	4410.0	1930.0	0.6433	-4546.496
15	2640.0	1350.0	0.4500	-1578.289
16	10000.0	2890.0	0.9633	-33058.793
17	3280.0	1380.0	0.4600	-2021.089

NP = 3000.0 (1 - EXP(-0.0002415 GP)) g/m^2 a
GP = -4140.0 LN (1 - NP/3000.0) g/m^2 a
Correlation coefficient: 0.9138

The equation reads

$$GPP = -4140 \ln (1 - NPP/3000) \quad . \qquad (3)$$

We are now able to calculate gross primary productivity levels and community respiration values for all net primary productivity values of our models. Since this Workshop is primarily interested in CO_2 levels, we need to convert the dry matter values as used in our models into CO_2 weights. We do this by assuming that the plant dry matter consists of 45% of carbon, which results in a conversion rate of

$$\text{g dry matter} = 1.65 \text{ g } CO_2 \quad .$$

Table 3 provides the total dry matter produced annually or the CO_2 equivalents for 10^0 latitudinal belts calculated from the Miami model in the manner described. Table 4 gives the same breakdown for average annual production rates per m^2 horizontal surface.

Table 3. Estimates of total annual gross and net primary productivity and dark respiration (10^9 of dry matter) of the land areas of 10^0 latitudinal belts.

Latitudinal Belt	Gross Productivity		Dark Respiration		Net Primary Productivity	
	CO_2E	(10^9 t)	CO_2E	(10^9 t)	CO_2E	(10^9 t)
90 - 80 N	0.03	0.017	0.01	0.0046	0.02	0.010
80 - 70 N	0.99	0.603	0.26	0.1606	0.83	0.503
70 - 60 N	13.31	8.067	4.47	2.710	8.91	5.402
60 - 50 N	25.41	15.401	9.11	5.521	15.88	9.627
50 - 40 N	34.73	21.048	13.54	8.209	20.55	12.454
40 - 30 N	38.38	23.260	16.55	10.032	20.99	12.721
30 - 20 N	38.35	23.245	19.55	11.850	18.62	11.282
20 - 10 N	42.32	25.646	22.81	13.827	19.97	12.104
10 - 0 N	69.23	41.958	40.40	24.484	29.73	18.017
10 - 0 S	86.39	52.360	52.13	31.596	34.01	20.613
20 - 10 S	45.22	27.408	23.31	14.125	21.99	13.326
30 - 20 S	25.95	15.730	12.04	7.295	13.85	8.395
40 - 30 S	10.70	6.485	4.53	2.743	6.02	3.649
50 - 40 S	2.18	1.324	0.85	0.513	1.29	0.782
60 - 50 S	0.45	0.270	0.19	0.113	0.26	0.160
70 - 60 S	0.54	0.325	0.14	0.082	0.42	0.252
80 - 70 S	0.22	0.131	0.14	0.082	0.17	0.106
90 - 80 S	.0	0.0	.0	0.0	.0	0.0
Total	434.40	263.275	220.02	133.348	213.52	129.404

Table 4. Estimates of average annual gross and net primary productivity and dark respiration (g/m^2 a of dry matter) of the land areas of 10^0 latitudinal belts.

Latitudinal Belt	Gross Productivity		Dark Respiration		Net Primary Productivity	
	CO_2E	(g/m^2 a)	CO_2E	(g/m^2 a)	CO_2E	(g/m^2 a)
90 - 80 N	111.54	67.6	29.63	17.96	65.84	39.9
80 - 70 N	300.30	182.0	80.12	48.56	251.13	152.2
70 - 60 N	1001.22	606.8	336.53	203.96	670.40	406.3
60 - 50 N	1738.28	1053.5	623.30	377.76	1086.53	658.5
50 - 40 N	2099.46	1272.4	818.99	496.36	1242.29	752.9
40 - 30 N	2456.69	1488.9	1059.73	642.26	1343.60	814.3
30 - 20 N	2525.99	1530.9	1287.76	780.46	1225.95	743.0
20 - 10 N	3724.05	2257.0	2007.98	1216.96	1757.58	1065.2
10 - 0 N	6840.57	4145.8	3991.78	2419.26	2937.50	1780.3
10 - 0 S	8247.20	4998.3	4976.83	3016.26	3246.71	1967.7
20 - 10 S	4775.93	2894.5	2461.57	1491.86	2322.21	1407.4
30 - 20 S	2782.23	1686.2	1290.40	782.06	1485.00	900.0
40 - 30 S	2617.40	1586.3	1107.25	671.06	1472.79	892.6
50 - 40 S	2310.66	1400.4	896.38	543.26	1364.72	827.1
60 - 50 S	2180.31	1321.4	911.39	552.36	1292.45	783.3
70 - 60 S	273.74	165.9	68.90	41.76	212.36	128.7
80 - 70 S	24.92	15.1	15.77	9.56	20.13	12.2
90 - 80 S	.0	0.0	.0	0.06	.0	0.0

As a second contribution to the objectives of this Workshop I can try to use the Miami model to forecast changes of the primary productivity in response to temperature changes. Equation (1) from the Miami model is sensitive to temperature and can be used to predict global changes in NPP in response to temperature changes.

If CO_2 increase of the atmosphere alters the temperature we may assume that this change influences also the productivity of the plants. Therefore we have calculated earlier (Lieth 1975b) what would happen if the world's temperature would rise by about 1^0C. The result of this calculation, again for 10^0 latitudinal belts, is given in Table 5. Note that a change in productivity may be expected in the order of 1% per degree Celsius on account of rise or fall of temperature alone and by about 5% if we assume that temperature and precipitation will change simultaneously. A change of 6% for the precipitation was assumed because the vapor saturation of the air changes by about that amount in the pertinent temperature range.

Table 5. Change in NPP caused by changes in temperature and/or precipitation calculated from the Miami Model.

Source: Lieth (1975b)

Lat. Belt	Area ($10^6 km^2$)	SMM NPP (t/km^2)	SMM -1^0C NPP (t/km^2)	(-Δ)	(%)	SMM -6% (-Δ)	Ppt. %	SMM -1^0C -6% NPP (t/km^2)	-Δ	Ppt (%)	SMM $+1^0C$ +6% NPP (t/km^2)	(+Δ)	Ppt (%)
70-60 N	13.3	387	356	31	8.0	1	0.3	355	32	8.0	426	39	11.0
60-50	14.7	645	608	37	5.8	8	1.2	600	45	7.0	690	45	7.0
50-40	16.5	804	781	23	2.8	26	3.2	755	49	6.0	849	45	5.6
40-30	15.6	860	854	6	0.7	38	4.4	816	44	5.1	873	13	1.5
30-20	15.2	553	547	6	1.1	28	5.0	519	34	6.1	580	27	4.9
20-10	11.4	894	891	3	0.3	42	4.7	849	45	7.5	956	62	7.0
10- 0	10.1	1823	1822	1	0.1	94	5.2	1728	95	5.2	1905	82	4.5
0-10	10.5	2024	2020	4	0.8	46	2.3	1974	50	2.5	2096	45	2.2
10-20	9.5	1275	1269	6	0.8	61	4.8	1208	67	5.2	1351	76	6.0
20-30	9.3	832	823	9	1.2	13	1.6	810	22	2.6	864	32	3.9
30-40 S	4.1	856	851	5	0.6	36	4.2	815	41	4.8	904	48	5.6
Total Land	149.4	124.7 × 10^9t	122.8 × 10^9t					118.45 × 10^9t			103.6 × 10^9t		
% Δ vs. SMM			-1.6				-3.4	-5			+4.8		

SMM = standard Miami model.
NPP = annual net primary productivity.
t/km^2 = metric tons per square kilometer.
Ppt. = annual precipitation.
Δ = difference of net primary productivity against the standard Miami model.
% = % change.

No attempt was made to calculate possible changes in production due to changes in higher CO_2 levels. A number of changes may be expected, however. Plants are sensitive to CO_2 changes and this may cause changes in their competitive power within a given plant community.

REFERENCES

Box, E. (1975), Quantitative Evaluation of Global Primary Productivity Models Generated by Computers, in H. Lieth and R.H. Whittaker, eds., *Primary Productivity of the Biosphere*, Ecological Studies 14, Springer, New York.

Box, E. (1978), *Geographical Dimensions of Terrestrial Net and Gross Primary Productivity: A First Attempt* (in preparation).

Lieth, H. (1973), Primary Production: Terrestrial Ecosystems, *J. of Human Ecology*, 1, 303-332.

Lieth, H. (1975a), Modeling the Primary Productivity of the World, in H. Lieth and R.H. Whittaker, eds., *Primary Productivity of the Biosphere*, Ecological Studies 14, Springer, New York.

Lieth, H. (1975b), Possible Effects of Climate Changes on Natural Vegetation, in R.J. Kopec, ed., *Atmospheric Quality and Climatic Change*, Univ. of North Carolina, Dept. of Geography, Chapel Hill.

Lieth, H. (1975c), The Primary Productivity in Ecosystems, Comparative Analysis of Global Patterns, in W.H. Van Dobben and R.H. Lowe-McConnel, eds., *Unifying Concepts in Ecology*, Junk, The Hague.

Lieth, H., and R.H. Whittaker, eds. (1975), *Primary Productivity of the Biosphere*, Ecological Studies 14, Springer, New York.

Lieth, H., and E. Box (1978), The Gross Primary Productivity Pattern of the Land Vegetation: A First Attempt, *Journal of Tropical Ecology* (in press).

A NONLINEAR INTERACTION MODEL BETWEEN LAND BIOTA AND THE ATMOSPHERE*

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INTRODUCTION

Problems associated with the simulation of the global carbon cycle (considering only material fluxes) are principally the following:

- Data on inventories and fluxes are very sparse and in part contradictory;

- The choice of models (i.e., number of boxes and assumed kinetics between them) is ad hoc; several models may fit the crude data of past and present, but may extrapolate to different prognoses.

Available Data on Inventories And Fluxes

It seems reasonably well established that from industrialization (1860) to now (1977), about $140 \pm 35 \times 10^9$ t C have been emitted into the atmosphere through the use of fossil fuels (Bolin, 1977). On the average, an increase in the use of fossil fuels over that period is observed, being at present about $4.8 \pm 0.5 \times 10^9$ t C/a. It is further observed that about 2.4×10^9 t C/a remain in the atmosphere. If only fossil fuels are considered, this would mean that about 50% remain in the atmosphere. If however, man's action on the land biota is included, deforestation and fuel wood may account for a considerable additional input (estimates range from 1 to 10×10^9 t/a the most probable values being between 2 and 5×10^9 t C/a). Thus, taking fossil fuel and biogenic CO_2 input together, a smaller fraction of the total emitted carbon will remain in the atmosphere (leading to the same increase of 2.4×10^9 t C/a). Under the influence of man the land biota may in fact be a source rather than a sink for atmospheric carbon, even under conditions of an increasing partial pressure of CO_2.

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*Preliminary report.

All simulations require initial values for the inventories (for instance for the year 1860). However, no such values exist, either for the total carbon mass of the land biota (apart from an estimate, surprisingly close to current ones, by the chemist J.v. Liebig in 1861), or for the atmosphere, except for the data beginning in about 1890, collected by Callendar (1958).

The Choice of Models

A great number of models with different numbers of boxes and different kinetics have been presented in recent years, which may be divided into two groups. The first are accurate simulation models trying to explain in as much detail as possible the present and future behavior of the carbon cycle within a limited range of parameter flexibility and a fixed set of kinetic rate expressions (Bacastow and Keeling, 1973; Craig, 1957; Oeschger et al., 1975; Revelle and Suess, 1957). The second are heuristic models which emphasize the exploration of principles with respect to stability and the dynamics of quasistationary states; in general these have greater flexibility with respect to structure and parameters (Avenhaus and Hartmann, 1975; Eriksson and Welander, 1956; Avenhaus et al., these Proceedings).

Our contribution may be classified within the second group of models. We have investigated in our four-box model the effect of different anthropogenic inputs of carbon from land biota, under the assumption of different net primary production rate expressions, controlling the transfer of carbon from the atmosphere to the biosphere. These strategies are linear in atmospheric carbon, bilinear in atmospheric and biotic carbon, and bilinear with an upper limit for growth with respect to the atmospheric CO_2 content (Michaelis-Menten case). We want to point out the similarities and differences between these models, thus having an instrument of prediction in the case of agreement. In a more general sense we have studied analytically the local and global stability of a two-compartment system controlled by the rate expression of the general form

$$\frac{dN_a}{dt} = k_{b\to a} N_a^{\alpha} N_b^{\beta} - k_{a\to b} N_a^{\gamma} N_b^{\delta} \quad ,$$

and $N_a + N_b$ = constant. We can show that this system exhibits global stability within the range of the physical domain when the following conditions are fulfilled:

$$\gamma > \alpha \text{ and } \beta \geq \delta \text{ or } \gamma \geq \alpha \text{ and } \beta > \delta \quad .$$

To this class of systems belong both the completely linear model ($\alpha = 0$, $\beta = 1$, $\gamma = 1$, $\delta = 0$) and the bilinear model ($\alpha = 0$, $\beta = 1$, $\gamma = 1$, $\delta = 1$). It can be shown that the extension to a four-box model assuming linear coupling of the two additional boxes does not change the basic results of these considerations.

MODEL DESCRIPTION

The present study deals with a four-box model (Figure 1) of the global carbon cycle, distinguishing between the carbon mass of the atmosphere (N_a), the carbon of the land biota (N_b), and the carbon of the mixed surface ocean layer (N_m) and the deep sea (N_d).

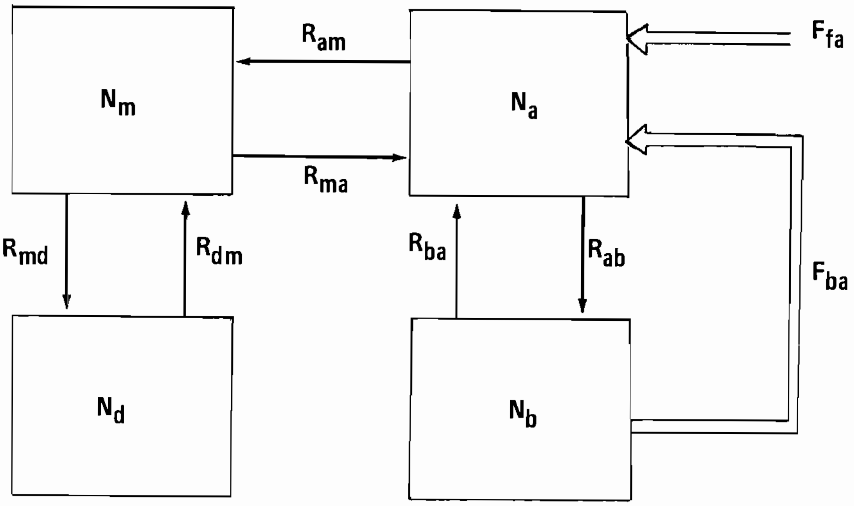

Figure 1. Model of the global carbon cycle.

The exchange rates between connected boxes i and j can be described, in general, by nonlinear expressions of the form

$$R_{ij} = k_{ij} \cdot N_i^{\alpha} \cdot N_j^{\beta} \quad ,$$

where α and β are (generally positive) real numbers determining the nonlinearity of the system, and k_{ij} are the corresponding rate constants. The anthropogenic flux of fossil carbon into the atmosphere is designated by F_{fa}, that of biotic carbon into the atmosphere by F_{ba}.

The exchange rates R_{am} and R_{ma} between atmosphere and surface ocean as well as R_{md} and R_{dm} between surface ocean and deep sea have been chosen to be of linear form. Essential nonlinearities were introduced only in R_{ab}, the net primary production. We investigated the following three cases.

1. The assimilation term

$$R_{ab} = k_{ab} N_a$$

is linearly dependent on the atmospheric carbon dioxide content, as was proposed, for instance, by Avenhaus and Hartmann (1975); and Avenhaus et al., these Proceedings.

2. The same flux,

$$R_{ab}' = k_{ab}' N_a N_b \quad ,$$

depends bilinearly on both N_a and N_b. We may expect that such a rate expression will keep the atmospheric carbon content rather stable, the surplus carbon being autocatalytically absorbed by the biosphere.

3. In

$$R_{ab}'' = k_{ab}'' \frac{N_a \cdot N_b}{K_m + N_a} \quad ,$$

the net primary production is described by means of a Michaelis-Menten equation, which contains an upper limit for the N_a-dependent growth of the biosphere. The Michaelis constant K_M is certainly different for different land biomes. In this oversimplified study we have taken its mean to be $K_M = 700 \times 10^9$ t C (Czihak et al., 1976).

For the inventories of the atmosphere and the land biota the values $N_a(1975) = 690 \times 10^9$ t C (Bolin, 1977) and $N_b(1975) = 835 \times 10^9$ t C (Whittaker and Likens, 1973) were chosen, whereas for

N_m and N_d the values for the stationary state of 736 and 35,560 × 10^9 t C respectively were used. Whittaker and Likens estimate the net primary production of the long-living plants to be 33.6 × 10^9 t C/a in 1975, from which we calculated the rate constants for the linear, the bilinear, and the Michaelis-Menten case. The determination of k''_{ab} follows in a straightforward manner for a given Michaelis constant, as does the rate constant for the bilinear process, which may be considered a special case of the Michaelis-Menten equation ($K_M >> N_a$). For the determination of the rate constant of the linear rate $k_{ab}N_a$, two distinct methods may be chosen:

- Setting the measured rate equal to the linear rate expression;
- Choosing the same relaxation time for the nonlinear and linearized rate expression.

The second method makes it possible to observe the nonlinear behavior of the system. The flux from the atmosphere to the mixed layer and vice versa was taken as 100 × 10^9 t C/a. (The more recently accepted value of 70 to 80 × 10^9 t C/a would lead to a greater accumulation of CO_2 in the atmosphere.) The exchange rate constant k_{dm} was set to be 1/1600 a^{-1}, according to Machta (1973).

Several functions for the increasing input of fossil fuel CO_2 into the atmosphere may be chosen. Rather than trying to fit the data to an exponential curve over a relatively short period of time (present growth: 4.3%), we have chosen to fit the data over the whole period from 1860 to 1974 to a logistic growth function characterized by a growth factor of 3.3% and a final cumulated input of 4800 × 10^9 t C (see Zimen, these Proceedings).

For the biogenic input of carbon into the atmosphere (as introduced by man), we proposed in this preliminary calculation a function of exponential form, with a present net output of 2.4 × 10^9 t C/a. (A few calculations have been done with even higher transfer rates, showing that above 12.5 × 10^9 t C/a the system is globally instable.)

NUMERICAL METHOD

The numerical calculations were carried out with the two computer programs DYNAMO III and CSMP III which allow the digital simulation of continuous processes on large-scale digital machines. Both programs provide application-oriented languages that allow models to be prepared directly and simply from either a block diagram representation or a set of ordinary differential equations. Contrary to DYNAMO, CSMP accepts FORTRAN statements, allowing the user to readily handle problems of considerable complexity.

For integration, DYNAMO uses the first-order Euler method with constant integration steps, while CSMP provides a variety of algorithms for numerical integration, ranging from the simple Euler method to sophisticated variable-step methods.

In our CSMP calculations we used the fourth-order Runge-Kutta formula (RKSFX). The DYNAMO III calculations were carried out on a UNIVAC 1108 of the University computing center, Frankfurt, and the CSMP III calculations on an IBM 370/169 of the Technical University computing center, Darmstadt.

RESULTS

A selected set of typical values of our results is shown in Table 1.

Table 1. Typical results.*

	$F_{ba}(1980) = 2.4$			$F_{ba}(1980) = 3.8$
	1	2	3	4
N_a (1980)	688	708	702	709
ΔN_a (1980)	1.8	2.3	2.1	2.4
N_a (2025)	838	900	879	890
N_b (1980)	842	791	807	787
ΔN_b (1980)	0.4	-1.1	-0.6	-1.6

*Inventories in 10^9 t C; rates and annual increases (denoted by Δ) in 10^9 t C/a (for further explanation see text).

Column 1 contains results obtained with a linear rate expression ($R_{ab} = k_{ab}N_a$), assuming F_{ba} (1980) = 2.4 × 10^9 t C/a.

Column 2 shows the linearized Michaelis-Menten calculations, and column 3 the full nonlinear Michaelis-Menten kinetics. The same net primary production of 33.6×10^9 t C/a yields different results for columns 1 and 2 as well as for columns 1 and 3, but nearly corresponding values for 2 and 3. (33.6×10^9 t C refers to the NPP of forests only.) The initial values taken for all three cases were $N_a(1860) = 630 \times 10^9$ t C, $N_b(1860) = 835 \times 10^9$ t C.

In column 4 we summarized the effect of a higher deforestation rate ($F_{ba}(1980) = 3.8 \times 10^9$ t C/a; $N_a(1860) = 620 \times 10^9$ t C, $N_b(1860) = 865 \times 10^9$ t C).

The correspondence with actual experimental values was obtained for the Michaelis-Menten kinetics (3 and 4) with a biogenic input of 2.4 and 3.8×10^9 t C respectively.

In summary, for the short-term behavior (50 to 150 years) one may use linear kinetic expressions even for the highly nonlinear rate R_{ab}, if one linearizes under the condition of equal relaxation times. For longer-term behavior one must certainly expect that the real nonlinear effects may not be neglected.

DISCUSSION

Within the limits of a four-box model this study centers around a detailed description of the interaction between land biota and atmosphere. Starting with a general expression of the Michaelis-Menten kinetics for net primary production, we could approximately reproduce the past and present, assuming a biotic carbon flux due to man $F_{ba}(1980) = 2$ to 4×10^9 t C/a. As special cases we may derive from this kinetics the bilinear as well as linear rate expression.

It is important to note that there are two fundamentally different methods to derive a linear rate constant from a measured flux. If the physical process follows a first-order rate expression, the evaluations, of course, converge. However, if one has a nonlinear physical rate law, the two methods may differ appreciably. For the case of Michaelis-Menten kinetics it follows that the ratio of the relaxation time τ, evaluated from an ad hoc linear rate expression, to τ'', evaluated by a linearization process of "true" nonlinear kinetics, is given by

$$\frac{\tau}{\tau''} = \frac{K_M}{K_M + N_{ao}} \cdot \frac{N_{bo}}{N_{ao} + N_{bo}} = P$$

(N_{ao} and N_{bo} denoting the values for the stationary state); evaluated for example $K_M = 700$, $N_{ao} = N_{bo} = 700$ yields: $\tau/\tau'' = 1/4$; $K_M = 100$, $N_{ao} = N_{bo} = 700$ yields $\tau/\tau'' = 1/16$. One may state the results also in the form of effective fluxes R_{ab} and R''_{ab}. Again under the assumption of equal relaxation times, the ratio is given by

$$\frac{R_{ab}}{R''_{ab}} = P \quad .$$

At present we are trying to evaluate the global Michaelis constant with respect to nutrient CO_2 by averaging over different biomes. We also hope to find an adequate mathematical description for the transfer function of biogenic carbon F_{ba}. Later on, we hope to present a regional model, taking into account major ecosystem types.

SUMMARY AND CONCLUSION

Assuming the most probable values for inventories and fluxes of the global carbon cycle, we were able to reproduce past and present values of atmospheric carbon by adding to the relatively well-known fossil fuel carbon flux the current man-made biogenic flux of about 2 to 4 × 10^9 t C/a. Larger biogenic carbon fluxes have a very sensitive effect on the stability of the atmosphere; for this reason we conclude that we must conserve the biosphere as much as possible. Under the condition of an intact biosphere adopting a 3.3% growth in fossil fuel use annually, the increase of CO_2 is less than predicted on the average (in 2025, between 850 and 900 × 10^9 t C).

REFERENCES

Avenhaus, R., and G. Hartmann (1975), *The Carbon Cycle of the Earth--A Material Balance Approach*, RR-75-45, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Bacastow, R., and C.D. Keeling (1973), Atmospheric Carbon Dioxide and Radiocarbon in the Natural Carbon Cycle, II. Changes from AD 1700 to 2070 as Deduced from a Geochemical Model, in G.M. Woodwell and E.V. Pecan, eds., *Carbon and the Biosphere*, CONF-720510, U.S. Atomic Energy Commission, Springfield, Virginia.

Bolin, B. (1977), Changes of Land Biota and Their Importance for the Carbon Cycle, *Science*, 196, 613.

Czihak, G., H. Langer, and H. Ziegler, eds. (1976), *Biologie*, Springer, Berlin.

Callendar, G.S. (1958), On the Amount of Carbon Dioxide in the Atmosphere, *Tellus*, 10, 243.

Craig, H. (1957), The Natural Distribution of Radiocarbon and the Exchange Time of Carbon Dioxide Between Atmosphere and Sea, *Tellus*, 9, 1.

Eriksson, E., and P. Welander (1956), On a Mathematical Model of the Carbon Cycle in Nature, *Tellus*, 8, 155.

Machta, L. (1973), Prediction of CO_2 in the Atmosphere, in G.M. Woodwell and E.V. Pecan, eds., *Carbon and the Biosphere*, CONF-720510, U.S. Atomic Energy Commission, Springfield, Virginia.

Oeschger, H., U. Siegenthaler, U. Schotterer, and A. Gugelmann (1975), A Box Diffusion Model to Study the Carbon Dioxide Exchange in Nature, *Tellus*, 27, 168.

Revelle, R., and H. Suess (1957), Carbon Dioxide Exchange Between Atmosphere and Ocean and the Question of an Increase of Atmospheric CO_2 During the Past Decades, *Tellus*, 9, 18.

Whittaker, R.H., and G.E. Likens (1973), Carbon in the Biota, in G.M. Woodwell and E.V. Pecan, eds., *Carbon and the Biosphere*, CONF-720510, U.S. Atomic Energy Commission, Springfield, Virginia.

MATHEMATICAL TREATMENT OF BOX MODELS FOR THE CO_2-CYCLE OF THE EARTH

R. Avenhaus, S. Fenyi, and H. Frick

Summary

The CO_2-cycle of the earth is described by a system of coupled first order differential equations. Equilibrium states of the undisturbed cycle and the dynamic behavior of the disturbed cycle are analyzed. The results are illustrated with some numerical calculations.

INTRODUCTION

In the past years several authors (see, e.g. [1,2,3]) have developed simple box models for the CO_2-cycle of the earth on the basis of which the terrestrial CO_2 mass flow has been described by systems of coupled first order differential equations. As we have analyzed material accountability problems in our Center for many years [4], we have considered these models from that mass balance point of view and thus have tried to apply our experiences in the nuclear area to the CO_2-problem.

It is clear that these oversimplified box models do not describe the complex dynamics of the CO_2-cycle adequately. The point of this study was an exhaustive mathematical treatment of a simple model in order to get an analytical understanding of some basic features as, e.g., equilibrium states, time constants, and effects of disturbances. This then could stimulate further work with more realistic models which, however, probably can be treated only numerically.

PROBLEM FORMULATION AND ANALYSIS

The four-box model for the CO_2-cycle of the earth may be described as follows. Given are the four boxes atmosphere (a), biosphere (b), upper mixed layer of the sea (m), and deep sea (d). At time t these boxes contain the CO_2 inventories $I^a(t)$, $I^b(t)$, $I^m(t)$, $I^d(t)$, measured in [mol]. In the time interval (t, t+dt) parts of the inventories are exchanged; the transition from box x to box y is determined by the exchange coefficient k^{xy} (measured in reciprocal years). In addition, at time t we have a change in the atmospheric CO_2 content as a result of burning fossil fuels. Therefore, we have the following relations for the CO_2 inventories in the different boxes at time t:

$$\frac{dI^a(t)}{dt} = -k^{ab} \cdot I^a(t) - k^{am} \cdot I^a(t) + k^{ba} \cdot I^b(t) + k^{ma} \cdot I^m(t) + n(t)$$

$$\frac{dI^b(t)}{dt} = k^{ab} \cdot I^a(t) - k^{ba} \cdot I^b(t)$$

$$\frac{dI^m(t)}{dt} = k^{am} \cdot I^a(t) + k^{dm} \cdot I^d(t) - k^{ma} \cdot I^m(t) - k^{md} \cdot I^m(t)$$

$$\frac{dI^d(t)}{dt} = k^{md} \cdot I^m(t) - k^{dm} \cdot I^d(t) \quad . \tag{1}$$

If we define the vector $\underline{I}(t) := (I^a(t), I^b(t), I^m(t), I^d(t))^\tau$, the four components of which describe the CO_2 inventories of the four boxes at time t, and furthermore the vector $\underline{n}(t) := (n(t), 0, 0, 0)^\tau$, then we can write the system (1) in matrix form

$$\frac{dI(t)}{dt} = A \cdot \underline{I}(t) + \underline{n}(t) \quad , \tag{2}$$

where the matrix A is given by

$$A = \begin{pmatrix} -k^{ab}-k^{am} & k^{ba} & k^{ma} & 0 \\ k^{ab} & k^{ba} & 0 & 0 \\ k^{am} & 0 & -k^{ma}-k^{md} & k^{dm} \\ 0 & 0 & k^{md} & -k^{dm} \end{pmatrix} .$$

Let us consider first the *undisturbed system*, i.e. $n(t) = 0$. Then the system (2) represents a material conserving transformation from state $\underline{I}(t)$ to the state $\underline{I}(t')$, $t' > t$:

$$I^a(t')+I^b(t')+I^m(t')+I^d(t') = I^a(t)+I^b(t)+I^m(t)+I^d(t) \qquad (3)$$

or, in other words,

$$\frac{d}{dt}(I^a(t) + I^b(t) + I^m(t) + I^d(t)) = 0 \quad .$$

This material conservation property is expressed by the fact that the elements of a column of matrix A add up to zero. Quite generally one may consider n-box-models (Machta [2], e.g., has considered a seven-box model) which are described by the system (2) where A is a n x n Matrix with column sums zero and non-negative off-diagonal elements. Now it can be shown that

i) For a n-box-model without closed (cyclical) pathways of exchange, where each box is connected with at least one other box, the matrix A of the system of differential equations (2) has the simple eigenvalue zero. The n-1 further eigenvalues are real and negative. Furthermore the matrix A has n linear independent eigenvectors.

ii) From i) it follows that there exists exactly one equilibrium state. If the system is at time $t = 0$ in this state, it is also for $t > 0$ in this state. If the system is at time $t = 0$ in a different state, then for $t \to \infty$ it tends to the equilibrium state. For our four-box model, the equilibrium state (normalized to unit atmospheric inventory) is given by

$$\underline{c}_1 := (1,\ k^{ab}/k^{ba},\ k^{am}/k^{ma},\ (k^{am}/k^{ma})\cdot(k^{md}/k^{dm}))^{\tau} \quad . \qquad (4)$$

iii) The speed of the transition from a disturbed to the equilibrium state is determined by the absolutely smallest eigenvalue. It is not possible to make simple statements about the dependency of this eigenvalue from the transition coefficients k^{xy}.

Second, let us consider the *disturbed system*. Formally, the solution of the system (2) of differential equations can be written in the following form:

$$\underline{I}(t) = \exp(A\cdot(t-t_0)) \cdot I(t_0) + \int_{t_0}^{t_1} \exp(A\cdot(t-s)) \cdot \underline{n}(s)ds \quad , \qquad (5)$$

where

$$\exp(A\cdot t) := \sum_{\nu=0}^{\infty} \frac{(A\cdot t)^{\nu}}{\nu!} \quad .$$

Explicit analytical solutions, however, can only be given for special forms of the disturbance $\underline{n}(t)$. Let us consider the four-box model, and for example let

$$\underline{n}(t) := \begin{cases} \underline{\mu}\cdot t & \text{for } t \geq 0 \quad , \quad \underline{\mu} := (\mu,\ 0,\ 0,\ 0)^t \\ 0 & \text{otherwise} \quad . \end{cases} \tag{6}$$

Let $\lambda_1 = 0$, λ_2, λ_3, and λ_4 be the eigenvalues of A and $\underline{c}_1$ (given by (4)), and $\underline{c}_2$, $\underline{c}_3$, $\underline{c}_4$ be the eigenvectors of A. Then the solution of (2) can be written as

$$\underline{I}(t) = \frac{K}{\delta}\cdot\underline{c}_1 + \sum_{i=2}^{4} \beta_i\cdot\underline{c}_i\cdot e^{\lambda_i\cdot t} + \frac{\mu}{\delta}\cdot\underline{c}_1\cdot t + \sum_{i=2}^{4}\gamma_i\cdot\underline{c}_i \quad , \tag{7}$$

where

$$\delta := 1+k^{ab}/k^{ba}+k^{am}/k^{ma}+(k^{am}/k^{ma})\cdot(k^{md}/k^{dm}) \quad ,$$

where

$$K := I_0^a + I_0^b + I_0^m + I_0^d$$

is the total inventory at time t = 0, and β_i and γ_i, i = 2, 3, 4 are constants determined by the initial condition $\underline{I}(0)$.

APPLICATIONS

Sawyer [1] has given estimates for the values of the exchange coefficients k^{xy} and the inventories $\underline{I}$ in the equilibrium state, which are listed in Table 1. With the help of our formalism we can check whether or not these inventories are consistent, i.e., whether or not they represent an eigenstate in the sense of relation (4). In Table 1, it is shown that Sawyer's data have to be modified only slightly such that they represent in fact an eigenstate.

Table 1. Exchange coefficients and relative inventories for the four-box model according to Sawyer [1], and consistent with eq. (4).

	k^{ab}	k^{ba}	k^{am}	k^{ma}	k^{md}	k^{dm}	I^a	I^b	I^m	I^d
Sawyer [1]	$\frac{1}{33}$	$\frac{1}{40}$	$\frac{1}{5}$	$\frac{1}{6}$	$\frac{1}{4}$	$\frac{1}{300}$	1	1.2	1.2	58
Consistent with (4)	$\frac{1}{33}$	$\frac{1}{40}$	$\frac{1}{5}$	$\frac{1}{6}$	$\frac{1}{6.2}$	$\frac{1}{300}$	1	1.21	1.2	58.06

Similar consistency checks can be made easily for other box models, e.g., the seven-box model by Machta [2].

As a further application of relation (4), we ask what the asymptotic value of the CO_2 content of the atmosphere would be if all known fossil fuels were burnt. According to Zimen et al. [3], see also Kester et al. [5], this would correspond to a final cumulated input of $N = 600\times10^{15}$ [mol]. If we start with $I_0^a = 51\times10^{15}$ [mol] at preindustrial time, i.e. before 1860 (see, e.g., the SCEP-report [6]), then we obtain with Sawyer's data $I_0^b = 62.2\times10^{15}$, $I_0^m = 61.7\times10^{15}$, $I_0^d = 2985.4\times10^{15}$ [mol]. This gives a total inventory $I_0 = 3160\times10^{15}$ [mol]. To answer our question, we have to add to this inventory the CO_2 from the burnt fossil fuels and distribute the total inventory according to (4). The result is

$$I_\infty^a = 61.2\times10^{15},\ I_\infty^b = 74\times10^{15},\ I_\infty^m = 73.4\times10^{15},\ I_\infty^d = 3552\times10^{15}\ \text{[mol]}.$$

This means that in the asymptotic state, 567×10^{15} [mol] of the 600×10^{15} [mol] go into the deep sea, and furthermore that the atmospheric content rises from 312 ppm(vol) as given today to 345 ppm(vol) in the asymptotic state.

Let us consider next the speed of the transition from a disturbed to the equilibrium state. With Sawyer's data we obtain the following numerical values for the eigenvalues:

$$\lambda_1 = -0.018, \quad \lambda_2 = -0.469, \quad \lambda_3 = -0.098 \quad .$$

This means that roughly 40 years after a disturbance has been stopped, 50% of this disturbance has been digested. It is interesting to note that this speed is determined primarily by the exchange between atmosphere and biosphere (as both exchange coefficients are "small" and of the same order of magnitude).

Finally, let us consider the effect of the present CO_2 releases into the atmosphere, due to the burning of fossil fuels. From relation (7) we can conclude the following: If we started today with the equilibrium value, and released a constant amount of CO_2 per unit time into the atmosphere, then, after a transition period of less than 100 years, the atmospheric inventory would be increased linearly such that *the equilibrium would always be maintained.* Only if the CO_2 amount released into the atmosphere per unit time is increased continuously (exponentially in the worst case), the CO_2 content of the atmosphere would exceed the equilibrium value. This result may throw a new light on recent proposals for the direct burial of the CO_2 from burnt fossil fuels into the deep sea.

CONCLUSION

As already mentioned, all considerations presented so far can be extended to box models with more than four boxes. It is, however, beyond the scope of our considerations to decide whether or not such models provide principally more insight into the CO_2-dynamics than simple four-box models.

Another aspect is the uncertainty of the values of the exchange coefficients as well as the inventories. An example is the large uncertainty of the exchange coefficient k^{dm}: Sawyer gives 1/300, whereas Machta gives 1/1600. The influence of this value on the eigenvalue λ_2, which determines the transaction time, however, is small, thus this uncertainty seems to play no major role. Nevertheless, it would be useful to perform a sensitivity analysis in order to get a feeling for the variability of inventories and time constants. We have started such analyses for discrete time models [7] and are currently working at the continuous time model.

With respect to the question for extending the considerations presented so far to nonlinear models we can only repeat that it is beyond our scope to decide in what sense such models might provide more insight, and furthermore that such models probably can be analyzed only numerically. We hope that the result of the analysis of simple box models gives some guidelines for this type of work.

REFERENCES

[1] Sawyer, J.S., Man-Made Carbon Dioxide and the Greenhouse Effect, *Nature*, 239 (1972) 23-26.

[2] Machta, L., *The Role of the Oceans and Biosphere in the Carbon Dioxide Cycle*, Proceedings of the 20th Nobel Symposium, Almqvist and Wiksell, Stockholm, 1971.

[3] Zimen, K.E. and F.K. Altenheim, The Future Burden of Industrial CO_2 on the Atmosphere and the Oceans, *Die Naturwissenschaften*, 28a (1973) 1747-1752.

[4] Avenhaus, R., *Material Accountability - Theory, Verification, Applications*, Wiley, New York-London, 1977.

[5] Kester, D.R. and R.M. Pytkowicz, Natural and Anthropogenic Changes in the Global Carbon Dioxide System, in W. Stumm, ed., *Global Chemical Cycles and their Alterations by Man*, Abakon Verlagsgesellschaft, Berlin, 1977.

[6] *Man's Impact on the Global Environment*, Report of the Study of Critical Environment Problems (SCEP), MIT Press, Cambridge, Massachusetts, 1970.

[7] Avenhaus, R. and G. Hartmann, *The Carbon Cycle of the Earth: A Material Balance Approach*, RR-75-45, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1975.

THE IMPACT ON CLIMATE AND ENVIRONMENT OF INCREASING ATMOSPHERIC CO_2 CONCENTRATIONS

INTRODUCTION TO THE CLIMATE/ENVIRONMENT ASPECTS OF CO_2 (A PESSIMISTIC VIEW)

J. Williams

THE CLIMATE SYSTEM

The global climate system consists of five subsystems: the atmosphere, oceans, cryosphere (ice and snow), biosphere and land surface. These components interact with each other through a wide variety of processes, such that the total climate system is highly complex and nonlinear. The climatic state is defined [1] as the average (together with the variability and other statistics) of the complete set of atmospheric, hydrospheric and cryospheric variables over a specified time interval and in a specified domain of the earth-atmosphere system. The time interval refers to a period longer than the life span of individual weather systems (of the order of several days) and longer than the theoretical time limit over which the behaviour of the atmosphere can be locally predicted (of the order of some weeks). Climatic variation can thus be defined as the difference between climatic states of the same kind, such as between one January (or winter or year) and the next January (or winter or year).

The climate system can be subdivided [2] into an internal system, consisting of the gaseous, liquid and ice envelopes surrounding the earth, and an external system, consisting of the underlying ground and space surrounding the earth. Sufficiently large changes in the external boundary conditions (configuration of the earth's crust, earth-sun orbital geometry) can obviously result in climatic variation. Variation can also be caused by changes in the internal climate system, such that changes in the large-scale distribution of the internal driving mechanisms of the atmosphere, ocean and ice occur. These changes in the system are manifested as feedbacks among the variables of the climate system [3].

INHERENT VARIABILITY

Since climatic states are defined in terms of finite time averages, they are subject to fluctuations of a statistical origin in addition to those of a physical nature (caused, for example, by changes in the amount of incoming solar radiation or the composition of the atmosphere). These statistical fluctuations are a result of day-to-day fluctuations in the weather and are unpredictable over time scales of climatological interest. They are therefore referred to as "climatic noise" or the "inherent variability of the climate system" [4,5].

Within a climatic record, therefore, a certain amount of the variability will be unpredictable (i.e. noise or *inherent* variability), but there may exist variations not associated with day-to-day weather fluctuations which may be predictable (here referred to as *natural* variability). Studies of observed atmospheric data [5] suggest that virtually all the observed month-to-month variability in the middle and high latitudes of the northern hemisphere can be attributed to inherent variability. Such a result does not speak well for the possibility of long-range prediction.

NATURAL VARIABILITY

In addition to the inherent variability of the climate system there is a natural variability of the system caused by changes in the external and/or internal conditions. The estimate of a change in climate caused by an increase in CO_2 concentration must take into account the fact that climate fluctuates naturally with time, which means that a long averaging time is necessary for specifying normal climate together with a long averaging time for detecting a significant change. It should also be pointed out that problems could arise because of the time scales of natural variability. The time constants for ocean heat storage, for example, can be sufficiently long, that by the time an observed trend is found to be significant, it may be too late to take remedial action with respect to the cause of the change, i.e. the increase in atmospheric CO_2 concentration.

REGIONAL VERSUS GLOBAL CHANGES

In order to discuss the effects of changing the atmospheric CO_2 concentration using observations or modeling, the simplest approach is to define climate as the global average surface temperature. A global average (or one-dimensional) model can be used to compute the change of "climate" for a change in atmospheric CO_2 concentration and we are presently able to make calculations of this kind although our lack of knowledge of feedbacks means that there are uncertainties in the results. With regard to observations, recent studies [6] have shown that not only the amplitude but also the direction of global trends in surface temperature during the last 100 years are uncertain.

Of more practical importance, however, is the question of regional climatic changes. That is, if it is determined that the global average surface temperature changes by x degrees for a doubling of the atmospheric CO_2 concentration, it is then necessary to determine the extent of corresponding regional climatic changes by using empirical evidence or the results of three-dimensional models of the climate system. It should be noted, though, that it is possible to have situations in which regional climate can change drastically over large areas without there being any substantial change in globally averaged temperature. Or, on the other hand, it is possible that a large globally averaged temperature change is a result of very large changes in only a few regions with no changes in the other areas. That is, regional climatic changes must be considered from the outset rather than as a secondary problem to be dealt with after the globally averaged effects are understood [7].

Observations of temperature from the period 1942-1972 can be used to illustrate the problems of determining regional and global average changes. Table 1 (from [9]) shows for each season the average temperature change for the area 15^0-80^0N during the period 1942-1972. Each of the seasons experienced a cooling, but of a different magnitude. For comparison, it should be pointed out that other estimates of the temperature change during this period have been made (for example, [10]) and these estimates differ from those given here [6,8].

Table 1. Average temperature change 15^0-80^0N during the period 1942-1972.

Source: [9]

Winter	$- 0.21^0C$
Summer	$- 0.19^0C$
Spring	$- 0.36^0C$
Autumn	$- 0.29^0C$
Average	$- 0.26^0C$

The change, during the same period, of zonally averaged temperature in each season is illustrated in Figure 1. During each season the changes in low latitudes, 15^0-30^0N, were not large. In winter, spring and autumn the largest changes are in the polar latitudes, while in summer the largest changes are in middle latitudes.

Figure 2 shows the isopleths of the slope of the regression line of winter mean temperature during the period 1942-1972. This map illustrates the point that a small hemispheric change can result from the occurrence of large and opposite regional trends. The hemispheric cooling is a result largely of the occurrence of two large areas of cooling in polar latitudes. In the period 1900-1941, which was one of hemispheric warming, the largest trends were again noted in the polar area of the northern hemisphere [6,10].

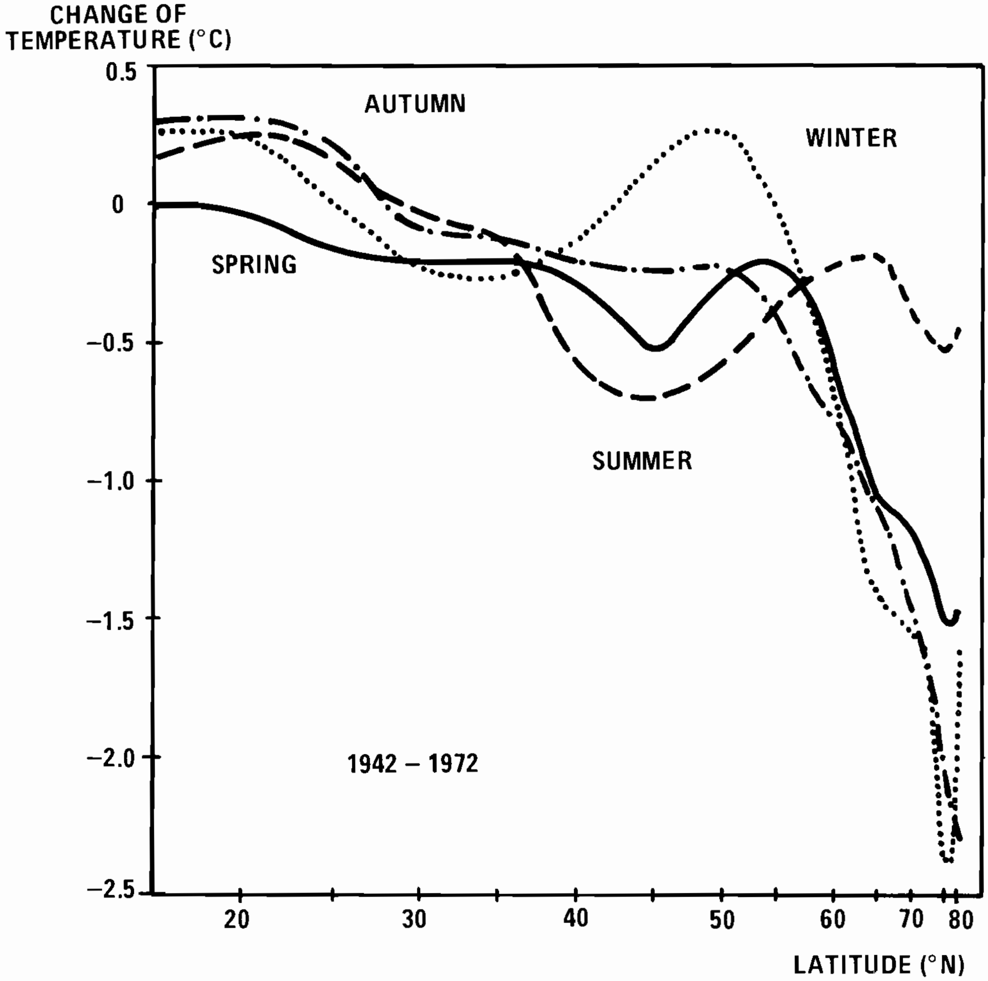

Figure 1. Meridional profile of the change in each season of the zonal mean temperature (C) during the period 1942-1972.

Source: [9]

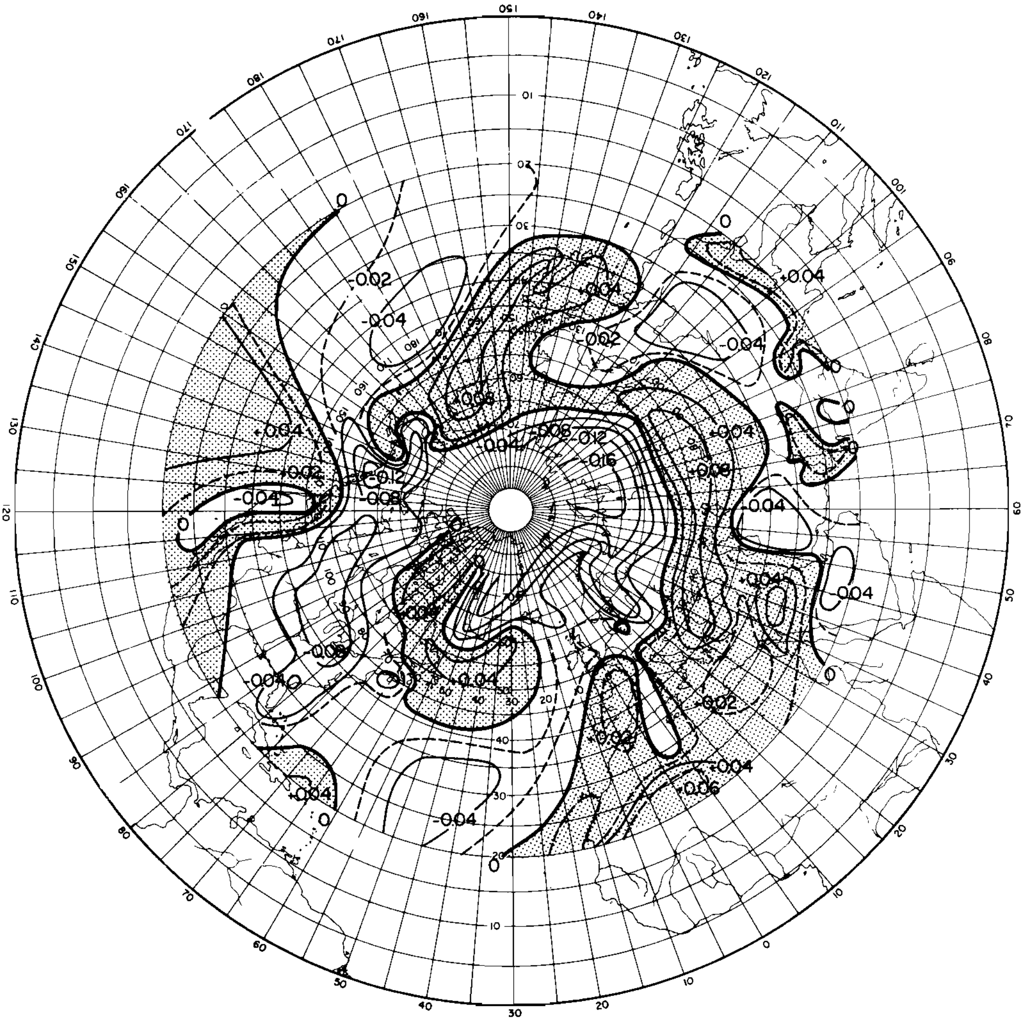

Figure 2. Isopleths of the slope of the regression line of winter mean temperature for 1942–1972 (C/yr.).

The implications of observational studies of recent climatic variations are several fold. The temperature variations have been seen to differ according to season and location. That is, different physical processes are acting to cause variations at different times of the year [8]. At the present time these processes are poorly understood and it is clear that for prediction of the effects of doubling CO_2 concentrations, knowledge of the dynamics of the climate system will have to be improved. A second implication of the studies is that, since we can not be certain of the size and sign of temperature changes over the oceans in the tropics and in the Southern Hemisphere, because of the poor observational network in these areas, the amplitude of *global* trends is certainly open to question, but even their sign may be considered uncertain [6]. Most model predictions of the effects of increasing the atmospheric CO_2 concentration (see [11,12] and papers presented at this Workshop) have considered the effects on globally averaged temperature. Since we have no accurate determination of the natural variability of global average temperature, detection of changes owing to CO_2 increases will be impossible.

A third implication of the observational studies is that the polar regions are more sensitive to climatic variations than tropical areas (although this is not necessarily the case in the summer season for example). It has been suggested [7], however, that the higher interannual variability of temperature in polar regions may only be a reflection of day-to-day variability, which is aliased into the very low frequencies (interdecadal trends) by the averaging process.

The occurrence of regional differences in temperature changes does imply that temperature *gradients* also change with time; such changes would be associated with circulation changes and, of particular significance, precipitation changes.

THE USE OF MODELS TO PREDICT CLIMATE VARIATIONS

Since there are obvious reasons for not going out to immediately double the atmospheric CO_2 concentration with the possibility that if the consequences are undesirable we can return immediately to present conditions, predictions must be made regarding the climate effects of doubling the atmospheric CO_2 concentration. There are basically two ways of making such predictions. The first is to use observational studies of analogous situations and the second is to use numerical models of the climate system.

The process of the climate system can be expressed in terms of a set of hydrodynamical and thermodynamical equations for the atmosphere, oceans and ice, together with equations of state and conservation laws for selected constituents (e.g. CO_2, water, ozone in the atmosphere). These equations describe the processes which determine distributions of temperature, pressure, density and velocity. Other processes (evaporation, condensation, precipitation, radiative processes, etc.) can also be described mathematically. The use of these equations to describe the climate system is the basis of climate modeling. However, because our knowledge of the physical system is incomplete and because of computational limitations, certain physical and numerical approximations must be made in the use of the equations and a hierarchy of climate models has been created, with different types of models using different physical and numerical approximations in the equations used to describe the process of the climate system.

Two types of climate models have been used so far in the study of the effect of increasing the atmospheric CO_2 concentration on climate. The first type is the horizontally averaged, one-dimensional vertical coordinate model, which determines the various radiative fluxes as a function of the vertical coordinate and considers other processes such as vertical convection, cloudiness, albedo, interaction between clouds and radiation, and water vapor distribution. Results of such models, showing considerable agreement, are described elsewhere in the proceedings of the workshop. In these introductory remarks it is only necessary to point out that although such models are useful, they still treat certain feedback mechanisms poorly (or not at all) and while they offer insights into *some* of the effects of increasing atmospheric CO_2 concentration, they can not, used alone, give predictions of future climate because they do not treat the three-dimensional climate system.

The second type of model used in the study of the impact of increasing atmospheric CO_2 concentration [13] is the three-dimensional circulation model of the atmosphere. The latter solves a time-dependent set of equations at grid points with a few degrees latitudinal and longitudinal resolution. Such models represent the best tools available at the present time for studying the processes of the climate system but again have shortcomings which limit the usefulness of the results. In particular, there is no coupled ocean circulation model and poor treatment of cloudiness, hydrological and subgrid scale processes. The models have also only been used so far with constant seasonal forcing rather than for an annual simulation, so the question of the different response in different seasons has not been addressed. The use of a three-dimensional model to study the effect of doubling of atmospheric CO_2 concentration indicated an average surface temperature increase of 2-3°C, but large temperature increases (up to 10°C) in the polar area [13]. The latter was attributed to ice-albedo-temperature feedback but Ramanathan [personal communication, 1977] has indicated that feedback involving the fixed cloud amounts in the model was also responsible for the large response in the polar area.

Given that there are still many limitations to the use of models to predict the effect on climate of increasing the atmospheric CO_2 concentration, Kellogg [14] has examined the period from 4000 to 8000 years ago, known as the Altithermal, when the world was several degrees warmer than it is now, as an analogue for the climate system with a warming due to increased atmospheric CO_2 concentration. This approach also has limitations. As Kellogg points out, the causes for that former warm period were different than the predicted future warm period. The map produced by Kellogg indicates precipitation anomalies during the Altithermal, but it is certain that these anomalies were not all simultaneous. The question of seasonal differences in changes is also not answerable with this approach.

DISCUSSION

This introductory paper has tried to outline the problems which arise when we try to estimate the effect on climate of increasing the atmospheric CO_2 concentration. The climate system is highly complex and nonlinear and our understanding of (and ability to predict) climatic variations is poor. Observational studies and the use of models have helped us to understand some of the processes and mechanisms of climatic variations, but we are still not in a position to make predictions.

Much work has concentrated on the impact on globally averaged temperature. Observational studies suggest, however, that we are unable to determine, with the available meteorological network, the present global average surface temperature and its recent changes. Regional changes in surface temperature differ according to season and location. The polar areas in winter, spring and autumn experience trends (on an interdecadal time scale) 5-7 times larger than those at other latitudes, but even the validity of this finding can be questioned. It is also clear that although it is easier to work with temperature, there are likely to be precipitation changes, of more significance at least on the short term, and these cannot be predicted without a much better understanding of climate dynamics.

While an "order-of-magnitude, state-of-the-art" estimate of the effect on surface temperature of doubling the atmospheric CO_2 concentration can be made, using a one-dimensional atmospheric model, the applicability of such an estimate to the three-dimensional climate system is not known and the estimates can thus best be used as indicators of the magnitude of the problem, not as predictions.

REFERENCES

[1] US Committee for GARP, *Understanding Climatic Change*, National Academy of Sciences, Washington DC, 1975.

[2] GARP, *The Physical Basis of Climate and Climate Modeling*, GARP Publications Series, No. 16, WMO-ICSU, Geneva, 1975.

[3] Schneider, S.H., and R.E. Dickinson, Climate Modeling, *Rev. Geophys. Space Phys.*, 12 (1974), 447-493.

[4] Leith, C.E., The Standard Error of Time-Average Estimates of Climatic Means, *J. Appl. Meteorol.*, 12 (1974), 1066-1069.

[5] Madden, R.A., Estimates of the Natural Variability of Time-Averaged Sea-Level Pressure, *Mon. Weather Rev.*, 104 (1976), 942-952.

[6] van Loon, H., and J. Williams, The Connection Between Trends of Mean Temperature and Circulation at the Surface: Part I, Winter, *Mon. Weather Rev.*, 104 (1976), 365-380.

[7] Geisler, J.E., ed., *Proceedings of the Workshop on Regional Climate and Stratospheric Change*, National Center for Atmospheric Research, Boulder, Colorado, 1977.

[8] van Loon, H., and J. Williams, The Connection Between Trends of Mean Temperature and Circulation at the Surface: Part II, Summer, *Mon. Weather Rev.*, 104 (1976), 1003-1011.

[9] Williams, J., and H. van Loon, The Connection Between Trends of Mean Temperature and Circulation at the Surface: Part III, Spring and Autumn, *Mon. Weather Rev.*, 104 (1976), 1592-1596.

[10] Mitchell, J.M., Recent Secular Changes of Global Temperature, *Ann. N.Y. Acad. Sci.*, 95 (1961), 235-250.

[11] Manabe, S., and R.T. Wetherald, Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity, *J. Atmos. Sci.*, 24 (1967), 241-259.

[12] Augustsson, T., and V. Ramanathan, A Radiative-Convective Model Study of the CO_2 Climate Problem, *J. Atmos. Sci.*, 34 (1977), 448-481.

[13] Manabe, S., and R.T. Wetherald, The Effects of Doubling the CO_2 Concentration on the Climate of a General Circulation Model, *J. Atmos. Sci.*, 32 (1975), 3-15.

[14] Kellogg, W.W., Effects of Human Activities on Global Climate - Part II, *WMO Bull.*, 27, 1(1978), 3-10.

THE POTENTIAL CONSEQUENCES OF INCREASING CO_2 LEVELS IN THE ATMOSPHERE

W. Bach

INTRODUCTION

Mankind is carrying out a large-scale geophysical experiment by changing the composition of the atmosphere and by increasing the CO_2 content of the atmosphere. On the basis of present climate data it is not possible to separate the climate change (signal) that might be caused by the increasing CO_2 levels in the atmosphere from the natural variability of climate (noise). And yet there is no time to wait until Nature supplies the results of our CO_2 experiment. Considering the lead time for remedial measures to become effective, it is essential to assess the potential consequences of the CO_2 impact well in advance to keep them within acceptable limits. Such measures require a better understanding of the carbon cycle, which is needed for better prediction of future CO_2 concentrations, which in turn are required as input for climate models that can predict the potential impacts on man and his environment. While some inferences can be drawn from similar climatic events in the past, we shall have to rely mainly on numerical model results. In this review emphasis is placed on the evaluation of the potential impact of the constantly increasing atmospheric CO_2 concentration on the general atmospheric circulation, on the shift of agroclimatic zones, on terrestrial and marine productivity, and on regional and global economic disruptions.

Table 1 summarizes estimates of future CO_2 concentrations for a variety of scenarios made with models reflecting perhaps the best state-of-the-art modeling. All the models predict a doubling of CO_2 between 2025 and 2050, except when the growth rate is reduced (see Zimen et al., 1977, case 4) or when fossil fuels are replaced by alternative energy sources (see Niehaus, 1976). Beyond 2100, peak atmospheric CO_2 concentrations might reach 4 to 8 times the preindustrial level (NAS, 1977).

EFFECT OF CO_2-INCREASE ON SURFACE AIR TEMPERATURE

Schneider (1975) has defined a useful surface temperature-CO_2-concentration sensitivity parameter γ_2, which gives an

Table 1. Overview of recent estimates on future CO_2 levels in the atmosphere.

Investigator and Scenario	Projected CO_2 levels (ppmV) in the atmosphere					Specifications
	2000	2025	2050	2075	2100	
Zimen et al. (1977)*						
case 1	375	425	780	1100	1240	Growth of biomass, $\beta = 0.35$; no deforestation, $\delta = 0$
case 2	375	425	805	1250	1610	No change in biomass, $\beta = 0$; no deforestation, $\delta = 0$
case 3	375	425	840	1290	1580	Net reduction of biomass, $\beta = 0.44$, $\delta = 0.32$
case 4	370	415	770	1200	1500	Growth rate $\alpha = 4\%/a$
	350	400	575	825	1110	$\alpha = 3\%/a$
	335	375	435	540	680	$\alpha = 2\%/a$
	320	340	375	390	430	$\alpha = 1\%/a$
Niehaus (1976)**						
Optimistic equilibrium strategy	383	450	500	545	570	Stabilization of population in 2050 at 8×10^9; primary energy consumption at 80×10^9 tce; 90% nuclear in 2100
Decrease of world forests	420	525	605	660	675	A 50% change of forests into agricultural land resulting in a 15% reduction of the biomass on land
No nuclear energy	450	690	1060	1430	1400	Gas and oil depleted around 2020; after that energy needs met by coal

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*Zimen et al. use a five-box model for the kinetics of CO_2 and a logistic function to estimate future CO_2 levels. The final cumulated input $Q_\infty = 200 \times 10^{21}$ J or 2237 ppmV CO_2; the buffer factor $\xi = 10$. Cases 1 to 3 use a constant growth rate of 4.3%/a of CO_2 and variable biomass factors; case 4 uses the biomass changes of case 3 and shows the impact of variable growth rates.

**Niehaus uses an eight-level tandem model based on nonlinear differential equations.

Table 1. (cont'd)

Investigator and Scenario	Projected CO_2 levels (ppmV) in the atmosphere					Specifications
	2000	2025	2050	2075	2100	
Nuclear power (LWR) and coal	430	530	740	1075	1300	In 2000 25% nuclear (LWR) relative increase in coal until 2100
CO_2 emission reduction strategy	380	440	470	465	450	75% advanced nuclear, 22% renewable energy sources, 3% coal; intensive recycling of resources
Keeling and Bacastow (1977)*						
case 1	377	638	1450	2088	2262	Growth cutoff parameter n = 2
case 2	377	522	870	1276	1595	Growth cutoff parameter n = 0.5

*Keeling and Bacastow use a modified logistic function having an adjustable growth cutoff parameter n. Large n means early exhaustion of readily available fossil reserves; small n means reduced use of fossil fuels and wider application of alternative energy sources.

estimate of surface temperature increase, ΔT_s, for a doubling of CO_2 from 300 to 600 ppm such that

$$\gamma_2 \equiv \frac{\Delta T_s}{\Delta [CO_2]} [CO_2] \quad , \tag{1}$$

where $\Delta[CO_2]$ is 300 ppm and $[CO_2]$ is 300 ppm. Table 2 shows the sensitivity of surface temperature to a doubling of CO_2 for diverse modeling attempts including surface energy balance models, 1-D radiative-convective models, and 3-D general circulation models. The differing results reflect the degree of parameterization and of incorporation of feedback mechanisms. Conventionally, cloudiness-surface temperature feedback and ice-albedo feedback are regarded as most important. Cess (1976) finds that the two components of cloud amount feedback--the positive feedback from enhanced infrared opacity of the atmosphere and the negative feedback from an increased planetary albedo--cancel each other, so that the cloud amount feedback is unimportant zonally as well as globally. Lian and Cess (1977) conclude that the ice-albedo feedback is a relatively mild mechanism amplifying global climate sensitivity by only about 25%.

Table 2. Computed surface air temperature changes for a doubling of CO_2 to 600 ppm.

Temperature sensitivity to a doubling of CO_2 (°C)	Specification	References
	1-D radiative-convective model (globally averaged)	Manabe and Wetherald (1967)
2.9	with fixed RH* and clear skies	
2.4	with fixed RH and average cloudiness	
1.4	with fixed AH** and clear skies	
1.3	with fixed AH and average cloudiness	
> 4	Surface energy balance model based on 3120 observations	Budyko (1969)
1.9	Radiative transfer scheme by Rodgers and Walshaw (1966) with radiative-convective model by Manabe and Wetherald (1967)	Manabe (1971)
0.8	1-D planetary radiation balance model with fixed lapse rate, RH, stratospheric temperature and cloudiness	Rasool and Schneider (1971)
	2-D energy balance model averaged over space and time with ice-temperature-albedo feedback, fixed RH and average clouds	Sellers (1973)
0.1	global average	
0.6	poleward of 60° N in winter	
1.3	Same as Sellers (1973) but changing to a two-layer gray-body approach for estimating infrared emission to space	Sellers (1974)
0.7	1-D global average model with diffuse thin clouds, fixed RH, fixed rainout of condensation water, quasi-isentropic lapse rate	Weare and Snell (1974)
1.5	1-D radiative-convective model with fixed RH and cloudiness	Ramanathan (1974)
	3-D GCM with interactive lapse rate and ocean "swamp" and hydrologic cycle; but fixed cloudiness, no CO_2-ocean buffering, and no coupling of deep oceans to atmosphere; heat transport by large-scale eddies computed explicitly	Manabe and Wetherald (1975)
2.9	global average	
> 7	north of 70° N	
4.93	Mean hemispheric temperature model based on a differential equation	Bryson and Dittberner (1976)

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*RH is relative humidity.
**AH is absolute humidity.

Table 2. (cont'd)

Temperature sensitivity to a doubling of CO_2 (°C)	Specification	References
	2-D annual zonally averaged steady-state hemispherical model with diffuse thin clouds as cloudiness feedback	Temkin and Snell (1976)
1.7	global annual average	
1.2	0 to 30° latitude	
1.2 to 2.0	30 to 60° latitude	
2.0 to 6.0	60 to 90° latitude	
	1-D radiative convective model	Wang et al. (1976)
≃ 3.2	with a fixed cloud-top temperature	
≃ 2.1	with a fixed cloud-top height	
	1-D radiative convective model	Augustsson and Ramanathan (1977)
1.9	for CO_2 bands 12 to 18 µm and constant RH and CTA*	
1.98	for CO_2 bands 12 to 18 µm plus 10 and 7.6 µm and for constant RH and CTA	
3.2	same but for constant RH and CTT**	

*CTA is cloud-top altitude.
**CTT is cloud-top temperature.

Apparently, the radiative-convective model is very sensitive to assumptions on cloud top and relative humidity, resulting in temperature ranges from 1.98 to 3.2 K due to CO_2 doubling (Augustsson and Ramanathan, 1977). They also found that absorption by the weak absorption bands of CO_2 which contribute 30% to the surface temperature change increases almost linearly with CO_2 concentration. This means that the warming effect of CO_2 on surface temperature may never saturate out. An earlier investigation by Rasool and Schneider (1971), which considered only the 15 µm bands, concluded that saturation would prevent a potential runaway greenhouse effect. Summarizing Table 2, it appears that present models estimate a surface temperature increase of 1.5 to 3 K with large amplifications near polar regions for a doubling of the CO_2 concentration from 300 to 600 ppm.

TOTAL ANTHROPOGENIC EFFECTS ON SURFACE AIR TEMPERATURE

Table 3 reveals that, except for changes in the surface albedo and the stratospheric ozone, all other anthropogenic effects

Table 3. Estimates of anthropogenic influences on the global mean surface air temperature.

Anthropogenic influences through	Increase over present value	Time period for the effect to occur	Change in the global mean surface temperature (^{0}C)	References
CO_2	+ 25%	2000	+ 0.5 to 1.0	Kellogg (1977a,b,c) Manabe and Wetherald (1975)
	+ 100%	2050	+ 1.5 to 3.0	
CF_2Cl_2, $CFCl_3$	+ 9-fold	2000	+ 0.1 to 0.4	Kellogg (1977a,b,c) Wang et al. (1976) Ramanathan (1975)
	+ 27-fold	2050	+ 0.2 to 1.0	
N_2O	+ 2-fold	2025	+ 0.5	Yung et al. (1976)
	+ 4-fold	2100	+ 1.0	
CH_4, NH_3	+ 2-fold	?	+ 0.4	Wang et al. (1976)
Aerosols	?	?	warming	Bach (1976a,b)
Direct emission of heat	+ 100-fold	2100	+ 1 to 2	Kellog (1977a,b,c)
H_2O in the stratosphere	+ 25%	?	+ 1.0	Wang et al. (1976)
Global surface albedo	+ 1.4%	2020	- 0.23	Flohn (1977a,b)
O_3 in the stratosphere	- 25%	?	- 0.47	Wang et al. (1976)
Natural climatic change			± 0.25	Natural Academy of Sciences (1975)

lead toward global warming. If we consider only small fractional changes, the various effects can be approximated by linear relationships and we can consider them as additive. Larger changes will most likely follow nonlinear relationships. On balance it appears that the overall effects might increase the global mean surface temperature by 0.8 to 1.2 K in 2000 and by 2 to 4 K in 2050 (with increases > 10 K in polar regions). Table 3 also demonstrates that it is above all the increasing CO_2 that is responsible for this warming trend.

CONSEQUENCES OF INCREASING CO_2 LEVELS

Effects on the Climate of a General Circulation Model

Present climate models are not yet adequate for reliable prediction of climatic changes. Thus it is advisable not to take too seriously the quantitative results obtained from such modeling (Manabe and Wetherald, 1975)(Table 4). Nevertheless, climate models are the only methods available for assessing the potential climatic impact of increasing CO_2. It is difficult, if not impossible, to assess the effects by empirical means, since such

Table 4. Calculated heat balance changes for an atmosphere with present CO_2 levels (standard) and twice the present CO_2 levels (2 × CO_2).

After: Manabe and Wetherald (1975)

Flux*	Standard (Ly/min)	2 × CO_2 (Ly/min)	Change (%)
	Surface of the Earth		
NSR	0.238	0.237	0.5
NLR	0.091	0.085	- 6.6
NR	0.147	0.152	3.3
LH	0.108	0.116	6.9
SH	0.039	0.036	- 7.7
	Top of the Atmosphere		
NSR	0.334	0.337	0.9
NLR	0.334	0.337	0.9

*NSR is net shortwave radiation; NLR, net longwave radiation; NR, net all-wave radiation; LR, latent heat flux; and SH, sensible heat flux.

CO_2 increases are unprecedented in modern climate history (ERDA, 1977); thus climate models are the best available tools. Manabe and Wetherald (1975) have run such experiments with a general circulation model, comparing the results of a control case with those of a case where the CO_2 concentration is doubled. The interesting results can be summarized as follows:

- The global average surface equilibrium temperature increase is 2.93 K. North of 70° N the temperatures are 7 to 10 K. This is due to the effects of snow-cover feedback and suppression of vertical mixing by stable stratification.

- The temperature of the stratosphere decreases because of the larger heat emission from the stratosphere into space due to increased CO_2. The cooling increases with height, reaching 6 K above 30 km; this tends to decrease the static stability.

- Relative humidity increases a few percent below 700 mb and decreases a few percent above 700 mb.

- The hydrologic cycle is more active by about 7%. This is due to an increase in the flux of downward radiation and a decrease in the Bowen ratio. Snowfall is reduced in amount and in extent.

- The extent of the snow cover is reduced and the surface albedo is lowered north of 50° N. There is a poleward displacement of the zone of maximum snow depth.

- At the earth's surface the net all-wave (downward) radiation increases by about 3.3% due to the increased greenhouse effect caused by CO_2 and H_2O. The upward flux of latent heat, i.e., evaporation, increases by about 7%, while that of sensible heat decreases by 7.7%. Thus evaporation becomes a more effective way of removing heat from the surface than the upward flux of sensible heat. At the top of the atmosphere there is a net upward longwave radiation increase of about 1%. This is because the stratospheric cooling and the increase in the height of the effective source of upward emission are overcome by the general warming of the troposphere. There is also a net downward increase of about 1% in the intensity of solar radiation. This is due to the lower surface albedo in polar areas and the increase absorption of isolation caused by the increase in both CO_2 and H_2O.

- There is a net decrease between 500 and 300 mb in eddy kinetic energy which is a measure of the dynamic processes in the atmosphere. The area of maximum net decrease in middle latitudes coincides with the region of reduced tropospheric meridional temperature gradient. The effects on the poleward transport of energy are reported in the next section.

While the model assessment of CO_2 doubling by Manabe and Wetherald (1975) is so far the most complete, some key ingredients needed for more realistic results could not yet be taken into consideration (Smagorinsky, 1977). These include: CO_2-ocean buffering, aerosol interactions, realistic geography, seasonal variations, cloud-temperature feedback, and the coupling of the deep sea to the atmosphere. These omissions might either reduce or enhance the climatic response. Thus current state-of-the-art modeling is still plagued with many uncertainties.

Effects on Atmospheric Circulation Patterns

According to Manabe and Wetherald (1975), the general activity of atmospheric circulation is characterized by the poleward transport of latent and heat energy. The general temperature increase due to a CO_2 increase slightly enhances the poleward transport of latent energy in middle latitudes. The equatorward transport of latent heat in low latitudes is larger because of the intensification of the Hadley cell. Consistent with the reduction of eddy kinetic energy in middle latitudes, the poleward transport of heat energy is also reduced. Poleward transport of heat energy from the tropics is, however, enhanced because of the intensified Hadley cell. Since the change in heat transport is mostly offset by a change in the transport of latent heat, the magnitude of the change in total heat transport becomes very small.

By plotting the secular course of surface air temperature for the northern hemisphere against the average meridional temperature gradient in the latitudinal belt of 25 to 70° N and against the cold period (November to March) precipitation recorded in steppe and forest-steppe regions of the USSR, Budyko (1977) could show that both the meridional temperature gradient and the amount of precipitation decrease with warming while they increase with cooling. Budyko and Vinnikov (1977) have shown that the average surface air temperature increase of 0.1°C over the past 10 years in the northern hemisphere produced a relative decrease in the meridional temperature gradient of 1% in winter and 0.5% for annual mean conditions. The decrease in precipitation during a warming period is due to the decrease in the mean meridional temperature gradient, which, in turn, is responsible for the reduction of the intensity of the atmospheric circulation. A weakened atmospheric circulation transfers less water vapor from oceans to land areas, thereby reducing the amount of precipitation. Thus it is conceivable that CO_2 increases via surface air temperature increases lead to decreases not only in the meridional temperature gradient but also in the intensity of the atmospheric circulation and the amount of precipitation, which could drastically affect agricultural productivity over central parts of Eurasia.

By combining the meridional potential temperature gradient, $\delta\theta/\delta y$, of the thermal Rossby number with the vertical potential temperature gradient, $\delta\theta/\delta z$, of the Richardson number, Smagorinsky (1963) has obtained the following nondimensional criterion:

$$\tan \Phi_z = -(h/a) \left(\frac{\delta\theta/\delta z}{\delta\theta/\delta y}\right) , \qquad (2)$$

where Φ_z is the latitude at which the wave number of the zonal flow becomes dynamically unstable and which is approximately the latitude of the transition of the Hadley regime to the Rossby regime (Bryson, 1974); h is a scale height, roughly 7.9 km, or the mean distance between the 750 mb and the 250 mb level; a is the radius of the earth (6387 km). This important circulation criterion thus determines the extent of the subtropical desert areas and the locations of the monsoonal and the Mediterranean regions.

The relationship between changes in the meridional and vertical temperature gradients and the latitude of subtropical anticyclones is shown in Figure 1. Note the sensitivity of the latitude of subtropical highs to small changes in temperature gradients (Bryson, 1973). Data presented by Ilesanmi (1971) for northern Nigeria show that the annual rainfall gradient south of the ITD (the intertropical discontinuity that is the northern boundary of the monsoon rains) is about 180 mm per degree of latitude. Comparison of the monthly position of the ITD in Nigeria with the monthly position of the Azores highs shows that a 1^0 change in the position of the ITD corresponds to only a $1/3^0$ change in the position of the highs, i.e., only 35 km. This is an almost unobservable change, which determines the extent of the Sahelian drought (Bryson, 1973).

Increasing CO_2 levels and hence decreasing meridional temperature gradients would shift the Hadley regime, and with it the dry belt, to the north (Figure 1). A rough assessment of the anthropogenic warming expected in the first half of the next century would indicate a northward shift of the Hadley regime in summer by about 200 to 300 km (Korff and Flohn, 1969; Flohn, 1973). Winter circulation conditions would be similar to present summer conditions, resulting in reduced precipitation in the subtropical zone of winter rains, including the Mediterranean, the Middle East as far as Turkestan and the Punjab, and California. The northward shift of the Azores highs would, of course, result in a concomitant northward shift of the tropical rain zone, thereby enhancing drought in northeastern Brazil. All this would be accompanied by shifts in the quasistationary troughs of the westerlies,

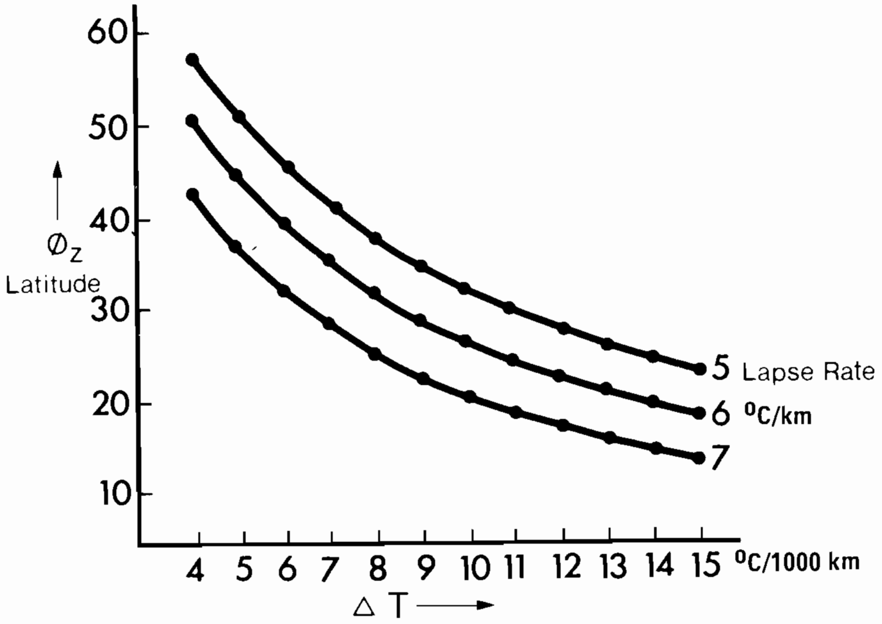

Figure 1. Shift of the subtropical highs as a function of the meridional and vertical temperature gradients.

Source: Bryson (1973)

leading to regional temperature and precipitation anomalies which in turn would affect agricultural productivity. Note that the potential conditions described here are somewhat different from those reconstructed for the Altithermal by Kellogg (1977c).

Bacastow (1976) has presented some evidence suggesting that the greater increase in the Mauna Loa CO_2 data in some years than in others is connected to the southern oscillation, a large-scale atmospheric and hydrospheric fluctuation occurring irregularly every one to five years. Newell and Weare (1977) imply that the modulation is due to a variable source rather than a variable sink.

Ramanathan (1977) has shown that the optically active gases CO_2, H_2O, and O_3 within the stratosphere emit longwave radiation downward into the troposphere, which has an appreciable warming effect on the wintertime polar troposphere. He suggests that this stratospheric warming may affect the tropospheric circulation.

Shift of Agroclimatic Zones

The effect of increased CO_2 levels on the atmospheric circulation pattern and hence on the temperature and precipitation distribution will result in a general poleward movement of agroclimatic zones (NAS, 1977). While tropical agriculture may suffer the least, the increased warming may result in more drought in higher latitude regions (Baes et al., 1976). Crop shifts accompanied by higher cost and less productivity may be the unwanted side effects. For example, summer temperature may become too high for optimum growth of such crops as corn and soy beans in Missouri, Iowa, Illinois, and Indiana, so that the Corn Belt may have to be shifted north into the acid podzols. This would require extensive fertilization and soil amelioration, in addition to substantial investment. Increased temperatures mean enhanced evapotranspiration; together with overgrazing in marginal lands, this may lead to desiccation, which in turn might bring the dust-bowl problems of the 1930s back to the Great Plains.

Effects on Terrestrial and Marine Productivity

In this section I make extensive use of the publication *Impacts of Climatic Change on the Biosphere* prepared by agricultural specialists in 1975 for the Climatic Impact Assessment Program (CIAP) of the US Department of Transportation. I think that the CIAP Monograph has a broader applicability so that it can very well be used to assess in a more general way the impact of climatic change on agricultural productivity.

The impact of climatic change on the biosphere can be approached in a number of ways. One is to study historic climatic changes and evaluate their effects on shifts of agroclimatic zones and agricultural productivity; another, to use statistical and physical models that relate productivity to climatic factors. The latter approach is emphasized here.

Most work in this area uses a simple linear regression expression where crop yield or some other measure of productivity is related to a function involving one or two independent variables such as temperature and rainfall. Such linear models assume that a change in productivity per unit change in the climatic variable is independent of the variable itself. Since this is unlikely, multiple regression expressions in the form of second-order polynomials are often used to account for nonlinear effects. Katz (1977) has pointed out that the coefficients of these models are not universal constants, but rather statistical estimates subject to sources of error, and that some possibly important climatic variables may not have been included in the models. These types of models use empirical relationships, and the question arises to what extent they agree with physical reality.

Thus the next step led from regression expressions to simulation models that describe actual growth processes in physical terms based on soil physics, plant physiology, and meteorology. A basic component of such models is the photosynthesis process.

The ecological models are a further step toward complexity. They incorporate, for example, different plant species and their distributions, different soil systems with organic matter decay, nutrient uptake, and recycling, and, above all, the various energy flows involved.

Agricultural productivity is very much dependent upon production methods, environmental stress--e.g., insect or disease outbreak--and the climatic regime, i.e., whether marginal or optimal, in which the crop is grown. Since each crop has its unique response to climatic variations (Biggs and Bartholic, 1973), each crop must be dealt with individually. In this review only a brief discussion of some of the world's major crops, namely, corn, wheat, and rice, and some marine resources, is possible.

Climatic Effects on Corn Production

More than 75% of US corn is produced in the 11 midwestern states of Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, Ohio, South Dakota, and Wisconsin (Benci et al., 1975), where the growing season is sufficiently long (> 120 days), corn growth is well adapted to the temperature and precipitation distribution, and the soils are fertile and flat with a good water-holding capacity.

The statement that each crop has its unique response to climatic variations is now demonstrated for corn (Biggs and Bartholic, 1973; Thompson, 1975). Figure 2 shows that the average June temperatures of 72^{0}F (22^{0}C) in the US corn belt are near optimum for corn growth. Any change in the summer temperatures would reduce the yield; for example, an increase of only 1^{0}C during August would reduce yields by 1.5 to 2 bu/acre, a 2% reduction in yield.

The relationship between corn yield and rainfall in the three summer months is shown in Figure 3. While small changes in rainfall are not significant in June and August, they become critical in July, when tasseling and silking occur--processes that depend upon soil moisture and temperature. For example, a 1-inch decrease in July rainfall could reduce corn yields by 5 bu/acre, a 6 to 7% reduction.

The percent changes in crop yield shown in Table 5 were calculated with a crop-weather-soil moisture model developed by Lepper et al. (1974). The results show, for example, that, based on the 1901-1972 weather and yield data, corn production would change by about 11% for each 1^{0}C change in average maximum temperatures over the summer months, and by about 1.5% for each 10%

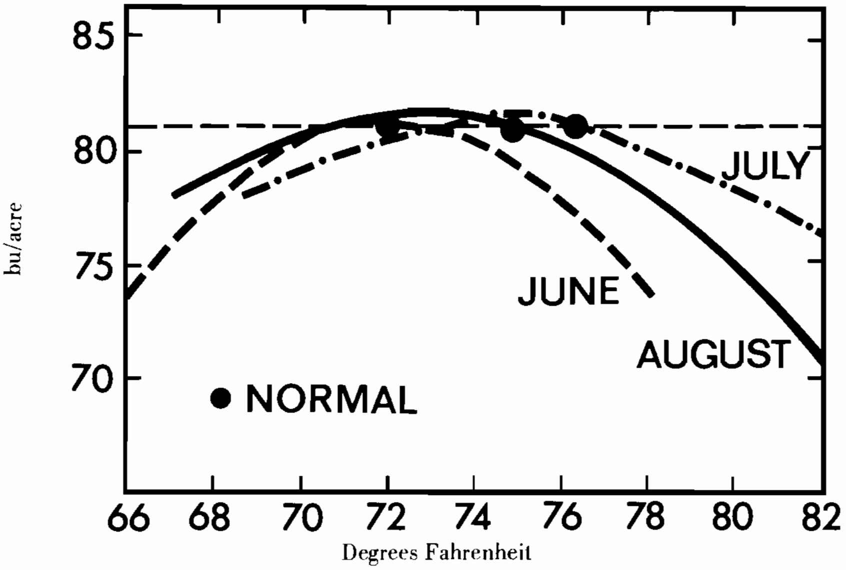

Figure 2. Response of corn yields to temperature in the US corn belt.

Source: Biggs and Bartholic (1973)

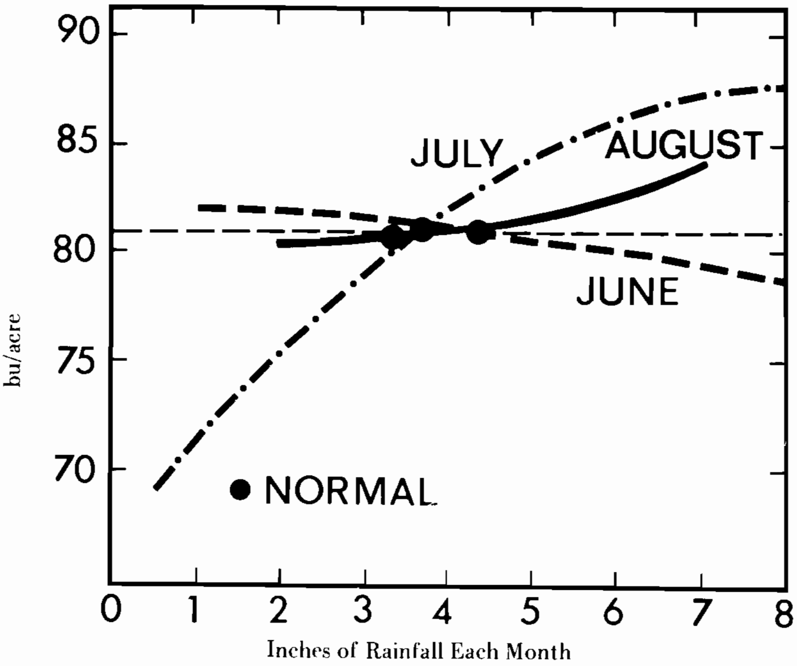

Figure 3. Response of corn yields to rainfall during different stages of growth in the US corn belt.

Source: Biggs and Bartholic (1973)

Table 5. Estimated percent change in corn yield due to changes in temperature and precipitation.

Source: Benci et al. (1975)

Temperature change (°C)	Change in precipitation (% of normal*)				
	- 20%	- 10%	0	+ 10%	+ 20%
- 2.0	19.8	21.2	22.7	24.2	25.6
- 1.0	8.4	9.8	11.3	12.8	14.2
0	- 2.9	- 1.5	0	1.5	2.9
+ 1.0	- 14.2	- 12.8	- 11.3	- 9.8	- 8.4
+ 2.0	- 25.6	- 24.2	- 22.7	- 21.2	- 19.8

*Normal = 85 ± 16 bu/acre, 1901-1972 average for selected stations in Missouri, Illinois, Indiana, Nebraska, Iowa, and Kansas.

change in precipitation. Such changes could have drastic economic consequences. In general, in the US corn belt warmer and drier conditions will decrease, and cooler and wetter conditions will increase, corn yields (Benci et al., 1975).

Climatic Effects on Wheat Production

Wheat is one of the world's major crops. It differs from other grains in that it needs a longer growing season and somewhat higher minimum growing temperatures, and is rather sensitive to low and high temperatures. The wheat growing areas of the world lie roughly in a belt between 20 and 50° N and 25 and 40° S, where precipitation ranges from about 300 to 1100 mm (Ramirez et al., 1975).

Multiple regression analysis and historical inferences have been used to analyze the climatic effects on wheat production. Table 6 shows the relationship between temperature increase and precipitation changes for six midwestern states. It appears that wetter areas, such as Indiana and Illinois, would experience a reduction in yields of up to 5 to 7 bu/acre with temperature increases of 1 to 2°C and precipitation increases of up to 30%. The drier areas, including Kansas and North Dakota, could slightly profit from a temperature and rainfall increase.

Other major wheat producing areas, such as Kazakhstan in the USSR, would experience yield reductions of as much as 20% for a temperature increase of 1°C and a precipitation decrease of 10%.

Table 6. Effects of climatic change on the average wheat yields in six states.

Source: Ramirez et al. (1975)

Climatic Change	Change in wheat yields (bu/acre)*					
	N. Dakota	S. Dakota	Kansas	Oklahoma	Illinois	Indiana
	An increase of 0.5^{0}C in temperature					
Change in precipitation (%)						
- 30	- 4.11	- 3.31	- 3.22	- 3.21	+ 2.44	+ 2.78
- 20	- 2.90	- 2.13	- 2.18	- 1.96	+ 1.61	+ 1.72
- 10	- 1.48	- 1.22	- 1.25	- 1.02	+ 0.58	+ 0.64
+ 10	+ 0.63	- 0.13	+ 0.36	- 0.09	- 2.05	- 1.59
+ 20	+ 1.98	+ 0.05	+ 1.04	- 0.10	- 3.66	- 2.74
+ 30	+ 3.21	+ 0.03	+ 1.61	- 0.42	- 5.48	- 3.91
	An increase of 1^{0}C in temperature					
Change in precipitation (%)						
- 30	- 4.56	- 3.92	- 3.61	- 3.98	+ 1.84	+ 2.31
- 20	- 3.35	- 2.75	- 2.75	- 2.72	+ 1.01	+ 1.25
- 10	- 1.93	- 4.66	- 1.62	- 1.79	- 0.02	+ 0.17
+ 10	+ 0.19	- 0.66	- 0.01	- 0.85	- 2.65	- 2.06
+ 20	+ 1.53	- 0.19	+ 0.65	- 0.85	- 4.25	- 3.21
+ 30	+ 2.77	- 0.65	+ 1.22	+ 1.18	- 6.08	- 4.39
	An increase of 2^{0}C in temperature					
Change in precipitation (%)						
- 30	- 6.71	- 4.39	- 4.41	- 6.57	+ 0.39	+ 1.32
- 20	- 4.39	- 3.22	- 3.37	- 5.31	- 0.44	+ 0.26
- 10	- 3.14	- 2.39	- 2.42	- 4.38	- 1.47	- 0.82
+ 10	- 0.69	- 1.13	- 0.82	- 3.45	- 4.10	- 3.05
+ 20	- 0.49	- 0.67	- 0.16	- 3.45	- 5.71	- 4.20
+ 30	+ 1.72	- 1.12	+ 0.42	- 3.77	- 7.53	- 5.38

*The average mean yields are for North Dakota, 25.0; South Dakota, 21.1; Kansas, 25.9; Oklahoma, 25.2; Illinois, 36.3; and Indiana, 36.3 bu/acre.

It appears that the bumper crops of the past decade, which were most likely due to unusually favorable climate, have come to an end. Responding to the large interannual climatic variations, Soviet wheat production has undergone notorious fluctuations. For example, the 1975 crop failure resulted in a mere 140 × 10^6 t (the official Soviet five-year plan calls for an average yield of about 215 × 10^6 t), whereas the year 1976 again saw a bumper crop of 223 × 10^6 t (Shapley, 1977).

Attempts have also been made to assess the income losses due to small climatic anomalies. Using monthly temperatures and rainfall, preseason moisture, technological trends, and soil type as model input, past spring wheat yields in the US could be reproduced with an accuracy of about 97% (Bryson, 1975). The results in Table 7 show that a 1°C temperature increase or a 20% rainfall decrease would each cost about \$130 × 10^6 in lost income.

Table 7. Gross spring wheat income losses in the USA due to deviations of temperature and precipitation from normal (M\$).*

Source: Bryson (1975)

Anomaly Period	ΔT = + 1°C	ΔT = -1°C	ΔR = +1mm	ΔR = -1mm	ΔR = +20%	ΔR = -20%
Preseason	-	-	+ 7	- 8	+ 21	- 30
April	+ 40	- 40	+ 3	- 3	+ 22	- 25
May	- 22	+ 13	+ 2	- 2	+ 4	- 37
June	- 70	+ 70	+ 2	- 2	+ 37	- 44
July	- 78	+ 92	-	-	- 2	- 2
Whole Season (all periods)	- 131	+ 136	+ 14	- 15	+ 82	- 139

*The following assumptions have been made: approx. 500 × 10^6 bu crop; a \$3.50/bu price; all other factors constant.

Climatic Effects on Rice Production

Rice is the most important crop in the world's poorest and most densely populated areas. A third of mankind depends on rice for more than half of its food (Stansel and Huke, 1975). Rice is a very versatile plant growing in a wide range of latitudes and altitudes, and climatic, soil, and water conditions. It is planted in Czechoslovakia at a latitude of 49° N and in Sumatra on the Equator; grown at elevations up to 3000 m in Nepal; and found in wet areas in Burma with 4500 mm rainfall during the growing season.

The growing season for rice begins and ends at mean temperatures of 15°C. In general, an increase in the mean temperature would lengthen the growing season, allow more flexibility in planting time, and extend the potential rice growing areas. The combined effects of temperature and precipitation changes on world rice production are shown in Table 8.

Table 8. Percent deviation from world rice production base as influenced by changes in temperature and precipitation.*

Source: Stansel and Huke (1975)

Precipitation change, (%)	Temperature change						Total precipitation change (%)
	- 2°C	- 1°C	- 0.5°C	+ 0.5°C	+ 1°C	+ 2°C	
- 15	- 19	- 13	- 8	- 4	0	3	- 8
- 10	- 17	- 11	- 6	- 2	2	5	- 6
- 5	- 13	- 7	- 2	2	6	9	- 2
+ 5	- 9	- 3	2	6	10	13	2
+ 10	- 5	1	6	10	14	17	6
+ 15	- 3	3	8	12	16	19	8
Total temperature change	- 11	- 5	0	4	8	11	

*Based on world production of 300 Mt.

Climatic Effects on Marine Resources

Like terrestrial organisms, marine organisms are affected by climate anomalies. As an example, Lorenzen (1975) reports the sudden appearance in 1879 of tilefish off the east coast of the USA, which spawned an intensive fishery. In 1883, the species had completely disappeared, only to reappear in 1898 with enough abundance to again support a fishery. This phenomenon has not yet been further explored. Another apparent response of fish stocks to climatic change has been reported. It is conspicuous that the period of warming reaching a temperature deviation of

+ 1.4°C from the long-term mean in the latitudinal belt 72.5 to 87.5° N in the 1940s (Budyko and Vinnikov, 1977) is closely associated with the rise of the West Greenland cod fishery which has subsequently nearly disappeared (Cushing, 1976).

The El Niño is another phenomenon that has attracted wide attention, because a whole fishing industry--the Peruvian anchovy catch--and the related guano fertilizer export depend on it. El Niño occurs in connection with a weak cold Humboldt Current and an incursion of warm tropical waters which prevent the coastal upwelling of nutrient-rich water. During 1975, El Niño equatorial primary production was less than 0.2 g of C/m^2/day, or one fifth the normal value (Cowles et al., 1977). Table 9 shows the El Niño incidences of 1957, 1965, 1969, and 1972 which were accompanied by drastic reductions in the anchovy catch.

Table 9. Annual Peruvian anchovy catch and incidences of El Niño (Mt)

Source: Idyll (1973)

1955	0.1		1964	8.9	
1956	0.2		1965	7.2	El Niño
1957	0.4	El Niño	1966	8.5	
1958	0.7		1967	9.8	
1959	1.9		1968	10.3	
1960	3.3		1969	8.5	El Niño
1961	4.7		1970	12.3	
1962	6.3		1971	10.3	
1963	6.4		1972	4.6	El Niño

LESSONS FROM PAST CLIMATES

The impact of higher CO_2 levels and hence higher temperatures can also be studied by finding analogous periods in the past. Evidence of the conditions in past climates can be obtained from ocean sediments (through the isotopic composition of planktonic and benthic fossils and the mineralogic composition); from the pollen type and concentration in layered lake and bog sediments; from ring width anomalies, density, and isotopic composition of tree rings; from oxygen isotope concentration and thickness of layered ice cores; from the extent and position of mountain glaciers and ice sheets, lake levels, and ancient sand dunes; and from a variety of archeological records (Kutzbach, 1975; Kellogg, 1977a, 1977b, 1977c).

The post-glacial Atlanticum, also known as the Altithermal or Hypsithermal, which existed roughly from 6000 to 4000 y BP, may serve as an example. During that period, middle latitude temperatures were 1 to 2 K, and subarctic temperatures were 2 to 3 K, both higher than today (Flohn, 1975, 1977a). Many places had higher rainfall; pollen records show that the monsoonal rainfall in the Thar Desert between Pakistan and India was 600 to 800 mm as compared to the present 200 mm. Inland lakes that are now in the dry belt, such as Lake Chad, were considerably larger, and the Arctic pack ice around the northern part of Greenland had all but disappeared.

Collecting information from more than 100 references, Kellogg (1977d) has constructed a map showing the Altithermal Period. in terms of "wetter" and "drier" relative to the present (Figure 4). The present dry belt, extending from West Africa to Rajasthan in India and the dry parts of western Australia and northern Mexico, had a wetter climate with presumably more favorable conditions for agriculture than today. The Prairie lands in North America and all of Scandinavia were drier than today. The large blank areas have yet to be filled in as information becomes available. The causes that produced the Altithermal Period are still highly speculative. They include solar output and orbital changes, and even higher CO_2 levels. There is yet another reason why the information given in Figure 4 should be interpreted with caution: the Altithermal appears to have evolved over a period of a few thousand years, while the present warming trend might reach equal magnitudes within half a century (Kellogg, 1977a, 1977b, 1977c).

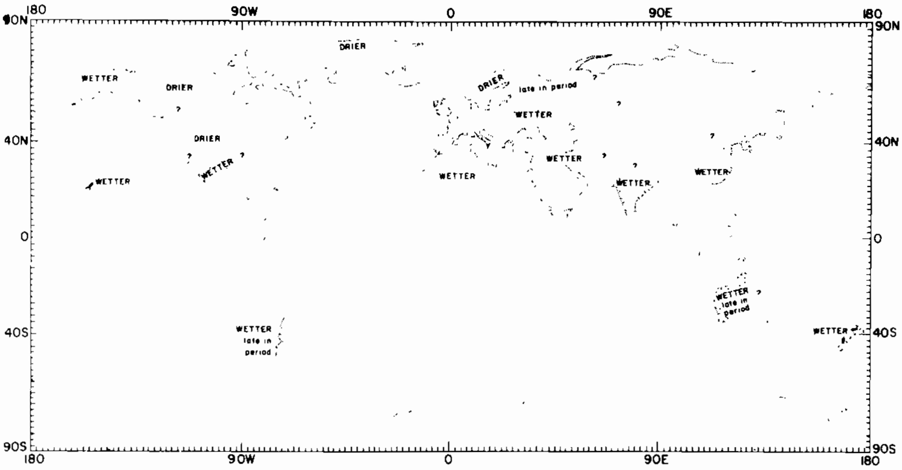

Figure 4. Schematic map of the rainfall distribution (mainly summer) during the Altithermal Period of 4000 to 8000 BP.

Source: Kellogg (1977b)

TELECONNECTIONS

The long-distance relationships between centers of action within the general atmospheric circulation are well-known phenomena. Similarly one might speak of teleconnections when analyzing the global interrelatedness of energy consumption, CO_2 increase, climatic change, shift in climatic zones, crop failures, increasing prices, food and economic crises, and famines.

The year 1972 may serve to demonstrate this point of global interdependence (Beltzner, 1976; Newell et al., 1976; Shapley, 1977). As indicated in Figure 5, in 1972 monsoonal failure and drought in Southeast Asia led to poor rice crops, while a very cold and relatively snowfree winter in the wheat producing USSR resulted in widespread crop failures. This forced the USSR to purchase 14×10^6 t, or 20% of all US grain export, which in turn increased wheat prices abroad from $60/t in early 1972 to $210/t in early 1974; to the dismay of the American consumer, it also raised the prices for bread on the home market.

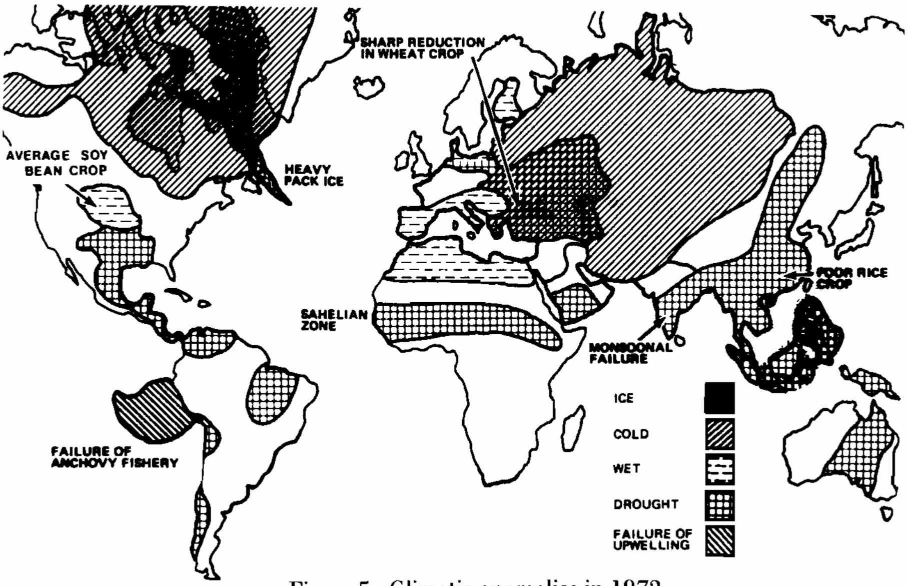

Figure 5. Climatic anomalies in 1972.

Source: McKay (1976)

Concomitantly there was a continuing drought in the Sahel zone, with an increased demand for food which could not be adequately supplied to the Sahel nor to the Indian disaster areas. On top of all this 1972 also experienced El Niño conditions off the Peruvian coast, ensuring failure of the anchovy fishery. The fishmeal normally used as chicken feed had to be replaced by soy beans, thereby increasing their demand and quadrupling their prices by June 1973. Despite good crops the US inland prices for food rose sharply.

The anomalous events of 1972 gave us a lesson and a clear message, namely that it would be prudent for society to make plans to cope with such climatic events even if they cannot be precisely predicted (Schneider with Mesirow, 1976; Schneider, 1976). Furthermore, predictions of average global conditions are not sufficient (Kellogg, 1977a, 1977b, 1977c, 1977d); it is essential to assess also the regional changes, especially in climatologically marginal regions.

CONCLUDING REMARKS AND RECOMMENDATIONS

This review has emphasized the potential consequences for agricultural productivity and world food supply of increasing atmospheric CO_2 levels and the resulting climate variations. Above all, increasing CO_2 raises the surface air temperature and changes the distribution of precipitation. The combined effects of these elements may already be adversely influencing food production in some regions. There is a high probability that the adverse effect will become more frequent and more widespread as the CO_2 concentration in the atmosphere continues to increase over the next decades.

In the face of the many recent warnings that Nature has supplied, there is still optimism among those who believe that technological manipulations can balance out the adverse effect of climatic variations. They maintain that, for example, the use of the combine (harvester), the breeding of more climate-resistant species, the use of fertilizers and pesticides, and the improvement of irrigation and drainage systems can effectively handle any potential climatic impacts. They point to the unusually high yields of the past 20 years, but are at odds to explain the crop disasters of recent years despite the constantly improving technology.

Most researchers agree that the relatively consistent and exceptionally high yield of agricultural products in North America from the mid-1950s to the early 1970s can probably be explained by a combination of improved technology and remarkably favorable climatic conditions. The subsequent return to a more variable climate has produced greater year-to-year fluctuations in agricultural output, resulting in worldwide food shortages and famines. The rapid decrease in world grain reserves is further evidence of the strong dependence of food production on the recent increase in climate variability. Despite advances in technology, food production has continued to suffer heavily in climatologically marginal areas and elsewhere.

The question is, what should be done about it? I should like to recommend that our efforts be directed toward the following:

- The prediction of adverse climatic conditions and their potential effects on food production, so that remedial actions can be taken in advance;

- The improvement of our understanding of the carbon cycle and climatological modeling, and of analogous climatic conditions in the past;

- The setting up of a world food reserve;

- The assessment of the impact of climate variations on other facets of society, such as industry, commerce, and recreation;

- The evaluation of the impact of climatic change in terms of economic losses, in order to accelerate remedial actions;

- The investigation of the relationship between the development of world energy demand and its impact on climate.

In conclusion I should like to emphasize that the CO_2 problem is intricately related to future energy demand. It is, therefore, the amount, and especially the type, of future energy use that will largely determine the anthropogenic contribution to climate change.

REFERENCES

Augustsson, T., and V. Ramanathan (1977), A Radiative-Convective Model Study of the CO_2 Climate Problem, *J. Atmos. Sci.*, 34, 448-451.

Bacastow, R.B. (1976), Modulation of Atmospheric CO_2 by the Southern Oscillation, *Nature*, 261, 116-118.

Bach, W. (1976a), Global Air Pollution and Climatic Change, *Revs. Geophys. Space Phys.*, 14, 429-474.

Bach, W. (1976b), Changes in the Composition of the Atmosphere and Their Impact Upon Climatic Variability - An Overview, *Bonner Meteorologische Abhandlungen*, Heft 24, Duemmler, Bonn.

Baes, C.F., H.E. Goeller, J.S. Olson, and R.M. Rotty (1976), *The Global Carbon Dioxide Problem*, Report ORNL-5194, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Beltzner, K., ed. (1976) *Living With Climatic Change*, Proceedings of a Conference, Toronto, Nov. 1975, American Meteorological Society, Boston.

Benci, J.F., et al. (1975), Effects of Hypothetical Climate Changes on Production and Yield of Corn, in *Impacts of Climatic Change on the Biosphere*, CIAP Monograph 5, pt. 2, Climatic Effects, 4-3 to 4-36.

Biggs, R.H., and J.F. Bartholic (1973), Agronomic Effects of Climatic Change, in A.J. Broderick, ed., *Proceedings of the Second Conference on CIAP*, US Department of Transportation, Washington, DC.

Bryson, R.A. (1973), *Climatic Modification by Air Pollution, II: The Sahelian Effect*, IES Report 9, Univ. of Wisconsin, Madison.

Bryson, R. (1974), A Perspective on Climatic Change, *Science*, 184, 753-760.

Bryson, R.A. (1975), *Cultural Sensitivity to Environmental Change, V: Some Cultural and Economic Consequences of Climatic Change*, IES Report 60, Univ. of Wisconsin, Madison.

Bryson, R.A., and G.J. Dittberner (1976), A Non-Equilibrium Model of Hemispheric Mean Surface Temperature, *J. Atmos. Sci.*, 33, 2094-2106.

Budyko, M.I. (1969), The Effect of Solar Radiation Variations on the Climate of the Earth, *Tellus*, 21, 611-619.

Budyko, M.I. (1977), On Present-Day Climatic Changes, *Tellus*, 29, 193-204.

Budyko, M.I., and K. Ya. Vinnikov (1977), Global Warming, in W. Stumm, ed., *Global Chemical Cycles and Their Alterations by Man*, Abakon Verlagsgesellschaft, Berlin.

Cess, R.D. (1976), Climate Change: An Appraisal of Atmospheric Feedback Mechanisms Employing Zonal Climatology, *J. Atmos. Sci.*, 33, 1831-1843.

Cowles, T.J., R.T. Barber, and O. Guillen (1977), Biological Consequences of the 1975 El Niño, *Science*, 195, 285-287.

Cushing, D.H. (1976), The Impact of Climatic Change on Fish Stocks in the North Atlantic, *Geographical J.*, 142, 217-227.

ERDA (1977), papers presented at the Workshop on Environmental Effects of Carbon Dioxide from Fossil Fuel Combustion, Miami, Florida, March 7-15.

Flohn, H. (1973), Geographische Aspekte der anthropogenen Klimamodifikation, *Hamburger Geogr. Studien*, Heft 28.

Flohn, H. (1975), Energie und Klima im 21. Jahrhundert, *Bild der Wissenschaft*, 11, 12, 82-88.

Flohn, H. (1977a), Großräumige Beeinflussung des Klimas durch menschlichen Eingriff? Historischer Überblick und künftige Aussichten, in C. König, ed., *Energie und Umwelt*, Vulkan Verlag, Essen.

Flohn, H. (1977b), Stehen wir vor einer Klima-Katastrophe?, *Umschau*, 17, 561-569.

Idyll, C.P. (1973), The Anchovy Crisis, *Sci. Am.*, 228, 22-29.

Ilesanmi, O.O. (1971), An Empirical Formulation of an ITD Rainfall Model for Tropics: A Case Study of Nigeria, *J. Appl. Meteorol.*, 10, 882-891.

Katz, R.W. (1977), Assessing the Impact of Climatic Change on Food Production, *Climatic Change*, 1, 85-96.

Keeling, C.D., and R.B. Bacastow (1977), *Impact of Industrial Gases on Climate*, draft paper.

Kellogg, W.W. (1977a), Emissions and the Climate, in C. König, ed., *Energie und Umwelt*, Vulkan Verlag, Essen.

Kellogg, W.W. (1977b), *Effects of Human Activities on Global Climate*, WMO Techn. Note No.156, WMO, Geneva.

Kellogg, W.W. (1977c), Global Influences of Mankind on the Climate, in J. Gribbin, ed., *Climate Change*, Cambridge Univ. Press, Cambridge (in press).

Kellogg, W.W. (1977d), *Global Precipitation Patterns During the Altithermal Period Compared with the Present* (in preparation).

Korff, H.C., and H. Flohn (1969), Zusammenhang zwischen dem Temperaturgefälle Äquator - Pol und den planetarischen Luftdruckgürteln, *Ann. Met., N.F.*, Heft 4, Deutsche Wetter Dienst, Offenbach am Main.

Kutzbach, J.E. (1975), Diagnostic Studies of Past Climates, in *The Physical Basis of Climate and Climate Modelling*, GARP Publications Series, No. 16, App. 1.3, WMO-ICSU, Geneva.

Lepper, R.A., E.C.A. Runge, and W.M. Walker (1974) Effect of Plant Available Stores Soil Moisture on Corn Yields, *Agron. J.*, 66, 723-733.

Lian, M.S., and R.D. Cess (1977), Energy Balance Climate Models: A Reappraisal of Ice-Albedo Feedback, *J. Atmos. Sci.*, 34, 1058-1062.

Lorenzen, C. (1975), Effects of Hypothetical Climatic Changes on Production and Yield of Marine Resources, in: *Impacts of Climatic Change on the Biosphere*, CIAP Monograph 5, pt. 2, Climatic Effects, 5-39 to 5-44.

Manabe, S., and R.T. Wetherald (1967), Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity, *J. Atmos. Sci.*, 24, 3, 241-259.

Manabe, S., and R.T. Wetherald (1975), The Effects of Doubling the CO_2 Concentration on the Climate of a General Circulation Model, *J. Atmos. Sci.*, 32, 1, 3-15

Manabe, S. (1971), Estimates of Future Change Due to the Increase of Carbon Dioxide Concentration in the Air, in W.H. Matthews, et al., eds., *Man's Impact on Climate*, MIT Press, Cambridge, Washington, DC.

National Academy of Sciences (1975), *Understanding Climatic Change*, Washington DC.

National Academy of Sciences (1977), *Energy and Climate*, Washington, DC.

Newell, R.E., M. Tanaka, and B. Misra (1976), Climate and Food Workshop: A Report, *Bull. Am. Meteorol. Soc.*, 57, 2, 192-198.

Newell, R.E., and B.C. Weare (1977), A Relationship Between Atmospheric CO_2 and Pacific Sea Surface Temperature, *Geophys. Res. Letters*, 4, 1, 1-2.

Niehaus, F. (1976), *A Non-Linear Eight Level Tandem Model to Calculate the Future CO_2 and C-14 Burden to the Atmosphere*, RM-76-35, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Ramanathan, V. (1974), A Simplified Stratospheric Radiative Transfer Model, in *Pre-prints, Second International Conference on Environmental Impact of Aerospace Operations in the High Atmosphere*, American Meteorological Society and American Institute of Aeronautics and Astronautics, San Diego, July.

Ramanathan, V. (1975), Greenhouse Effect Due to Chlorofluorocarbons: Climatic Implications, *Science*, 190, 50-52.

Ramanathan, V. (1977), Tropospheric-Stratospheric Feedback Mechanism: Stratospheric Warming and Its Effect on the Polar Energy Budget and the Tropospheric Circulation, *J. Atmos. Sci.*, 34, 439-447.

Ramirez, J.M., C.M. Sakamoto, and R.E. Jensen (1975), Wheat, in *Impacts of Climatic Change on the Biosphere*, CIAP Monograph 5, pt. 2, Climatic Effects, 4-37 to 4-90.

Rasool, S.I., and S.H. Schneider (1971), Atmospheric Carbon Dioxide and Aerosols: Effects of Large Increases on Global Climate, *Science*, 173, 138-141.

Schneider, S.H. (1975), On the Carbon Dioxide-Climate Confusion, *J. Atmos. Sci.*, 32, 11, 2060-2066.

Schneider, S.H. (1976), Is There Really a Food-Climate Crisis?, in R.J. Kopec, ed., *Atmospheric Quality and Climate Change*, Studies in Geogr., No. 9, Univ. of North Carolina, Chapel Hill, 1976.

Schneider, S.H., with L.E. Mesirow (1976), *The Genesis Strategy*, Plenum Press, New York, 1976.

Sellers, W.D. (1973), A New Global Climatic Model, *J. Appl. Meteorol.*, 12, 241-254.

Sellers, W.D. (1974), A Reassessment of the Effect of CO_2 Variations on a Simple Global Climatic Model, *J. Appl. Meteorol.*, 13, 831-833.

Shapley, D. (1977), Soviet Grain Harvests: CIA Study Pessimistic on Effects of Weather, *Science*, 195, 377-378.

Smagorinksy, J. (1963), General Circulation Experiments with the Primitive Equations, I. The Basic Experiment, *Monthly Weather Review*, 91, 99-164.

Smagorinsky, J. (1977), Modeling and Predictability, in *Energy and Climate*, National Academy of Sciences, Washington, DC.

Stansel, J., and R.E. Huke (1975), Rice, in *Impacts of Climatic Change on the Biosphere*, CIAP Monograph 5, pt. 2, Climatic Effects, 4-90 to 4-132.

Temkin, R.L., and F.M. Snell (1976), An Annual Zonally Averaged Hemispherical Climatic Model with Diffuse Cloudiness Feedback, *J. Atmos. Sci.*, 33, 1671-1685.

Thompson, L.M. (1975), Weather Variability, Climatic Change, and Grain Production, *Science*, 188, 535-541.

Wang, W.C., Y.L. Yung, A.A. Lacis, T. Mo, and J.E. Hansen (1976), Greenhouse Effects Due to Man-Made Perturbations of Trace Gases, *Science*, 194, 685-690.

Weare, B.C., and F.M. Snell (1974), A Diffuse Thin Cloud Atmospheric Structure as a Feedback Mechanism in Global Climatic Modeling, *J. Atmos. Sci.*, 31, 1725-1734.

Yung, Y.L., W.C. Wang, and A.A. Lacis (1976), Greenhouse Effect Due to Atmospheric Nitrous Oxide, *Geophys. Res. Letters*, 3, 619-621.

Zimen, K.E., P. Offermann, and G. Hartmann (1977), Source Functions of CO_2 and Future CO_2 Burden in the Atmosphere, *Z. Naturforsch.*, 32a, 1544-1554.

CRYOSPHERIC RESPONSES TO A GLOBAL TEMPERATURE INCREASE

R.G. Barry

INTRODUCTION

The term *cryosphere* embraces all terrestrial manifestations of ice. The likely nature of possible changes in the cryosphere that would follow a global warming induced by an increase in the atmospheric content of CO_2 is the topic of this paper.

Data on the extent of snow and ice are summarized in Table 1. At present, perennial ice covers 7% of the world's ocean and 11% of the land surface, primarily in high latitudes. Land ice has by far the largest volume, nearly all of which is in the Antarctic and Greenland ice sheets. The snow cover is about two thirds on land, one third on sea ice, and is about twice as extensive in the northern hemisphere as in the southern (Mellor, 1964). The snowline rises equatorward from sea level at approximately 65° S and 90° N, with the highest snowline elevations occurring in the subtropics of central Asia and Bolivia-Peru above 6000 m as a result of dryness and high solar radiation intensities (Hermes, 1965).

CRYOSPHERIC SENSITIVITY

The response of snow and ice covers to climatic factors varies greatly in terms of time scale. Typical residence times of solid precipitation in the various reservoirs are approximately: 10^{-1} to 1 year for seasonal snow cover, 1 to 10 years for sea ice, and 10^3 to 10^5 years for ground ice and ice sheets. In each case certain phases of the seasonal regime are particularly critical for the occurrence of snow or ice and their response to climatic variations. Of primary importance are the times of seasonal temperature transition across the 0°C threshold (or -1.8°C in the case of sea water). Other threshold effects, which influence radiative and turbulent energy exchanges, arise as a result of the large albedo differences between snow cover (about 0.80) and snow-free ground (0.10 - 0.25), or between ice (0.65) and water (0.05 - 0.10).

Snow cover maps prepared by Dickson and Posey (1967) indicate that, in all months, extensive areas of North America and Eurasia have a probability of snow cover (exceeding 1 inch) ranging from 0 to 50%. This wide range is apparent in the large year-to-year variability in northern hemisphere snow cover, especially in Eurasia (Wiesnet and Matson, 1976). Global warming could eliminate the occurrence of snow covers in the broad areas of low frequency depicted by Dickson and Posey.

Table 1. Components of the cryosphere

After: Untersteiner (1975).

	Area (10^6 km^2)	Volume (10^6 km^3 water)
Land ice:	16	31
Antarctica	13.9	28
Greenland	1.8	2.7
Ground ice (excl. Antarctic)		
contin. permafrost	7.5	$<$ 2**
discontin. permafrost	17.3	$<$ .5**
Sea ice:		
Antarcitic-Sep.	20	.05
March	2.5	
Arctic - Sep.	8.4	
March	15	
Snow cover*-March (North America, Eurasia)	38	

* Data from Wiesnet and Matson (1976).
** Upper limits assume ice rather than frozen rock comprises this volume.

Total snow, land ice, sea ice (from Kukla and Kukla, 1974):

	Area (10^6 km^2)
Jan. - N. hemisphere	58
S. hemisphere	18
July - N. hemisphere	14
S. hemisphere	25
Global mean annual	59

Sea ice in the southern hemisphere displays a wide seasonal variation in extent (Mellor, 1964), as a result of the well-mixed structure of the waters on the shelf around Antarctica. In contrast, in the largely closed Arctic Ocean, a shallow layer of low salinity, maintained by continental runoff and ice melt in summer, forms a pronounced pycnocline at 25 to 50 m depth. Hence freezing occurs readily and there is rather limited summer breakup (Aagard and Coachman, 1975).

In the case of ground ice or ice sheets, the long residence times greatly reduce their sensitivity to any climatic change.

Nevertheless, change does occur on long time scales, as illustrated by the geological and oceanographic records of glacial history. Land ice increased to cover approximately 25% at the Last Glacial Maximum (18,000 years ago).

CRYOSPHERIC RESPONSES TO A CO_2-INDUCED WARMING

It is assumed for the purposes of this discussion that an eventual doubling of atmospheric CO_2 content would result in an average global warming of 1.5°C, with a rise of 5 to 6°C in polar latitudes (Manabe and Wetherald, 1975). The seasonal characteristics of such a change are not yet certain, although the increases would probably be greatest in winter. There is a high likelihood that the time scale of a CO_2 doubling will be 50 to 100 years. Since the CO_2-temperature relationship appears to be logarithmic, a second CO_2 doubling could cause a general 3°C rise (Kellogg, 1977). Possible effects of such temperature increases near the surface are now considered for the major components of the cryosphere.

Snow

The effects of a warming on snowfall and snowcover will differ according to latitude. In low and middle latitudes, where the occurrence of snow rather than rain is frequently marginal, warming will decrease the frequency of snowfall and the duration of snowcover on the ground. Manley (1969) shows, for example, that the period with snow lying in Britain was a minimum in the 1920s and 1930s, corresponding to the period of maximum warmth. Investigations in the equatorial mountains of New Guinea show that the rising snowline associated with an *inferred* warming of 0.6°C over the last century has caused a retreat of the glaciers on Mount Jaya (Carstenz) and disappearance of several small ice bodies on other mountains in Irian Jaya (western New Guinea) (Allison and Kruss, 1977).

In high latitudes, where snowfall is limited by the low vapor content of the air, due to low temperatures, warmer winters are generally more snowy. At Barrow, Alaska, for example, for the 30 winters 1946 - 1976 there is a -.57 correlation between freezing degree-days and snowfall during December - February. In Labrador-Ungava and Keewatin, snowy winter months tend to be associated with an average temperature departure of +1° to 3°C (Brinkmann and Barry, 1972).

While increased snowfall will provide a deeper snowpack, the duration of snowcover is likely to be only marginally affected, at least in the Arctic. Weller and Holmgren (1974) show that the snowmelt period at Barrow lasts about 5 to 7 days and melt requires only 2 to 3 $kJcm^{-2}$.

Sea Ice

Any changes in sea ice extent could have major climatic significance. Estimates of the possible magnitudes of changes in ice thickness and extent can be derived from empirical and modeling studies.

For the Antarctic, Budd (1975a) calculates that 1°C change in annual mean temperature corresponds to a 70 day variation in the duration of sea ice and a 2.5° latitude variation in maximum extent at the Antarctic Circle. It is possible that non-linearities would act to augment the simple temperature effect. For example, retreat of the Antarctic ice two weeks earlier than usual would cause a 7% increase in ocean heating (Fletcher, 1969), which could amplify the initial effect, although Budd's results indicate that the feedback may *not* be of the unstable type.

The Arctic pack ice has been extensively studied. Observational evidence suggests that snow cover persisting on the Arctic pack ice through early summer, until the solar radiation has passed its maximum and incipient melt has resulted in an increase in stratus cloud cover, can considerably delay the summer melt. Chernigovskiy (1967) shows that the net radiation available to a bare ice surface in the Arctic is five times that of ice with an only partially-melted snow cover. Nevertheless, the model of Maykut and Untersteiner (1971) demonstrates that the thickness of sea ice remains essentially unchanged for snow covers of between 0 and 70 cm. Although summer ablation losses on bare ice are large, the ice simultaneously grows by bottom accretion. The ice only thickens significantly in the model for snow depths in excess of 100 cm.

Simple estimates of changes in ice thickness due to warming can be based on empirical relationships to freezing degree-days (Bilello, 1961). Under present winter conditions at Barrow, Alaska, with a freezing degree-day total of 4833°C, Bilello's equation gives an ice thickness of 247 cm. Assuming an ice growth period of 270 days, a 5°C rise would lead to a reduction of 15%, and a 10°C rise a reduction of 34%, in ice thickness (J.C. Rogers, personal communication 1977).

Analogous empirical relationships have been developed for late summer retreat of the pack ice margin off Barrow by J.C. Rogers (Figure 1). There is a correlation of 0.81 between distance to the limit of 4/8 ice concentration north of Point Barrow on 15 September and the thawing degree-day total (see Barry, 1977). The mean distance for 1953 - 1975 was 155 km. A rise in mean summer temperature of 5°C would increase this to 600 km and a rise of 10°C to 1000 km. A 600 km retreat around the Arctic Basin would leave a core of pack ice only about 1500 km in diameter. Considerable uncertainty exists over the changes needed to remove the pack and maintain open water. Budyko (1966) estimated that a +4°C summer temperature anomaly

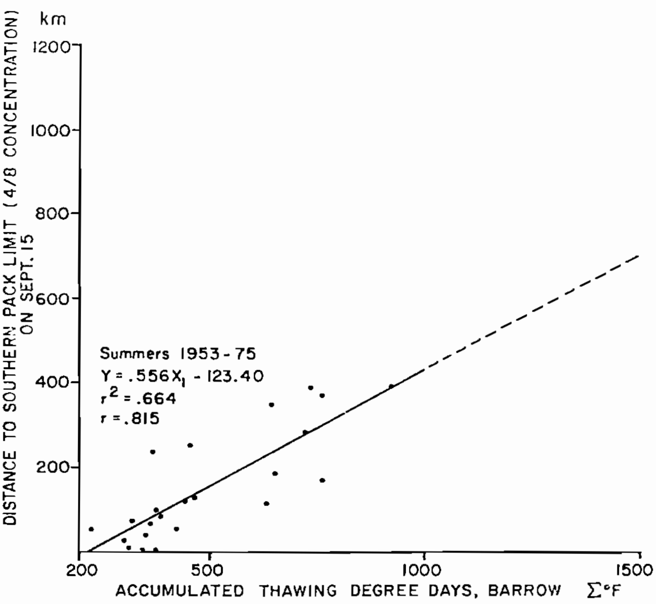

Figure 1. Distance to 4/8 ice concentration on September 15 off Point Barrow versus accumulated thawing degree days, 1953-1975. Projections illustrate possible implications of higher summer temperatures such as might occur with increasing CO_2 levels, assuming that a linear relationship obtains.

Source: Rogers (1977)

would remove the pack within four years with only winter ice occurring thereafter. Nevertheless, there is good evidence from sedimentary records in the Arctic Basin that the pack ice cover has been present for at least the last 700,000 years (Clark, 1971) despite worldwide glacial - interglacial fluctuations. Indications of rather more open conditions come from the distribution of pumice and driftwood in the Canadian Arctic Archipelago during the Thermal Maximum (Hypsithermal) about 5000 BP (Blake, 1970).

Several model experiments have been performed to assess the possible atmospheric effects of an ice-free Arctic Ocean (Donn and Shaw, 1966; MacCracken, 1970; Fletcher et al., 1973; Newson, 1973; Warshaw and Rapp, 1973). The results all show a major warming of the lower troposphere over the Arctic Basin and a cooling over continental areas in middle latitudes, but these simulations do not take account of oceanic advection effects. Empirical estimates by Drozdov (cited by Lamb, 1971) based on +5°C temperature anomalies in the Arctic, suggest large precipitation increases over most of the Arctic and in low latitudes, but decreases over middle latitude continents, in both warm and cold seasons of the year.

Permafrost

Quantitative assessments of the effects of a warming on temperatures in permanently-frozen ground are provided by Lachenbruch et al. (1966). With an equilibrium profile of $\partial T/\partial z$ for the present surface temperature of -5^0C, 25% of the present 400 m thickness at Cape Thompson, Alaska, is unstable (Figure 2). A warming of 2^0C over 75 to 100 years is inferred. However, Lachenbruch et al. note that an imbalance of 335 $Jcm^{-2}yr^{-1}$ (80 cal $cm^{-2}yr^{-1}$) over 60 years would melt only about 0.6 m of ice at the surface.

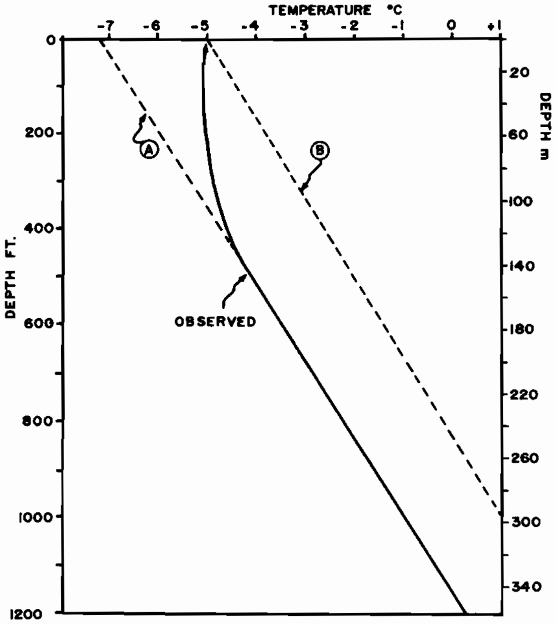

Figure 2. Ground temperature profile at Cape Thompson, Alaska. (A) shows the hypothetical original profile prior to the recent warming; (B) shows the equilibrium profile for the present conditions.
After: Lachenbruch et al. (1966)

A warming trend would be most significant, in terms of effects on soil moisture and vegetation, in the areas of discontinuous permafrost along the southern margins. Thie (1974) finds general melting and retreat of the permafrost over the last 120 years in Manitoba, for example.

Ice Sheets

The effects of a warming on large ice sheets are likely to be complex. As outlined above, warming may augment precipitation in polar latitudes giving more accumulation but, if the net effect were to cause a negative mass balance, world sea levels would begin to rise. Mercer (1968) has suggested that higher summer temperatures during the Last Interglacial (125,000 BP) caused destabilization and disintegration of most of the West Antarctic ice sheet and a 5 to 6 m rise in sea level. The temperature increase during this period was 1°C in the western North Atlantic (Sancetta et al., 1972), but up to 6° to 7°C for a mean annual temperature in the USSR and central Siberia according to pollen evidence (Frenzel, 1973; p. 123). Mercer (1978) now sees the warming asociated with atmospheric CO_2 increase as a possible cause of the deglaciation of West Antarctica in the future. Hughes (1975) has examined possible mechanisms for disintegration in West Antarctica. He suggests that instability of ice streams entering the Ross Sea initiated an event of this type prior to 10,000 BP. Disintegration could be triggered either by the warming itself, by interaction of the rising sea level with the grounded ice, or by internal ice processes. Hollin (1970) postulates that such major ice sheet "surges" would lead to 10 to 30 m rises of sea level in less than 100 years.

The rate of propagation of a surface warming to the base of a 2000 m thick ice sheet has been calculated using a thermodynamic model by M.D. Jenssen (personal communication 1977). In response to a 10°C surface warming, the basal temperature rises 0.4°C after 5000 years and 5.9°C after 50,000 years (Figure 3). This suggests that any direct response by the ice to a climatic warming should be considerably lagged.

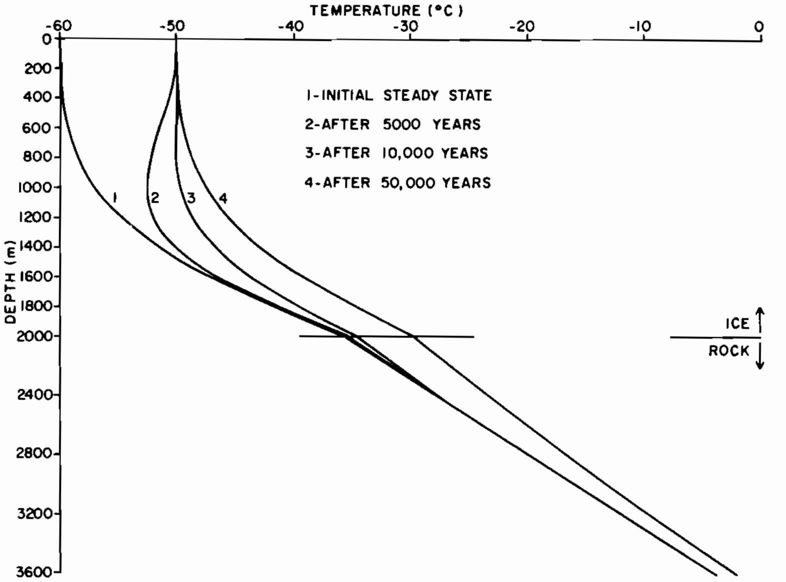

Figure 3. Temperature profiles in ice computed by a thermodynamic model. The assumed conditions are $0.2 m\ yr^{-1}$ of accumulation, frictional heating $0.01°C\ m^{-1}$ at the base, geothermal heat flux $0.02°C\ m^{-1}$; thermal diffusivities are $42 m^2\ yr^{-1}$ for ice, $32 m^2\ yr^{-1}$ for rock.

Source: Jenssen (1977)

Mountain Glaciers

Observational evidence in many countries shows substantial glacier retreat since the Little Ice Age which culminated ca. 1750. Hoinkes (1968) shows that in the Alps, general glacier retreat since the 1920s has been mainly due to a longer ablation season. Results from individual glaciers are often unreliable since surge behavior in glaciers does not appear to be climatically induced (Budd, 1975b) although decoupling of the ice from its bed by basal meltwater may be a primary causal factor (Weertman, 1969). Indeed, the magnitude of surges may be inversely related to the general temperature level. Denton and Karlên (1977) report that surges of glaciers in the St. Elias Mountains have been successively smaller in this century than in the last, matching the general glacier retreat.

Conclusions and Outstanding Problems

In summary, based on our present knowledge, it appears that warming effects would be negligible on the century time-scale for major ice sheets and ground ice. Changes in seasonal snowfall in high latitude or in Arctic pack ice may also be minimal for an initial doubling of CO_2. Any increase in winter snowfall would probably be offset by increased summer melt. For the pack ice, it is possible that greater melt, by leading to more pools and open water, would increase the stratus cover and reduce the solar radiation input. The critical factor here would be an increase in meridional advection in the atmosphere and the ocean. In both cases, however, negative feedbacks are a possibility for a limited warming.

In several areas our data or understanding of climate-cryosphere interactions are at present inadequate to evaluate the effects of increased temperature. Major deficiencies exist in terms of data on snow cover extent and depth. Satellite records of snow cover are available only since 1967 and it is not yet possible to assess the typical year-to-year variability (Kukla and Kukla, 1974; Wiesnet and Matson, 1976). The age structure, thickness, and mass balance of the Arctic Ocean ice are still poorly known (Koerner, 1973). There are few published data on the thickness of permafrost or on changes in ground ice temperature and thickness during this century. The decay and disappearance of areas of ground ice is perhaps less known than the occurrence of its formation in new sediments. Likewise, the minimum extent of land ice during previous warmer episodes is generally much less well documented than periods of maximum extent. The long-term mass balance of the major ice sheets is also less certainly known than that of many smaller glacier systems.

Many research problems remain. A major question concerns the effects of a temperature rise on the melting of glaciers and ice sheets, and therefore on world sea level. Sea levels rose about 5 to 6 m during the Last Interglacial (120,000 BP) and fell to about 120 ± 40 m during the Last Glacial Maximum (20,000 - 18,000 BP). Since then, sea level has risen to its present position, although there is dispute as to the precise character of this trend. Moreover, the eustatic change related to changes in ice volume is greatly complicated by isostatic responses to ice unloading and by meltwater loading of the ocean floor. Recent calculations (Farrell and Clark, 1976) indicate that sea level changes during the last 5000 years (since the Hypsithermal) can be explained without invoking eustatic effects.

REFERENCES

Aagard, K., and L.K. Coachman (1975), Toward an Ice-Free Arctic Ocean, *EOS*, 56, 484-486.

Allison, I., and P. Kruss (1977), Estimation of Recent Climate Change in Irian Jaya by Numerical Modelling of Its Tropical Glaciers, *Arctic and Alpine Research*, 9, 49-60.

Barry, R.G. (1977), Study of Climatic Effects on Fast Ice Extent and Its Seasonal Decay Along the Beaufort-Chukchi Coasts, in *Environmental Assessment of the Alaskan Continental Shelf*, Annual Reports of Principal Investigators for the Year Ending March 1977, Vol. XIV, Transport, U.S. Dept. of Commerce, NOAA, and U.S. Dept. of Interior, BLM, Boulder, Colo.

Bilello, M. (1961), Formation, Growth and Decay of Sea Ice in the Canadian Arctic Archipelago, *Arctic*, 14, 2-25.

Blake, W., Jr. (1970), Studies in the Glacial History of Arctic Canada, I. Pumice, Radiocarbon Dates, and Differential Postglacial Uplift in Eastern Queen Elizabeth Islands, *Can. J. Earth Sci.*, 7, 634-664.

Brinkmann, W.A.R., and R.G. Barry (1972), Palaeoclimatological Aspects of Synoptic Climatology of Keewatin, Northwest Territories, Canada, *Palaeogeogr., Palaeoclimatol., Palaeocol.*, 11, 77-91.

Budd, W.F. (1975a), Antarctic Sea-Ice Variations from Satellite Sensing in Relation to Climate, *Journal of Glaciology*, 15, 73, 417-427.

Budd, W.F. (1975b), A First Simple Model for Periodically Self-Surging Glaciers, *Journal of Glaciology*, 14, 70, 3-22.

Budyko, M.I. (1966), Polar Ice and Climate, in J.O. Fletcher, ed., *Proceedings of the Symposium on the Arctic Heat Budget and Atmospheric Circulation*, RM-5233-NSF, Rand Corp., Santa Monica, Cal., 3-22.

Chernigovskiy, N.T. (1967), Radiation Regime of the Central Arctic Basin, *WMO Tech. Note 87*, Geneva 107-115.

Clark, D.L. (1971), The Arctic Ocean Ice Cover and Its Late Cenozoic History, *Bull. Amer. Geol. Soc.*, 82, 3313-3323.

Denton, G.H., and W. Karlén (1977), Holocene Glacial and Tree-Line Variations in the White River Valley and Skolai Pass, Alaska and Yukon Territory, *Quat. Res.*, 7, 63-111.

Dickson, R.R., and J. Posey (1967), Maps of Snow-Cover Probability for the Northern Hemisphere, *Mon. Weather Rev.*, 95, 347-352.

Donn, W.L., and D.M. Shaw (1966), The Heat Budget of an Ice-Free and an Ice-Covered Arctic Ocean, *J. Geophys. Res.*, 71, 1087-1093.

Farrell, W.E., and J.A. Clark (1976), On Postglacial Sea Level, *Geophy. J.R. Astron. Soc.*, 46, 647-667.

Fletcher, J.O. (1969), *Ice Extent on the Southern Ocean and Its Relation to World Climate*, RM-5793, Rand Corp., Santa Monica., Cal.

Fletcher, J.O., Y. Mintz, A. Arakawa, and T. Fox (1973), Numerical Simulation of the Influence of Arctic Sea Ice on Climate, *WMO Tech. Note 129*, Geneva, 181-218.

Frenzel, B. (1973), *Climatic Fluctuations of the Ice Age*, Case Western Reserve Univ. Press, Cleveland, Ohio.

Hermes, K. (1965), Der Verlauf der Schneegrenze, *Geogr. Taschenbuch 1964*, 5, 58-71.

Hoinkes, H.C. (1968), Glacier Variations and Weather, *Journal of Glaciology*, 7, 3-19.

Hollin, J.T. (1970), Interglacial Climates and Antarctic Ice Surges, *Quat. Res.*, 2, 401-408.

Hughes, T. (1975), The West Antarctic Ice Sheet: Instability, Disintegration and Initiation of Ice Ages, *Rev. Geophys. Space Phys.*, 13, 502-526.

Jenssen, M.D. (1977), personal communication.

Kellogg, W.W. (1977), Effects of Human Activities on Global Climate, Part I, *WMO Bull.*, 26, 229-240; Part II, *WMO Bull.*, 27, 1 (1978), 3-10.

Koerner, R.M. (1973), The Mass Balance of the Sea Ice of the Arctic Ocean, *Journal of Glaciology*, 12, 65, 173-185.

Kukla, G.J., and H.J. Kukla (1974), Increased Surface Albedo in the Northern Hemisphere, *Science*, 183, 709-714.

Lachenbruch, A.H., G.W. Greene, and B.V. Marshall (1966), Permafrost and Geothermal Regimes, in N.J. Wilimovsky and J.N. Wolfe, eds., *Environment of the Cape Thompson Region, Alaska*, U.S. Atomic Energy Commission, Washington, DC, 149-163.

Lamb, H.H. (1971), Climate-Engineering Schemes to Meet a Climate Emergency, *Earth-Sci. Rev.*, 7, 87-95.

MacCracken, M.C. (1970), *Tests of Ice Age Theories Using a Zonal Atmospheric Model*, UCRL-72803, Lawrence Radiation Lab., Livermore, Cal.

Manabe, S., and R.T. Wetherald (1975), The Effect of Doubling the CO_2 Concentration on the Climate of a General Circulation Model, *J. Atmos. Sci.*, 32, 3-15.

Manley, G. (1969), Snowfall in Britain Over the Past 300 Years, *Weather*, 24, 428-437.

Maykut, G.A., and N. Untersteiner (1971), Some Results from a Time Dependent Thermodynamic Model of Sea Ice, *J. Geophys. Res.*, 76, 1550-1575.

Mellor, M. (1964), Snow and Ice on the Earth's Surface, *Cold Regions Science and Engineering Monogr.*, II-C-1, U.S. Army CRREL, Hanover, N.J.

Mercer, J.H. (1968), Antarctic Ice and Sangamon Sea Level, *Int. Assoc. Sci. Hydrol.*, 79, 217-225.

Mercer, J.H. (1978), West Antarctic Ice Sheet and CO_2 Greenhouse Effect: A Threat of Disaster, *Nature*, 271, 5643, 321-325.

Newson, R.L. (1973), Response of a General Circulation Model of the Atmosphere to Removal of the Arctic Ice Cap, *Nature*, 241, 39-40.

Rogers, J.C. (1977), personal communication.

Sancetta, C., J. Imbrie, N.G. Kipp, A. McIntyre, and W.F. Ruddiman (1972), Climate Record in the North Atlantic Deep-Sea Core V 23-82: Comparison of the Last and Present Interglacials Based on Quantitative Time Series, *Quat. Res.*, 2, 363-367.

Thie, J. (1974), Distribution and Thawing of Permafrost in the Southern Part of the Discontinuous Permafrost Zone in Manitoba, *Arctic*, 27, 189-200.

Untersteiner, N. (1975), Sea Ice and Ice Sheets and Their Role in Climatic Variations, in *The Physical Basis of Climate and Climatic Modelling*, GARP Publ. Ser. 16, World Meteorological Organization, Geneva, 206-226.

Warshaw, M., and R.A. Rapp (1973), An Experiment on the Sensitivity of a Global Circulation Model, *J. Appl. Meteorol.*, 12, 43-49.

Weertman, J. (1969), Water Lubrication Mechanism of Glacier Surges, *Can. J. Earth Sci.*, 6, 929-942.

Weller, G., and B. Holmgren (1974), The Microclimates of the Arctic Tundra, *J. Appl. Meteorol.*, 13, 854-862.

Wiesnet, D.R., and M. Matson (1976), A Possible Forecasting Technique for Winter Snow Cover in the Northern Hemisphere and Eurasia, *Mon. Weather Rev.*, 104, 828-835.

THE EFFECTS OF DOUBLING THE CO_2 CONCENTRATION ON RADIATIVE-CONVECTIVE EQUILIBRIUM

P.R. Rowntree and J. Walker

Abstract

A single column radiative-convective equilibrium model has been used to investigate the dependence of the effects of doubling CO_2 on the assumptions made for the temperature and humidity structure. It is found that, relative to a convective parameterization which generates a moist adiabatic lapse rate, a convective adjustment to a fixed lapse rate exaggerates the effect of doubling CO_2 for surface temperatures above about 280 K, but makes little difference at lower temperatures. The results are quite sensitive to the assumptions made for relative humidity, indicating the need for a realistic parameterization of convection in CO_2 experiments.

INTRODUCTION

Because of the considerable expense of mounting satisfactory general circulation model (GCM) experiments to assess the effects on climate of an increase in CO_2, single column models have been used by several workers in the field (e.g., Manabe and Wetherald 1967, Schneider 1975, Augustsson and Ramanathan 1977). Such models have obvious limitations in that they omit possibly important feedback effects such as those due to ice/snow and cloud. Moreover they can treat only a globally averaged radiative equilibrium and so can give no indication of any geographical variations in the effects. Nevertheless such models have a useful role to play in assessing the sensitivity of the results to details of the models such as the radiative treatment and assumptions concerning cloud amount and altitude and relative humidity (e.g., Augustsson and Ramanathan 1977).

The present paper examines the sensitivity of results on the effects on temperature of doubling CO_2 in a radiative-convective equilibrium model to variations in the assumptions concerning temperature structure and relative humidity. Previous experiments with such models have used a convective adjustment (CA) to a fixed lapse rate (typically $\partial T/\partial z = -6.5K\ km^{-1}$) whenever the model lapse rate exceeded this value. Some of the experiments reported here use the same assumption while others use a penetrative convection (PC) scheme developed for a GCM.

The equilibrium state generated by the scheme is close to the moist adiabatic lapse rate so that $(-\partial T/\partial z)$ decreases as temperature T increases due to the associated increase in saturation vapor pressure. Consequently, a rise in surface temperature due to a doubling of CO_2 is associated with a larger rise in the middle and upper troposphere temperatures. It is not clear whether this will increase the response because the water vapor feedback is increased, or reduce it because of the increase in upward radiation at the top of the atmosphere due to the warmer upper troposphere. The experiments reported here are mostly designed to answer this question.

The results should also provide a useful comparison with the GCM results with idealized geography reported by Manabe and Wetherald (1975). The moist CA they used also tends to adjust temperatures toward the moist adiabatic lapse rate, and produces a warming of about 2 K near the surface equatorward of 45^0 latitude with an upper tropospheric warming of over 3 K. If the effects of the greater upper warming are important, then it could be misleading to compare their results with those from a single column model which assumes a fixed lapse rate.

Manabe and Wetherald (1967) pointed out that an assumption of constant relative humidity was more realistic than one of constant absolute humidity and gave a considerable increase in the effect of doubling CO_2 due to the water vapor feedback effect. Cess (1976) has suggested that relative humidity tends to increase slightly with temperature, and Augustsson and Ramanathan (1977) have shown that the dependence suggested by Cess increased the response in their model from 1.98 K to 2.61 K. The model used here generates a relative humidity profile; the radiation scheme can use this profile or it can use fixed absolute or relative humidities. Experiments with these different assumptions are reported here to facilitate further assessments of the roles of water vapor feedback and variations of relative humidity.

THE MODEL

Outline

The model was derived from the U.K. Meteorological Office eleven-layer global GCM by eliminating the dynamics and leaving only the boundary layer parameterization of heat and moisture fluxes and the convective and radiative parameterizations. The surface is treated as moist land. The boundaries between the model layers are shown in Table 1.

Table 1[†]

Layer		11	10	9	8	7	6	5	4	3	2	1	
Boundaries (σ)	1.0		.975	.9	.79	.65	.51	.37	.27	.195	.125	.06	0

[†] $\sigma = p/p_*$ where p is pressure, p_* surface pressure.

Diurnal variation of zenith angle z was omitted but the daytime mean zenith angle cosine was used in pathlength calculations. The model was integrated to an equilibrium state defined by changes in upward longwave flux at the surface of less than 0.01 W m^{-2} over a 50-day period with a comparably small change in the upward flux at the top of the atmosphere. This typically required around 500 days integration starting with an atmosphere typical of the tropics.

Boundary Layer Parameterization

Although the boundary layer scheme can include mixing of temperature and moisture throughout the bottom three model layers, this was eliminated in the experiments discussed here; thus the scheme reduces to a parameterization of surface fluxes in terms of the temperature and humidity of the surface and the bottom model layer. With a moist surface, most of the surface radiative excess is transferred to the atmosphere in the form of latent heat with this scheme except at low temperatures. Details of the formulation are in Saker (1975) and are irrelevant in the present context.

Convective Parameterization

The convective scheme is based on the concept of the parcel theory, with a simple treatment of entrainment, detrainment, and evaporation of precipitation. We imagine an ensemble of buoyant plumes of different radii, temperatures, and humidities. Their characteristics will determine their entrainment rates and hence their upward extent. The less buoyant plumes will terminate and detrain through the lack of buoyancy at a lower level than more buoyant plumes which may, in favorable conditions, reach the heights accessible to an undilute parcel. Rather than attempt to treat plumes of different characteristics separately, we have considered the mean characteristics of the ensemble. These are modified by an entrainment rate which decreases with height as the mean plume radius is assumed to increase, and by a detrainment of air from less buoyant plumes as they die; since this detrainment is at environment buoyancy it enhances the positive mean buoyancy of the ensemble. The environment is modified by the removal of entrained air, detrainment of moist air, the compensating subsidence, and the evaporation of precipitation.

This scheme tends to generate a moist adiabatic lapse rate in the troposphere. This is similar to the real atmosphere in regions such as the warmer parts of the tropics where the heat balance is dominated by the radiative cooling and convective latent heat release; i.e. horizontal energy flux convergence either by horizontal eddies or by vertical circulations is not an important factor. Elsewhere the observed lapse rate is usually less steep than the moist adiabatic and the effects of the decrease of lapse rate with increasing temperature on the response to doubling CO_2 may be absent. However, in the tropics the similarity of the temperature structure in different regions suggests that even where adiabatic warming is important, the temperature structure may be forced to be similar to that in regions of deep convection.

Radiative Parameterization

The radiation scheme is similar in approach to that described by Manabe and Strickler (1964). It allows for four clouds--low, medium, and high layer clouds and a convective cloud. The clouds can be at any height and fill any number of model layers. Cloud overlap is assumed to be random. Solar radiation is absorbed and scattered by atmospheric gases and clouds and by the earth's surface. The absorptions by ozone, CO_2, and water vapor are determined as a function of the effective optical thickness. No temperature dependence is included and both ozone and CO_2 absorptivities are assumed independent of pressure for solar wavelengths. The solar absorptivity curves for ozone, CO_2, and water vapor have been taken from Manabe and Möller (1961) and the gases are assumed to absorb radiation independently of one another.

The treatment of infrared radiation is based on the emissivity or "grey body" approximation in which the atmosphere is assumed to absorb equally at every frequency so that it is possible to define transmission functions for the whole spectrum once and for all by integrating over the line structure of the atmospheric absorption spectrum. The absorption bands which contribute most to the longwave radiation are the 6.3 μm band and the rotation band of water vapor, the 15 μm band of CO_2, and the 9.6 μm band of ozone. The weak absorption which fills the atmospheric window (8-13 μm) and is attributed to the water vapor continuum is treated as a separate term and included in the scheme as a function not only of effective optical thickness but also of the pathlength weighted mean water vapor pressure. Band overlap is allowed for by dividing the infrared spectrum into five regions as shown in Table 2. The emissivities and absorptivities of the individual gases for these spectral divisions were calculated using a scheme based upon the Mayer-Goody random band model (Hunt and Mattingly, 1976). Values of $\sum S_i$ and $\sum\sqrt{(S_i\alpha_i)}$ (where S_i = line strength,

Table 2. Division of the longwave spectrum demonstrating the regions of overlap.

Spectral region (cm^{-1})	0-500, 1200-2850	500-700	700-800	800-900, 1100-1200	900-1100
Water vapor bands	X	X	X	X	X
Water vapor continuum			X	X	X
CO_2		X	X		
Ozone					X
X - Gas included in this region					

α_i = half width) were calculated for small spectral intervals from the spectroscopic data of McClatchey et al. (1973) and used in the random band model to give values of transmissivity

$$\int_{\nu_1}^{\nu_2} \tau_\nu(u,T)B_\nu(T)d\nu \Big/ B(T)$$

and absorptivity

$$\int_{\nu_1}^{\nu_2} (1 - \tau_\nu(u,T))\frac{dB_\nu(T)}{dT}d\nu \Big/ \frac{dB(T)}{dT}$$

over these intervals as functions of optical depth (u) where τ_ν is the transmission function at frequency ν and B the Planck function. For CO_2, for example, the spectral region 500 to 800 cm^{-1} was divided into six intervals of 50 cm^{-1} and the total transmissivities and absorptivities obtained by summing the individual values. The temperature variation of the spectral line data and the Planck function were included in the random band model and transmission functions calculated at intervals of 30 K from 203 K to 323 K. However, in view of the computational expense of including this temperature variation in the radiation scheme, values of transmissivity and absorptivity for 263 K were used as representative of the whole atmosphere. The results of Rodgers and Walshaw (1966) show that the error in neglecting temperature dependence is small although a recent paper by Augustsson and Ramanathan (1977) suggests that it may be important in assessing the effects of increasing CO_2. The pressure dependence of the transmission of CO_2 and water vapor is included by defining an effective optical depth (u_r) by

$$u_r = \int_{u(z)}^{u(z')} \left(\frac{p}{p_o}\right)^{0.9} du$$

where p = pressure, p_o = standard pressure. The surface and clouds are treated as black bodies with the exception of high cloud which is given an emissivity of 0.5.

It should be noted that the scheme neglects the CO_2 bands near 7.6 and 10 μm, which contribute about 0.12 K to the temperature effect of doubling CO_2 in calculations by Augustsson and Ramanathan (1977).

EXPERIMENTS ON THE EFFECTS OF THE LAPSE RATE ASSUMPTION

With Fixed Absolute Humidity

The effect of doubling CO_2 on surface temperature was found by Manabe and Wetherald (1967) to be smaller with fixed absolute humidity than with fixed relative humidity. Our experiments show little temperature dependence for this result. For cos z = 0.225 the PC gives 0.78 K, and the CA gives 1.29 K. The latter result is very close to Manabe and Wetherald's whether with or without cloud. (We used zero cloud.) The much smaller response with PC is due to the greater increase in upper than in lower tropospheric temperatures with this scheme and the weaker opposite effect with the CA.

With Fixed Relative Humidity (no cloud)

With fixed relative humidity, a positive feedback is to be expected from water vapor. The model was run with the relative humidities used by Manabe and Wetherald (1976), i.e. RH = 0.77 $(\sigma - .02)/0.98$, firstly using a CA scheme with two different fixed lapse rates (5 and 6.5 K/km) and then using the PC scheme. Varying the fixed lapse rate affected the results little, but the temperature dependent lapse rates of the PC scheme gave quite different results as shown for a range of surface temperatures (T_*) in Table 3.[†]

[†] It should be explained that these results were obtained by graphical interpolation from results calculated generally at cos z intervals of .0125 (T_* intervals of order 6 K). Because of roundoff errors in the temperature calculations, the radiative fluxes at the top of the atmosphere were out of balance by up to ± 0.7 Wm^{-2}. Adjustments were made for this before plotting the results.

Table 3. Effect of doubling CO_2 with fixed RH (no cloud).[†]

T_*(K)	270	280	290	300
ΔT_*(PC)	1.52	1.57	1.65	1.70
ΔT_*(CA)	1.56	1.68	1.92	2.46

[†] PC = Penetrative convection; CA = Convective adjustment (6.5 K/km)

The much weaker variation with T_* in the PC scheme shows that the damping effect of higher upper tropospheric temperatures is greater than the enhancing effect of the associated increase in water vapor. The result with the CA for $\overline{\cos z} = 0.25$ (the mean zenith angle used by Manabe and Wetherald (1967)) was a heating of 2.76 K with $T_* = 306$ K a little less than the 2.92 K they obtained with $T_* = 307$ K. These results suggest that they would have obtained a very different result with a more realistic T_* (e.g. $T_* = 288$ K, the T_* they obtained with cloud).

With Fixed Relative Humidity (average cloudiness)

A more realistic assumption than a clear atmosphere is to assume average cloudiness. The cloudiness assumed here is shown in Table 4.

Table 4. Clouds used in computations.

Type	Amount	Top (σ)	Base (σ)	Solar Reflectivity	Solar Absorptivity	Longwave Absorptivity
High	20%	.27	.37	.2	.05	.5
Medium	10%	.51	.65	.6	.1	1.0
Low	25%	.79	.90	.7	.1	1.0

These specifications are quite similar to those used by Manabe and Wetherald (1967) though low cloud amount is 6.3% less.

Table 5 shows the results with the CA and the PC schemes. The results are of a similar character to those without clouds, but somewhat lower especially for high temperatures. No temperature dependence is evident with the PC scheme. The differences from the clear case are much less than suggested by

Table 5. Effect of doubling CO_2 with fixed RH (cloudy).

T_*(K)	270	280	290	300
ΔT_*(PC)	1.40	1.44	1.40	1.40
ΔT_*(CA)		1.64	1.88	2.20

Manabe and Wetherald (1967) apparently because of the higher temperatures they used in the clear case, as discussed earlier. The results with the CA scheme for $\overline{\cos z} = 0.25$ give a CO_2 doubling effect of 1.85 K compared to Augustsson and Ramanathan's (1977) 1.86 K when omitting the 10 and 7.6 µm CO_2 bands. Manabe and Wetherald (1967) obtained 2.36 K, but Manabe (1971), using the more accurate Rodgers-Walshaw radiation scheme, obtained 1.9 K. Use of the PC scheme gives an effect some 0.5 K smaller at the surface. However, results for the upper troposphere (230 mb) are 2.6 K for the PC scheme, 1.4 K for the CA scheme.

EXPERIMENTS ON EFFECTS OF HUMIDITY ASSUMPTIONS

Experiments have been made with three different assumptions for relative humidity:

(i) Constant values as used above; see Table 6.

(ii) Constant values as obtained from the PC scheme for clear skies with $\overline{\cos z} = .225$ ($T_* = 293$ K). These values (see Table 6) are chosen for comparability with those in (iii) below.

(iii) The values generated by the model's convection scheme.

For each set, a minimum specific humidity of 3×10^{-6} is applied, provided this does not exceed the saturation specific humidity $q_s(T)$.

Table 6. Relative humidities used in experiments (in %).

Layer	11	10	9	8	7	6	5	4	3	2	1
RH (i)	76.0	72.1	64.7	54.8	43.8	32.7	23.4	16.5	10.8	5.4	0.2
RH (ii)	90.0	84.7	84.4	81.0	67.6	61.7	54.8	100	0	0	0

The results (Table 7) are clearly very sensitive to the relative humidity assumption. In particular, the use of the model humidities gives much bigger responses partly, as the second experiment shows, because the air is moister, and also because the convection scheme generates relative humidities which increase with temperature at about 0.7%/K in the lower 500 mb. Although, as Cess (1976) points out, observed northern hemisphere summer and winter data show a similar variation, the zonal averages presented by Telegadas and London (1954) vary little in the region north of 40°N where the largest temperature changes occur; moreover it is likely that the observed moistening of the tropics and subtropics from winter to summer is largely due to changes in the meridional circulation.

Table 7. Effect of doubling CO_2 with different RH assumptions (no cloud).

T_*(K)	270	280	290	300
T_*				
RH(i)	1.52	1.57	1.65	1.70
RH(ii)	-	1.84	2.06	1.86
RH(iii)	1.66	1.80	2.19	2.70

It is nevertheless instructive to consider why the model's RH increases with temperature. The humidity is determined in the convection scheme by a balance between the moistening effects of detrainment of moist air and evaporation of precipitation--both assumed proportional to $(1-RH)q_s(T)$--and the drying effects of subsidence--proportional to $\partial q/\partial p$ or, to a first approximation, to RH $\partial q_s/\partial p$. Thus

$$(1-RH)q_s(T) \propto RH\ \partial q_s/\partial p \propto RH(q_s/T^2)(\partial T/\partial p)$$

by the Clausius-Clapeyron relation. Thus

$$RH = 1/(1 + C(\partial T/\partial p)(1/T^2))$$

where C is the proportionality constant. As, with a moist adiabatic lapse rate, $\partial T/\partial p$ decreases with increasing T as does $(1/T^2)$, the equilibrium RH increases with T. Clearly the result is quite sensitive to details of the convection scheme such as detrainment and evaporation. The justification for the formulations used in these experiments is weak and there is much scope for further sophistication. The particular results presented in this section should thus be treated only as an indication of the importance of the treatment of moisture in the convective parameterization. The convection scheme used by Manabe and Wetherald (1975) appears to give a rather different variation of relative humidity with temperature, with a moistening of the lower and drying of the middle troposphere.

REFERENCES

Augustsson, T., and V. Ramanathan (1977), A Radiative-Convective Model Study of the CO_2 Climate Problem, *J. Atmos. Sci.*, 34, 448-451.

Cess, R.D. (1976), Climate Change: An Appraisal of Atmospheric Feedback Mechanisms Employing Zonal Climatology, *J. Atmos. Sci.*, 33, 1831-1843.

Hunt, G.E., and S.R. Mattingly (1976), Infra-Red Radiative Transfer in Planetary Atmospheres--I: Effects of Computational and Spectroscopic Economies on Thermal Heating/Cooling Rates, *J. Quant. Spectros. Radiative Trans.*, 16, 505-520.

Manabe, S. (1971), Estimates of Future Changes of Climate Due to Increase of Carbon Dioxide Concentration in the Air, in W.H. Matthews, W.W. Kellogg, and G.D. Robinson, eds., *Man's Impact on Climate*, MIT Press, Cambridge, Massachusetts.

Manabe, S., and F. Möller (1961), On the Radiative Equilibrium and Heat Balance of the Atmosphere, *Mon. Weather Rev.*, 89, 503-532.

Manabe, S., and R.F. Strickler (1964), Thermal Equilibrium of the Atmosphere With a Convective Adjustment, *J. Atmos. Sci.*, 21, 361-385.

Manabe, S., and R.T. Wetherald (1967), Thermal Equilibrium of the Atmosphere With a Given Distribution of Relative Humidity, *J. Atmos. Sci.*, 24, 241-259.

Manabe, S., and R.T. Wetherald (1975), The Effects of Doubling the CO_2 Concentration on the Climate of a General Circulation Model, *J. Atmos. Sci.*, 32, 3-15.

McClatchey, R.A., et al. (1973), *AFCRL Atmospheric Line Parameters Compilation*, Environmental Research Paper, No. 434, AFCRL-TR-73-0096, Air Force Cambridge Research Labs, Bedford, Massachusetts.

Rodgers, C.D., and C.D. Walshaw (1966), The Computation of Infra-Red Cooling Rate in Planetary Atmospheres, *Quart. J. Roy. Meteor. Soc.*, 92, 67-92.

Saker, N.J. (1975), *An 11-Layer General Circulation Model*, Met 0 20 Technical Note No. II/30, Meteorological Office, Bracknell, UK.

Schneider, S.H. (1975), On the Carbon Dioxide--Climate Confusion, *J. Atmos. Sci.*, 32, 2060-2066.

Telegadas, K., and J. London (1954), *A Physical Model of Northern Hemisphere Troposphere for Winter and Summer*, Scientific Report No. 1, Contract AF 19(122)-165, Dept. of Met. and Oceanogr., New York University, New York.

GLOBAL TEMPERATURE CHANGES: RELATIVE IMPORTANCE OF DIFFERENT PARAMETERS AS CALCULATED WITH A RADIATIVE-CONVECTIVE MODEL

R.A. Reck

Abstract

In our atmospheric studies we have used a radiative-convective model to calculate the response of the calculated temperature profile to a variety of changes in atmospheric constituents, CO_2, H_2O, O_3, and airborne particles as well as to changes in surface albedo and Rayleigh scattering. In the troposphere the response decreases with altitude at about the same rate as the temperature, reaching 80% of its surface value at 8.3 km (336 mb). In the stratosphere the response increases as the calculated temperature increases. When airborne particles are present the response to other parameters is reduced. We believe these results illustrate the difficult nature of attempting to make predictions of the climatic consequences due to changes in any one global parameter since many are of significant size.

INTRODUCTION

This paper discusses calculations which demonstrate the response of the temperature profile, T, calculated with a one-dimensional radiative-convective atmospheric (RCA) model, to variations in the magnitude, Q, of the present atmospheric constituents and physical parameters $(\frac{\partial T}{\partial Q})$. Only to the limited extent that the model responds to trends in the same manner as the real atmosphere do these calculations provide an estimate of the response of the real atmosphere.

By comparison with the real atmosphere this RCA model is very simplified and neglects the general circulation of the atmosphere and all the detailed mechanisms by which energy and momentum are transferred by different scale processes in the atmosphere. It does not provide a full hydrologic cycle and also neglects important but complicated feedback mechanisms such as changes in ice-extent and cloud abundance and height with changes in temperature. The present work evaluates only the response of this RCA model to changes in the physical parameters which the model uses.

THE MODEL

The RCA model has been used by us for several years [1]. It was developed over many years by workers at the Geophysical Fluid Dynamics Laboratory at Princeton University and was brought to its present form by Manabe and Wetherald [2]. It was modified by us to include the role of airborne particles. In this RCA model, solar radiation is considered to be absorbed by ozone, CO_2, and water, and absorbed and backscattered by water clouds, airborne particles, and the earth's surface. The ozone, CO_2, water, water clouds, airborne particles, and the earth's surface also radiate and absorb infrared radiation. A temperature is initially assumed for each of nine vertically-aligned points in the atmosphere. If the temperature decrease with altitude is greater than the critical adiabatic lapse rate, energy is removed from the lower altitudes and placed higher up. A forward time integration of the solar and infrared flux imbalance is performed until a radiative-convective steady-state temperature is asymptotically approached at each of the nine points. Fixed relative humidity permits the water vapor content of the atmosphere to change with the temperature during the calculation. The particle layer is assumed fixed with an extinction coefficient of 0.1 km^{-1} because this is in the range of the average global value.

MODEL PARAMETERS STUDIED

The averaged model parameters have the values listed in Table 1; for the purposes of this study they were varied as shown. Three layers of water clouds are included (as described in [1]).

METHOD OF CALCULATION

In these studies one model parameter at a time is varied from its present value and a new vertical steady-state temperature profile is calculated. Temperature profiles have been determined for the discrete values of the parameters shown in Table 1.

The calculated temperature profiles were obtained at each of the nine points in the vertical between 8.9 mb (32 km for the standard atmosphere) and 991 mb (0.07 km for the standard atmosphere). At each level the several calculated temperatures were used to obtain a least-squares fit with an uncertainty in the calculated temperature $\Delta T < \pm 0.01$ K. In all cases the temperature data at a given pressure were smooth and monotonic, but none were found to be linear. From the parameterized fitting the partial derivative of the temperature with respect to the parameter was calculated directly for the present value of the parameter and those results appear in Table 2.

Table 1. Model parameters and the values for which temperature calculations were made.

Parameter	Assumed Value	Probable Error	Fits	Values Used for This Study
Surface Relative Humidity, h*	74^{A}	$+5, -0^{B}$	%	57, 62, 67, 72, 77, 87
"Dry" Limit Water Concentration, h_s	$2\text{-}5 \times 10^{-6\,D}$	$1\text{-}2\times10^{-6\,D}$	g/g air	$1.5, 3, 6, 9, 24\times10^{-6}$
Ozone Concentration, O_3	See Table 2	1-2% of Amt. Present^{E}	g/g air	See Table 2
Carbon Dioxide Concentration, CO_2	$496 \times 10^{-6\,F}$	$\pm 0.2 \times 10^{-6\,F}$	g/g air	$228, 456, 684, 912\times10^{-6}$
Rayleigh Scattering, R	7^{C}	0.1	%	4, 5, 6, 7, 8, 8.5
Airborne Particles Extinction Coefficient, σ_v	0.1^{G}	0.002^{G}	km^{-1}	0.01, 0.05, 0.1, 0.15, 0.2
Surface Albedo ω_s	14.02^{H}	$<1^{H}$	%	5, 7, 10, 16, 20, 30

A) Schutz, C., and W.L. Gates, Global Climatic Data for Surface, 800 mb and 400 mb: January, Advanced Research Projects Agency, Arlington, Virginia, 1971.

B) United States Air Force, ed., *Handbook of Geophysics*, revised edition, Macmillan Co., New York, 1960, Ch. 20.

C) Manabe, S., and R.T. Wetherald, Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity, *J. Atmos. Sci.*, 24 (1967), 241-259.

D) de Jonckhure, C.G., A Measurement of the Mixing Ratio of Water Vapor from 15 to 45 km, *Quart, J.R. Met. Soc.*, 101 (1975), 217-226; Chaloner, C.P., J.R. Drummond, J.R. Houghton, R.F. Jarnot, and H.K. Roscoe, Stratospheric Measurements of H_2O and the Diurnal Change of NO and NO_2, *Nature*, 258 (1975), 696-697.

E) Lowenstein, M., H.F. Savage, and R.C. Whitten, Seasonal Variations of NO and O_3 at Altitudes of 18.3 and 21.3 km, *J. Atmos. Sci.*, 32 (1975), 2185-2190.

F) Pales, J.C., and C.D. Keeling, The Concentration of Atmospheric Carbon Dioxide in Hawaii, *J. Geophys. Res.*, 70 (1965), 6053.

G) Shaw, G.E., Properties of the Background Global Aerosol and Their Effects on Climate, *Science*, 192 (1976), 1334-1336.

H) Hummel, J.R. and R.A. Reck, *Development of a Global Surface Albedo Model*, presented at the Meteorology Section, American Geophysical Union, San Francisco, December 1977; GMR-2607, General Motors Research Laboratories, Warren, Michigan, 1978.

Table 2. Absolute values of the partial derivative of the temperature with respect to the model parameters, holding other parameters constant.

Level No.	P	$(\frac{\partial T}{\partial h^*})_{74\%}$	$(\frac{\partial T}{\partial \omega_s})_{14.0}$	$(\frac{\partial T}{\partial h_s})_{3\times10^{-6}}$	$(\frac{\partial T}{\partial O_3})_{100\%}$	$(\frac{\partial T}{\partial CO_2})_{456\times10^{-6}}$	$(\frac{\partial T}{\partial R})_{7\%}$	$(\frac{\partial T}{\partial q})_{0.1}$
	Units:mb	K/%	K/%	K/ppmm	K/%	K/ppmm	K/%	K km
1	8.9	7.84×10^{-3}	8.71×10^{-2}	8.40×10^{-1}	1.35×10^{-1}	1.96×10^{-2}	1.29×10^{-3}	0.523
2	74	2.60×10^{-3}	0.208	5.22×10^{-1}	1.9×10^{-1}	5.4×10^{-4}	7.09×10^{-2}	1.89
3	189	2.36×10^{-2}	0.370	2.84×10^{-1}	2.33×10^{-2}	4.06×10^{-4}	0.294	3.86
4	336	7.17×10^{-2}	0.796	2.90×10^{-2}	2.54×10^{-3}	3.57×10^{-3}	0.707	5.08
5	500	7.74×10^{-2}	0.859	3.09×10^{-2}	2.78×10^{-3}	3.85×10^{-3}	0.764	5.50
6	664	8.18×10^{-2}	0.903	3.25×10^{-2}	2.97×10^{-3}	4.06×10^{-3}	0.807	4.78
7	811	8.50×10^{-2}	0.942	3.36×10^{-2}	3.11×10^{-3}	4.22×10^{-3}	0.839	6.02
8	926	8.71×10^{-2}	0.965	3.44×10^{-2}	3.18×10^{-3}	4.32×10^{-3}	0.858	6.17
9	991	8.85×10^{-2}	0.980	3.47×10^{-2}	3.25×10^{-3}	4.39×10^{-3}	1.111	6.25

RESULTS

In the *troposphere* these calculations show that:

- The greatest temperature response occurs at the earth's surface. This is because the atmosphere has its greatest thermal effect at the earth's surface where it is most dense.

- The temperature response to all constituents decreases linearly with height at roughly the same rate as the temperature, reaching ~80% of the surface value at 336 mb (8.3 km).

- The temperature response to the values of Rayleigh scattering decreases at twice the rate of the other parameters, reaching 64% of the surface value at 336 mb.

- When Mie scattering particles are included in the model the temperature response of the parameters surface relative humidity, CO_2, and surface albedo is less.

In the *stratosphere* our calculations indicate that:

- The temperature response to "tropospheric" parameter changes (e.g. surface relative humidity, Rayleigh scattering and airborne particles extinction coefficient) decreases from the lower to the upper stratosphere. This is because only the lowest layers are *directly* influenced by these quantities.

- The temperature response to "atmospheric" or to "stratospheric" parameters (e.g. CO_2, h_s) increases with altitude in the stratosphere, in the same manner as the temperature increases with altitude.

- The height dependence of the temperature response to O_3 reaches a maximum in our model at ~74 mb.

DISCUSSION

To gain some perspective on the relative importance of the calculated temperature responses we have listed in Table 3 the calculated surface temperature change (ΔT_s in ^{0}K) for a 1% increase in each of the parameters listed. The calcuated values for N_2O, CH_4, C_2H_4, CCl_4, CH_3Cl, HNO_3, NH_3 and SO_2 are taken from Wang et al. [3] and have been calculated for a model which does not include airborne particles; values for CF_2Cl_2 and $CFCl_3$ are from Reck and Fry [4] and include particles; and the value for $CHCl_3$ is from a model by Ramanathan [5] which also does not include airborne particles. These numbers indicate T_s

Table 3.

	Present Value	Units	ΔT_s	Relative Rank
ω_s	14.01	%	- 0.14	1
R	7.0	%	- 0.078	0.56
h*	74	%	0.065	0.46
CO_2	330	ppmv	0.020	0.14
σ_v	0.1	km^{-1}	- 0.0063	0.057
N_2O	637	ppbv	0.0044	0.031
O_3	0.37	atm-cm	- 0.0032	0.023
CH_4	1.6	ppmv	0.002	0.014
h_s	3.5	ppmv	0.0012	0.0086
$CHCl_3$	$<2 \times 10^{-4}$	ppmv	0.0010	0.0071
NH_3	6×10^{-3}	ppmv	0.0009	0.006
HNO_3	$10^{-3} - 10^{-2}$	ppmv	0.00060	0.004
$CFCl_3$	2.3×10^{-4}	ppmv	0.00035	0.0025
SO_2	2	ppmv	0.00020	0.0014
CF_2Cl_2	1.3×10^{-4}	ppmv	0.00019	0.0014
C_2H_4	2×10^{-4}	ppmv	0.0001	0.0007
CH_3Cl	5×10^{-4}	ppmv	0.0001	0.0007
CCl_4	1×10^{-4}	ppmv	0.0001	0.0007

ΔT_s = surface temperature change (K) for 1% increase in the present average value.

is more than five times more sensitive to changes in surface albedo and surface relative humidity than to other parameters. If in the recently developed surface albedo model by Hummel and Reck [6] the amount of arable land was increased by 1% and its surface albedo changed from that of black soil (0.07) to that of crops (0.25) for one third of the year, by the estimates of the present calculations it would lower the earth's surface temperature about 1 K. In a similar way we can consider that manmade lakes and reservoirs (estimated to cover 300,000 km^2) may have increased T_s about 0.4 K.

If the present calculations for CO_2 are compared with those for the general circulation model of Manabe and Wetherald [7] it suggests that the present values are on the small side (possibly for the real atmosphere too). What have also been neglected in these calculations (except for fixed relative humidity) are the many important feedback mechanisms and non-linear effects which spontaneously occur when the temperature changes. The feedbacks are not easily described since they vary greatly with both latitude and season. In the case of a global average stratospheric ozone increase the absence of airborne particles in the lower troposphere changes the calculated ΔT_s from a slight cooling to slight heating [8]. Certainly intense feedback mechanisms could be possible with changes in CO_2, cloud cover, and global ice abundance.

We believe the results of this very simplistic atmospheric model demonstrate the difficult nature of attempting to make predictions of the climatic consequences due to changes in any one global parameter since many parameters can be of significance. To predict man's contribution to climatic changes it is essential that the effect of all parameters be adequately described.

REFERENCES

[1] Reck, R.A., Thermal and Radiative Effects of Atmospheric Aerosols in the Northern Hemisphere Calculated Using a Radiative-Convective Model, *Atmos. Env.*, 10 (1976), 611-617.

[2] Manabe, S., and R.T. Wetherald, Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity, *J. Atmos. Sci.* 24 (1967), 241-259.

[3] Wang, W.C., Y.L. Yung, A.A. Lacis, T. Mo, and J.E. Hansen, Greenhouse Effects Due to Man-Made Perturbations of Trace Gases, *Science*, 194 (1976), 685.

[4] Reck, R.A., and D.L. Fry, *The Direct Effect of Chlorofluoromethanes on the Atmospheric Temperature*, GMR-2564, General Motors Research Laboratories, Warren, Michigan, 1977.

[5] Ramanathan, V., Greenhouse Effect Due to Chlorofluorocarbons: Climatic Implications, *Science*, 190 (1975), 50-52.

[6] Hummel, J.R., and R.A. Reck, *Development of a Global Surface Albedo Model*, presented at the Meteorology Section, American Geophysical Union, San Francisco, December 1977; GMR-2607, General Motors Research Laboratories, Warren, Michigan, 1978.

[7] Manabe, S., and R.T. Wetherald, The Effects of Doubling the CO_2 Concentration on the Climate of a General Circulation Model, *J. Atmos. Sci.*, 32 (1975), 3-15.

[8] Reck, R.A., Stratospheric Ozone Effects on Temperature, *Science*, 192 (1976), 557-559.

FACTORS OF THE GREENHOUSE EFFECT OF THE ATMOSPHERE AND THEIR INFLUENCE ON CLIMATE

K.Ya. Kondratyev and A.M. Bunakova

The radiation balance of the atmosphere is essentially determined by the presence of optically active minor atmospheric constituents such as water vapor, CO_2, ozone, and aerosols. One of the basic processes for determining the influence of radiation factors on climate is the greenhouse effect of the atmosphere. The atmosphere is comparatively transparent for solar radiation, but it prevents, to a considerable extent, the loss of heat owing to the emission of longwave radiation from the earth's surface into outer space. It is only in the atmospheric transparency window in the wavelength interval of 7 to 14 μm that the thermal emission of a cloudless atmosphere is small in comparison to that of the earth's surface. Thus the study of atmospheric optical properties in the transparency window and the adjacent spectral regions is of primary importance for revealing information on the physical nature of the greenhouse effect, and for estimating its contribution to variability and influence on climate. A similar but from the viewpoint of details different situation takes place on other planets as well. (Serious attention has been paid to investigating the greenhouse effect on Venus and Mars [1,2].)

The traditional approach to studying the greenhouse effect and especially its variations is to determine the contribution of CO_2. One of the most popular hypotheses concerning climate variations both in the geological past and at present is that temperature variations result from changes in the CO_2 content in the atmosphere, followed by variations of the greenhouse effect [3,4,5]. However, it is well known that the absorption spectrum of the atmosphere in the transparency window is determined by the influence of the 15 μm CO_2 band, by gaseous constituents such as water vapor and ozone, and by aerosols. From the theoretical point of view of climate changes, the primary role here belongs to those constituents with long-terms trends. For example, chlorofluorocarbons (freons) are atmospheric constituents that are exclusively of anthropogenic origin and are thrown out into the atmosphere in ever increasing quantities.

Lovelock [6] first attracted attention to the urgent need for studying freons and their possible destructive influence on the ozone layer (see [7]). Since then, in spite of growing interest in the problem of freons, only one paper has appeared, namely that by Ramanathan [8] which investigates the longwave radiation transfer while taking account of freons.

The atmosphere also contains a number of other minor constituents such as nitrogen oxides, methane, ammonia, ethylene, and sulphur dioxide. These all have absorption bands in the wavelength interval 7 to 14 μm and thus also contribute to the greenhouse effect of the atmosphere, especially if one takes into account that their concentration is subject to considerable variations under the influence of anthropogenic effects (e.g. intensive use of organic fertilizers, fuel burning [9]).

This paper considers the contribution of freons and other minor gaseous constituents to the atmospheric greenhouse effect, and discusses possible relevant climatic consequences.

According to Lovelock's data [6], at present the relative concentration of freons F-11 and F-12 in the atmosphere constitutes 0.1-0.2 ppbv. This concentration is expected to amount to 2 ppbv by the end of this century, taking into account the photolysis taking place in the stratosphere and the tropospheric-stratospheric transfer at the current level of atmospheric pollution. This figure agrees with the conclusion made earlier by Molina and Rowland [10]: at the present rate of atmospheric pollution, the concentration of freons in the atmosphere may increase by 20 to 30 times relative to the current value (0.1-0.2 ppbv). (Here it should be noted that F-11 and F-12 has a characteristic lifetime in the atmosphere of the order of 10 years.)

Ramanathan [8] was the first to attempt to measure the influence of the increase in the concentration of freons on the radiation balance of the earth's surface-atmosphere system. The surface temperature rise owing to the presence of freons is illustrated in Figure 1. As can be seen, the greenhouse effect of freons may become significant. More precise calculations of surface temperature changes made by Ramanathan et al. [11], within the framework of a model of radiative-convective equilibrium, agree with the results of [8].

Ramanathan's basic conclusion [8]--that account should be taken of the contribution of freons to the greenhouse effect--has been confirmed completely by Wardle and Evans [12]. Their work, which appeared soon after Ramanathan's publication, showed independently that atmospheric pollution caused by freons and by a change in the radiation balance of the earth-atmosphere system may influence climate more than other anthropogenic factors such as an increase in the concentration of CO_2 and aerosols. Using a very simple climatic model, Wardle and Evans showed the considerable influence of freons, even in current concentrations, on the radiation balance; at this time the danger of the freon-ozone situation had not been proven.

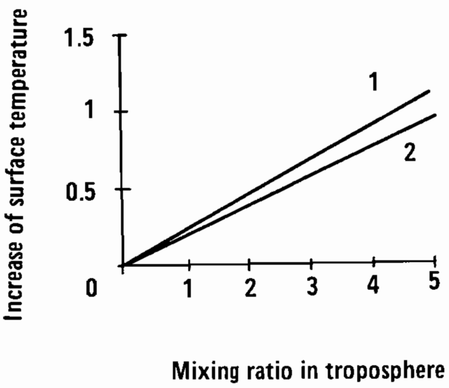

Figure 1. Increase of surface temperature as a function of tropospheric concentrations of CF_2Cl_2(1) and $CFCl_3$(2). (The results were obtained for global-averaged conditions--50% cloudiness.)

The theoretical climate model suggested by Sellers [13] gives an increase in the mean global temperature of about 1°C, if we assume that the decrease in the infrared atmospheric transparency owing to freons is 0.33%. Estimates based on data of current conditions in Canada (where the concentration of freons in the troposphere constitutes 0.2%) lead to the conclusion that the mean global temperature has already increased by 0.13°C owing to the influence of freons. The results indicate that changes in the greenhouse effect caused by freons may influence the climate more fundamentally than have the anthropogenic impacts of CO_2 and aerosols.

A recent paper by Wang et al. [14] emphasizes that the gases of anthropogenic origin (including freons) may radically change the earth's climate by "closing" completely the atmospheric transparency window for the outgoing thermal emissions of the earth's surface. In this connection, let us discuss the contribution of some atmospheric pollutants to the greenhouse effect.

Table 1 gives the major results of calculations by Wang et al. [14]; doubling the NO concentration leads to an increase in the mean temperature of the earth's suface by 0.7°K. (A long-term temperature change of over 0.1°K is potentially unavoidable and a change of about 1°K reflects inevitable radical climate variations.) Doubling of the methane and ammonia concentrations must result in an additive temperature increase by 0.3 and 0.1°K, respectively. Table 1 also shows possible temperature changes of the earth's surface caused by variations of the concentrations of HNO_3, C_2H_4, NO_2, CCl_2F_2, CCl_3F, CH_3Cl, and CCl_4, and, for comparison, gives temperature changes owing to water vapor, CO_2 and ozone. Note that the total greenhouse effect of doubling concentrations of N_2O, CH_4, NH_3, and HNO_3 amounts to 1.2°K. If the concentration of freons increases by an order of magnitude, their influence becomes notable too.

Table 1. Greenhouse effect due to variations in concentration of various minor atmospheric constituents.

Source: [14,15]

Component	Center of the band µm	Estimated current concentration ppmv*	Increase in concentration n times	Greenhouse effect (^{0}K)	
				At fixed temperature of cloud upper boundary	At fixed height of cloud upper boundary
N_2O	7.78; 17.0; 4.5	0.28	2	0.68	0.44
CH_4	7.66	1.6	2	0.28	0.20
NH_3	10.53	6×10^{-3}	2	0.12	0.09
HNO_3	5.9; 7.5; 11.3; 21.8	$4.87\ 10^{-3}$mm STP	2	0.08	0.06
C_2H_4	10.5	2×10^{-4}	2	0.01	0.01
NO_2	8.69; 7.35	2×10^{-3}	2	0.03	0.02
CCl_2F_2	9.13; 8.68; 10.93	1×10^{-4}	20	0.54	0.36
CCl_3F	9.22; 11.82	1×10^{-4}	20		
CH_3Cl	13.66; 9.85; 7.14	5×10^{-4}	2	0.02	0.01
CCl_4	12.99	1×10^{-4}	2		
H_2O	6.25; 10; 20; 10	75% relat. humid.	2**	1.03	0.65
CO_2	15.0	330	1.25	0.79	0.53
O_3	9.6	3.43 mm STP	0.75	-0.47	-0.34

*These mixing ratios refer to the level of the earth's surface, and for O_3 and HNO_3 the total content in the atmospheric thickness is given.

**The doubling of the H_2O content above 11 km is assumed. Below this level the water vapor content is determined by the condition of a fixed relative humidity. The greenhouse effect caused by the doubling of the concentration of CH_2Cl_2, $CHCl_3$, C_6H_6, and PAN is negligible (<0.01^{0}K).

There are quantitative discrepancies in the results of calculations obtained in [14] and in [8]: according to [14], the greenhouse effect owing to freons is considerably smaller than that obtained in [8] (0.9°K). Nevertheless, the general qualitative conclusion formulated by Ramanathan [8] holds true: a considerable increase of the concentration of freons in the atmosphere introduces climatic changes.

Results obtained by Wang et al. [14] definitely underscore the need to consider some minor constituents whose influence had been previously (and incorrectly) assumed to be negligible. It is therefore important to monitor global trends in the concentration of such minor constituents. In the near future the most important factors will be the increase of concentration of CO_2, freons, and variations in the water vapor content in the stratosphere. On the whole, data obtained indicate the probability of a climate warming owing to the anthropogenic produce of minor gaseous constituents; this is particularly important for land regions in moderate and high latitudes of the northern hemisphere. Apparently, the aerosol cooling cannot compensate for the effect of a climate warming. Reliable quantitative estimations are only possible using more complete climate models and a thorough accounting of aerosol effects. The study of climate-forming factors on other planets is therefore important.

CONCLUSIONS

The prevailing hypothesis that the origin of current and possibly future climate changes can be attributed exclusively to variations in the CO_2 content is a very rough simplification of reality. Even taken by itself, the CO_2 hypothesis is disturbed by a whole number of limitations. For instance, it was shown long ago [16,17] that the greenhouse effect of CO_2 is limited by the influence of "saturation": since the infrared radiation absorption caused by the 15 μm CO_2 band is very intensive (especially if we take into account the overlapping of the CO_2 and the H_2O bands), the increase in CO_2 concentration results in a very small increase of atmospheric emission. This conclusion has recently been confirmed by the convincing calculations of Smirnov [18].

Since anthropogenic changes in the composition of the atmosphere are several, it is natural that theoretical estimations of their influence on the greenhouse effect and climate must take account of all vital constituents and in this respect Table 1 may serve as an initial reference. Therefore, the conclusions as to the role of various constituents should be taken into account in planning a system for monitoring important (from the viewpoint of the climate change) parameters and factors. Of particular importance are investigations of absorption spectra of climatically essential atmospheric pollutants. The problem of the influence of atmospheric aerosols on the greenhouse effect has not been considered in this paper. There is no doubt, however, that this is a problem of primary importance.

Various theoretical climate models can form the basis for evaluating the influence of atmospheric composition on the climate. Numerical experiments on climate sensitivity to various parameters (e.g., the concentration of CO_2) cannot be considered as completely revealing the corresponding cause and effect relations. To make such evaluations more reliable, it is essential to take account of the real dynamics and interaction of continuous changes in the composition of the atmosphere (instead, for instance, of using the conditional assumption of the doubling of CO_2 concentration). Even complete three-dimensional models require further improvement in the consideration of the mechanisms responsible for climate changes, particularly from the point of view of adequate accounting for the interaction between the atmosphere, ocean, and the cryosphere.

REFERENCES

[1] Kondratyev, K.Ya., *Meteorology of Planets*, Leningrad Univ. Press, Leningrad, 1977.

[2] Kondratyev, K.Ya., and N.I. Moskalenko, *Thermal Emission of Planets*, Gidrometeoizdat, Leningrad, 1977.

[3] World Meteorological Organization, *Report of the Scientific Workshop on Atmospheric Carbon Dioxide*, No. 474, Geneva, 1977.

[4] Kondratyev, K.Ya., *Recent Developments in the Theory of Climate*, Gidrometeoizdat, Leningrad, 1976.

[5] Sekihara, K., Possible Climatic Changes from Carbon Dioxide Increase in the Atmosphere, in J.O.M. Bockris, ed., *Environmental Chemistry*, Plenum, New York, 1977.

[6] Lovelock, J.E., R.J. Maggs, and R.J. Wade, Halogenated Hydrocarbons In and Over the Atlantic, *Nature*, 241 (1973), 194-196.

[7] Kondratyev, K.Ya., and D.V. Pozdniakov, The Stratosphere and Freons, *Akad. Nauk. SSR, Fizika atmosferyiokeana*, 12, 7 (1976), 683-695 (in Russian).

[8] Ramanathan, V., Greenhouse Effect Due to Chlorofluorocarbons: Climatic Implications, *Science*, 190 (1975), 50-52.

[9] McElroy, M.B., Chemical Processes in the Solar System: A Kinetic Perspective, *Intern. Rev. Sci., Phys. Chem.*, 9 (1976), 127.

[10] Molina, M.J., and F.S. Rowland, Stratospheric Sink for Chlorofluoromethanes-Chlorine Atomic-Catalysed Destruction of Ozone, *Nature*, 249 (1974), 810.

[11] Ramanathan, V., L.B. Callis, and R.E. Boughner, Sensitivity of Surface Temperature and Atmospheric Temperature to Perturbations in the Stratospheric Concentration of Ozone and Nitrogen-Dioxide, *J. Atmos. Sci.*, 33 (1976), 1092-1112.

[12] Wardle, D.I., and W.F.J. Evans, *The Effect of Freon Usage on the Global Climate: The Greenhouse Effect*, Atmospher. Res. Rept., No. APRB 40 8, 1976.

[13] Sellers, W.D., A Global Climatic Model Based on the Energy Balance of the Earth-Atmosphere System, *J. Appl. Meteorol.*, 8 (1969), 392-400.

[14] Wang, W.C., Y.L. Yung, A.A. Lacis, T. Mo, and J.E. Hansen, Greenhouse Effects Due to Man-Made Perturbations of Trace Gases, *Science*, 194 (1976), 685.

[15] Morcillo, J., L.J. Zamorano, and J.M.V. Heredia, Infrared Intensities of CH_2F_2, CH_2Cl_2 and CF_2Cl_2, *Spectrochim. Acta*, 22 (1966), 1969.

[16] Kondratyev, K.Ya., and L.I. Nedovesova, On the Thermal Emission of Carbon Dioxide in the Atmosphere, *Izv. Akad. Nauk. SSR, Geofizicheskaya*, 8, 12 (1958) (in Russian).

[17] Kondratyev, K.Ya., and H.J. Niilisk, On the Problem of Carbon Dioxide Thermal Radiation in the Atmosphere, *Problemy fiziki atmosfery* (Problems of Atmospheric Physics), 2 (1963), 28-47 (in Russian).

[18] Smirnov, B.M., Man's Impact on the Earth's Atmosphere, *Priroda* (Nature), 4, 10 (1977).

DIFFUSION AND TRANSFER OF CLIMATICALLY RELEVANT GASES CLOSE TO THE EARTH'S SURFACE

G.D. Djolov

The production and transmission of concentrated amounts of energy are the keystones for the rapid rise in our standard of living. At present, fossil fuels are the major source of energy. Since the late nineteenth century, this has caused an ever accelerating rate of CO_2 release through combustion. About 50% of the CO_2 has remained in the atmosphere. Many investigators have shown that a further increase of CO_2 content in the atmosphere can influence the climate of the earth in several ways.

The main carbon reservoirs--atmosphere, ocean, biosphere--establish a dynamic equilibrium of CO_2 and other climatically relevant gases through different mechanisms. Analysis of the transfer of those gases reveals that the exchange among the reservoirs, which can serve as sinks or sources, finally takes place through the molecular sublayer of the atmosphere covering both the earth's surface (land and ocean) and the biosphere (green plants). This fact can be useful in enhancing our understanding of the carbon cycle problem.

The study of diffusion and transport of gases close to the earth's surface is facilitated by the fact that at low heights in the surface layer, adiabatic conditions can be assumed on the basis of similarity theory. Thus $z/L \rightarrow 0$, which L is the Obukhov-Monin length scale. For heights close to the earth's surface ($z \rightarrow 0$), this condition is always fulfilled. Also close to the earth's surface turbulent eddies are confined to the vertical direction, so that the use of the semi-empirical equation of turbulent diffusion is justified.

The interaction between admixture and underlying surface has been increasingly studied in recent decades. If stationary conditions and a horizontally homogeneous field of concentration for heights $z >> z_0$ (where z_0 is the roughness) are assumed, the vertical flux of the substance q is given by the expression:

$$P = K_q \frac{\partial q}{\partial z} \quad . \qquad (1)$$

In adiabatic conditions the coefficient of turbulent exchange for passive substance q has the form:

$$K_q = \alpha_q \kappa u_* z \quad , \tag{2}$$

where α_q is the ratio of the exchange coefficient for the admixture and the momentum ($\alpha_q \approx 1.15$ according to [1]), κ is the Karman constant, and u_* is the friction velocity.

Using (2), the log distribution of the admixture follows from equation (1):

$$q(z_2) - q(z_1) = \frac{q_*}{\alpha_q} \ln \frac{z_2}{z_1} \quad , \tag{3}$$

where

$$q_* = \frac{P}{\kappa u_*} \tag{4}$$

is the scale of the diffusing admixture.

Equation (3) cannot be used in immediate proximity to the earth's surface, because it does not record the molecular effects that cannot be neglected in this region. It is therefore necessary to take into account the kinematic coefficient of the air ν and the coefficient of molecular diffusion of the admixture x_q, and to introduce the mean height of the surface roughness h_0 ($h_0 = 30z_0$). On the basis of similarity theory, (3) can be replaced by:

$$q_z - q_s = q_* \psi(\frac{z}{z_0}, Re_*, S_c) \tag{5}$$

where q is the concentration of the admixture on the earth's surface, $Re_* = u_* z_0/\nu$ is the surface Reynolds number, and $Sc = \nu/x_q$ is the Schmidt number. Let us attempt to specify (5). After taking into account that for heights greater than z_0 the concentration satisfies a formula of type (3), we can write

$$q_z - q_s = \delta q_0 + \frac{q_*}{\alpha_q} \ln \frac{z}{z_0} \quad , \tag{6}$$

where δq_0 is a new function independent of z and therefore has the form

$$\delta q_0 = q_* \kappa B^{-1}(Re_*, Sc) \quad . \tag{7}$$

Function κB^{-1} is called molecular resistance. The introduction of two more parameters with a velocity dimension, $\beta_z = \frac{\kappa u_* q_*}{q_z}$ and $\beta_s = \frac{\kappa u_* q_*}{q_s}$ characterizing the interaction of the diffusing admixture with the underlying surface at height z and at the surface respectively, proves convenient. Then, by means of (6) and (7), we obtain for the dimensionless concentration at height z:

$$\frac{q_z}{q_*} = \frac{\kappa u_*}{\beta_z} = \frac{\kappa u_*}{\beta_s} + \kappa B^{-1} + \frac{1}{\alpha_q} \ln \frac{z}{z_0} \quad ; \tag{8}$$

that is, the resistance of the diffusion process at height z is equal to the sum of the surface, molecular, and aerodynamic resistances. Combining the molecular and aerodynamic resistances, we can define the roughness of the diffusing admixture

$$z_q = z_0 \exp (- \alpha_q \kappa B^{-1}) \quad , \tag{9}$$

which is analogous to the roughness of impulse z_0.

Let us now examine the available experimental data. Most of these [2-4] were obtained over completely absorbing surfaces $\beta_s = \infty$ so that κB^{-1} or z_q can be defined. The formula for the molecular heat resistance,

$$\kappa B^{-1} = a(30Re_*)^m Sc^n \quad , \tag{10}$$

proposed in [5], proved to be valid also for weightless admixture, as was to be expected because x_q is close to the coefficient of molecular heat transfer. The constants determined have the following values: $a = 0.5$; $m = 0.45$; $n \doteq 0.8$. This formula was proposed for $10 < Re_* < 10^4$ and values Sc close to unity. It is more appropriate [6] for surfaces with evenly distributed roughnesses, for instance vineyards, while κB^{-1} in certain conditions depends only slightly on Re_* and has values $2 > \kappa B^{-1} > 1$. As can be seen from these data, z_q may differ substantially from z_0; as a rule it is smaller than z_0, in certain conditions by several orders.

Let us now look at the experimental data on β_s. In experiments with iodine over grass [7] it was shown that β_s has the order of B in the four experiments with numbers 5-8 being respectively equal to: 0.096; 0.08; 0.029; 0.56. According to [8], $\beta_s = 0.8$ cm/s when SO_2 is precipitated on grass, while according to [9] β_s/u_* is in the 0.033 to 0.2 interval for all surfaces without Riffle glass and from 0.0067 to 0.45 for Riffle glass.

Experiments with aerosol particles (radius $r = 0.3\mu m$) over grass gave other data [10]. Here β_s/u_* is in the 0.01 to 0.11 range, molecular transfer being neglected and the calculations made for height $z = z_0$. In that case (10) cannot be used, as Sc becomes too big and the particles moving in a Brownian manner interact with the underlying surface in a complicated way. Let us adduce some data from [11]: $\beta_s/u_* = 0.007$ for Aitken nuclei ($r = 0.04\mu m$) on moss, from Lycopodium spores on humid moss $\beta_z/u_* = 0.08$, and on grass $\beta_z/u_* = 0.05$. With bigger particles the effect of gravitational precipitation must be taken into account.

Unfortunately the experimental data on β_s are inadequate. A reasonable interval in real conditions is $1\ \text{cm/s} < \beta_s < 15\ \text{cm/s}$.

Let us now examine the boundary cases of complete absorption and reflection of the diffusing admixture by the earth's surface, by submitting some analytical solutions and investigating their asymptotic representations. Let us take the case of diffusion from an all instantaneous flat source:

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial z} K_q(z)\frac{\partial q}{\partial z} , \tag{11}$$

with initial condition

$$q = Q\delta(z - h) \tag{12}$$

and boundary conditions in infinity

$$q = 0 \text{ at } t \rightarrow \infty \text{ and } q = 0 \text{ at } z \rightarrow \infty \quad , \tag{13}$$

where Q is the power of the source, t the time, h the height of the source, and δ the delta function. The boundary condition close to the earth's surface then has the form:

$$P = K_q \frac{\partial q}{\partial z} = \beta q \text{ at } z = z_p \quad , \tag{14}$$

where $z_p = z_q$ from (9) with complete absorption and $z_q = 0$ with complete reflection.

The solution to (11) in conditions (12), (13), and (14) for a completely absorbing surface ($\beta_s = \infty$) assumes the form:

$$q^a(\xi,\tau) = \frac{1}{2} \int_0^\infty 1^{-\tau x^2/\delta} \frac{[J_0(x\sqrt{\xi})Y_0(x\sqrt{\xi_q}) - Y_0(x\sqrt{\xi})J_0(x\sqrt{\xi_q})]}{J_0^2(x\sqrt{\xi_q}) - Y_0^2(x\sqrt{\xi_q})}$$

$$[J_0(x)Y_0(x\sqrt{\xi_q}) - Y_0(x)J_0(x\sqrt{\xi_q})]xdx \quad , \tag{15}$$

and that for a completely reflecting one ($\beta_s = 0$):

$$q^r(\xi,\tau) = \frac{2}{\tau} 1^{-2 \frac{3+1}{\tau}} I_0(\frac{4\sqrt{\xi}}{\tau}) \quad , \tag{16}$$

where $\tau = 2\kappa u_* t/h$, $\xi = z/h$, $\xi_q = z_q/h$, and q^a and q^r are the dimensionless concentrations in the case of absorption and reflection. These allow us to investigate the asymptotic representations of (15) and (16) for short and long diffusion times. They show that the differences between the cases of absorption and reflection are greatest in immediate proximity to the underlying surface.

It is advisable, when seeking quantitative evaluations of the interaction effect of climatically relevant gases, to simulate cases close to reality by making use of some real values that hold for the studied gas. This is done by the author in [12]. The solution to nondimensional equation of turbulent diffusion is numerical. An implicit scheme is used, which ensures stability. The solution is found by the Thomas method which is most effective in solving three-diagonal matrices.

As can be seen from Figure 1, the concentration distribution is affected by the properties of the underlying surface (value of β).

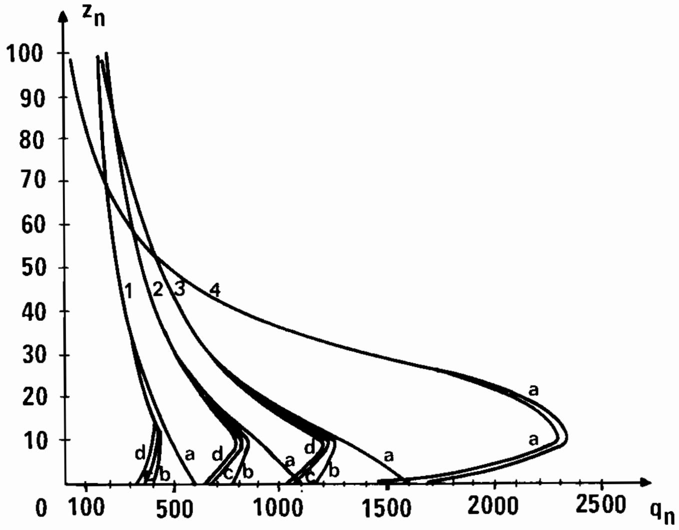

Figure 1. Vertical distribution of impurities: (1) x = 50; (2) x_n = 30; (3) x_n = 20; (4) x_n = 0.6; (a) $\beta = 0$; (b) $\beta = 1$; (c) $\beta = 5$; (d) $\beta = 15$.

CONCLUSION

When the transfer and diffusion of gases close to the earth's surface are examined, the way in which they interact with different types of underlying surfaces has to be properly recorded. The molecular sublayer must also be taken into account.

Apparently the study should be extended to permit calculation of the turnover time of different climatically relevant gases through the molecular sublayer.

More extensive data are needed for the specification of the universal function for the molecular resistance and the interaction constant β for n different gases.

REFERENCES

[1] Yaglom, A., Data on Turbulence Characteristics in Atmospheric Surface-Layer, *Izv. Akad. Nauk. SSR, Fiz. Atmos. Okeana,* 10 (1974), 566.

[2] Chamberlain, A.C., Transport of Gases To and From Grass and Grass-Like Surfaces, *Proceedings, Royal Society, Ser. A,* 290 (1966), 236-265.

[3] Chamberlain, A.C., Transport of Gases To and From Surfaces with Bluff and Wave-Like Roughness Elements, *Quarterly Journal of the Royal Meteorological Society,* 94 (1968), 318-332.

[4] Barry, P.J., and R. Munn, Uses of Radioactive Tracers in Studying Mass Transfer in the Atmospheric Boundary Layer, *Physics of Fluids,* Supplement to Vol. 10 (1967), 263-266.

[5] Owen, P.R., and W.R. Thompson, Heat Transfer Across Rough Surfaces, *Journal of Fluid Mechanics,* 15 (1963), 321-334.

[6] Garrat, J.R., and B.B. Hicks, Momentum, Heat and Water-Vapor Transfer To and From Natural and Artificial Surfaces, *Quarterly Journal of the Royal Meteorological Society,* 99, 422 (1973), 680.

[7] Chamberlain, A.C., and R.C. Chadwick, Transportation of Iodine from Atmosphere to Ground, *Tellus,* 18 (1966), 226-237.

[8] Chamberlain, A.C., *Duration of* SO_2 *Gaseous Diffusion,* presented at the 2nd IUTAM-IUGG International Symposium on Turbulent Diffusion in Environmental Pollution, Charlottesville, Va., 1973; also published in F.N. Frenkiel and R.E. Munn, eds., *Advances in Geophysics,* Vols. 18A and 18B (1974).

[9] Chamberlain, A.C., Deposition, in I.A. Singer, M.E. Smith, and E.W. Bierly, eds., *Conference on AEC Meteorological Activities, May 19-22, 1964,* Brookhaven National Laboratory, Upton, N.Y., 1965.

[10] Bysova, N.L., and K. Makhon'ko, The Interaction of Aerosol with the Ground Surface, *Izvestiya of Academy of Sciences, USSR, Atmospheric and Oceanic Physics,* 4, 9 (1968), 1000-1003.

[11] Clough, W.S., Deposition of Particles on Moss and Grass Surfaces, *Atmos. Environ.,* 9, 12 (1975), 1113-1119.

[12] Yordanov, D.L., and G.D. Djolov, On the Interaction of Diffusing Admixture with Earth's Surface, *Doklady Bolgarskoe Academii Nauk,* 29, 6 (1976), 835-836.

THE INTERACTION BETWEEN ENERGY STRATEGIES AND THE CO_2 QUESTION

CLIMATIC LIMITS TO GROWTH: HOW SOON? HOW SERIOUS?

S.H. Schneider

State-of-the-art climatic models suggest that if present energy consumption and production growth trends continue, the earth may be faced with potentially major and possibly irreversible global climatic changes. By the year 2000, these changes could be as large as any documented since the end of the last ice age. The earth's surface temperature apparently has varied by about 5°C between glacial and interglacial extremes.

Although climate has changed considerably due to natural events throughout geological history, the earth is now at the stage where man may be causing significant inadvertent climate modifications through energy use. We can expect this anthropogenic influence to grow with increasing discharges of environmental pollutants.

Anthropogenic influences on the climate system often are unprecedented in history. Thus to predict their effects, a climate theory in the form of mathematical models is needed since we can't look backward for direct answers. However, current models are unable to yield more than order-of-magnitude estimates and controversy surrounds even these.

From what scientists now know, the largest single influence on future climatic conditions is expected to be caused by a steady increase in atmospheric carbon dioxide (CO_2) concentration--a result of the extended burning of fossil fuels such as oil and coal. An infrared radiation absorber, CO_2 tends to reradiate back to earth some of the heat our planet normally radiates out into space. This is the so-called greenhouse effect which many climate models suggest could raise the global mean surface temperature 1°C by the turn of this century and 2 to 3°C by the middle of the 21st century. These seemingly insignificant changes are sufficient to disrupt the earthly heat and water balance, specific implications of which will be discussed later.

There are other trace gases with strong infrared absorptions in the atmosphere which could also increase in concentration. Notable among these is nitrous oxide (N_2O), a by-product of chemical reactions in the soil and oceans. N_2O might be increasing as a result of the rapid growth in the use of nitrogen fertilizers--essential ingredients needed to step up food production for the world's growing population.

The following table indicates other sources of N_2O:

Comparison of natural and human sources of fixed nitrogen.

Source: Delwiche (1977)

	Rate Tg/yr
"Natural" (historic) biological	60
Atmospheric processes	7.4
Grain legumes	40.6
Hay and pasture legumes	28.4
Fossil fuel and other combustion	19.8
Industrial fixation	40

Relatively little is known about the overall global climatic implications of the nitrogen cycle, but some evidence indicates that an increased amount of N_2O in the atmosphere contributes to a breakdown of the ozone layer, our stratospheric protection against harmful ultraviolet rays of the sun. Enhanced dosages of UV radiation could lead to more cases of human skin cancer and biological damage to plants and animals.

These are still highly controversial issues owing to large uncertainties about both photochemical and climatic factors concerning ozone. Less controversial is the possibility that N_2O could also contribute to the greenhouse effect.

Although human activities--most notably the increasing use of nitrogen fertilizers--pose a serious interference in this geochemical cycle, the combustion of CO_2 fossil fuels for energy is likely to bear much more serious consequences for global climatic change. The future impact of N_2O on climate seems to be at most about 1°C by the middle of the next century, several fold less than current estimates of CO_2 effects.

CO_2: THE BIGGEST GLOBAL ISSUE

CO_2 is known to be a relatively stable gas chemically; and it is believed that somewhat less than one half of the added CO_2 goes into solution in the oceans or is taken up by some of the forests of the world. But tropical forests may be shrinking due to mankind's activities, so the biosphere may not be absorbing as much CO_2 as expected.

Observations show that the CO_2 content of the atmosphere has increased from its pre-Industrial Revolution level, which is estimated to have been between 265 to about 290 ppmv, to a present value of 330 ppmv (about .03% of the atmosphere). Assuming a continued increase of 3 to 4 percent annually in fossil fuel use, of which roughly one half continues to remain airborne, the level will approach 440 ppmv by the year 2000 and may *double* its pre-Industrial Revolution value by the middle of the next century.

Oceanographers have concluded that, even though the entire ocean volume has a very large capacity for the added CO_2, the slow rate of surface water and deep water mixing implies that the oceans would need centuries to absorb most of the excess airborne CO_2. Thus, much of what we are adding will probably remain in the atmosphere for some time.

ATMOSPHERIC AEROSOLS--MUCH UNCERTAINTY REMAINS

Burning fossil fuels also adds particulate matter (aerosols) to the atmosphere. However, current numerical model experiments with atmospheric anthropogenic aerosols are more ambiguous than the CO_2 experiments, and doubt remains as to whether aerosols might heat or cool the earth's surface; furthermore, there are few results on how they might influence the physics of clouds. Anthropogenic aerosols may act as cloud condensation nuclei or ice nuclei and thereby affect cloud processes, although little is understood about this subject. Most model results are still not able to assess confidently whether aerosols might contribute to cooling or heating the climate, let alone gauge an overall magnitude of effect. Of course, this ambiguity is not equivalent to the statement that aerosols therefore pose no serious global climatic problem. In fact, there is evidence that aerosols, locally and regionally, may contribute to precipitation anomalies around urban areas.

LOCAL AND REGIONAL EFFECTS--ALREADY AN ESTABLISHED EFFECT

Urban-industrial areas cause local changes in temperature and probably also in rainfall, thunderstorms, and related climatic elements. This may be due to the fact that a significant quantity of heat is released locally and much of the area is paved over, thus reducing the cooling effects of evaporation. Also, burning fossil fuels adds particulate matter, or aerosols, to the atmosphere. Some evidence points to anthropogenic aerosols acting as cloud condensation nuclei or ice nuclei, promoting anomalous precipitation around urban areas where more particulates are produced. Little is understood about this subject, just as there is considerable question as to whether aerosols might contribute to a heating or cooling of the earth's surface.

But extremely large concentrations of surface heating could trigger some atmospheric convective instabilities that might lead to severe convective storms. And who might be liable for damages from such storms is a legal problem that has not been sufficiently considered.

However, there may be a larger future problem than this local scale modification if present increases in energy use continue. Such growth has the potential for creating regional "heat islands" (from extensive urban sprawl or energy generating power parks) which could force changes in atmospheric patterns that might well extend beyond a particular region.

IMPLICATIONS OF A CO_2-WARMED EARTH

Briefly, what are some of the implications of a warmer earth should CO_2 prove, as it now seems, the dominant human influence on climate?

There will almost surely be shifts of the agriculturally productive areas. Some models suggest that land areas in the subtropics may become more productive as a result of a more favorable rainfall, the growing season will be longer at high and midlatitudes; but there may be less rainfall in some places that are now "breadbaskets" such as the midwestern United States. The southern Rocky Mountains or the Sierra watershed regions could also be seriously affected.

Energy-induced climatic changes affect human health, ecosystems, and sociopolitical systems--all highly interrelated. Human health is often strongly influenced by local climates, and animal species (including humans) or an ecosystem (such as food crops) in a marginal environment may not be capable of existing stably under prolonged climatic stress.

Lowered crop yields that in some places would result from inadvertent climate modifications would most likely place severe stresses on human societies. While other areas might benefit from climate changes, it is not yet possible to say definitively where this would occur. What impact climatic changes might have on the quality of life may be the most significant problem of all, while perhaps the least quantifiable.

FACTS AND VALUES

It still remains to refine present knowledge of the climatic system and to improve substantially state-of-the-art estimates of inadvertent climatic effects of human activities. Tackling these subjects not only requires further research, but some social definition of "acceptable risk".

It is unlikely that scientists will provide reasonable certainty of the magnitude and timing of potential climate modifications before the atmosphere "performs the experiment" itself. Certain proof of the CO_2 greenhouse theory will come only after roughly a generation, since scientists believe that, if the present models are roughly correct, climatic change from CO_2 increases can be unambiguously detected by the end of this century. That is, the warming predicted will be a large enough "signal" (about 1^0K) to exceed the "noise" (about 0.5^0K) of the natural climatic fluctuations.

Do we want to take the chance of adopting a "wait-and-see attitude" until present estimates can be verified? If we have underestimated the effects of CO_2 in our present theories, then we could already be moving toward significant climatic change for which *additional years of study only commits posterity to an even larger consequence than if action were taken now to reduce the input of* CO_2.

Since it takes at least a generation to significantly alter energy production technologies or economic dependence on energy use, public policymakers must begin to consider the predictions of climatic theory today when most scientists--including this one--are generally dissatisfied with the state of the art of climatic theory and modeling. Even though there is still debate--and will be for decades--in scientific circles, society should not allow this to obscure the urgency of the problem

No scientist has sufficiently expert credentials to tell society what level of climatic (or any other) risk is "acceptable" or how those risks should be weighed against the benefits of fossil fuel energy. Scientists are only experts in estimating the potential range of risks and benefits, the confidence with which present estimates can be viewed, and roughly how long it will be before research can narrow the range of uncertainties relative to the occurrence of those risks and benefits.

Perhaps, for those issues where the uncertainties appear to be easily reduced by research well before the worst consequences are expected, the correct public policy would be only to encourage more research. But for a number of climatic issues, we need to consider taking actions now, in addition to studying more, for the worst expected consequences are already knocking at the climatic door.

ACTION IN THE FACT OF UNCERTAINTY: SOME SUGGESTIONS

But what can be done to hedge against possibly committing future generations to potentially irreversible climatic changes? No action (including inaction) in the face of such uncertainties is without risks, and choosing these is a value issue. Nevertheless, several steps to minimize society's vulnerability to such changes are suggested here. The idea of minimizing vulnerability to climatic changes by maintaining flexibility and reserve capacities--of food or water, for instance--is what I have previously called a "Genesis Strategy" (Schneider with Mesirow, 1976). These are:

1. *Learn the Range of Possibilities so that Facts and Values Can be More Easily Disentangled:* Personal value judgments of how to react to the risks of CO_2 in the face of technical uncertainty need to be considered now. We can *hope* present mathematical models have overestimated the problem and continue adding CO_2 to the atmosphere, or we can play it safer and behave as though the models are underestimating the potential adverse effects and act now to reduce CO_2 input or minimize our vulnerability to climatic changes.

2. *Focus Current Energy Debate on Growth Rate Issues, Particularly for Third World Countries:* Recognize now the urgency and immediacy of the energy growth debate and what it will mean to constrain the amounts of CO_2 released. Many countries are striving to improve their standards of living through the use of more energy, and they are not likely to agree voluntarily to a halt of such "progress". Should the heavy energy consumers in developed countries compensate by cutting back per capita energy use in exchange for a lowered birth rate in developing countries? (I have called this the "Global Survival Compromise" (Schneider with Mesirow, 1976).)

3. *Conserve Energy and Develop Viable Solar or Other Renewable Resources:* Striving to become more energy end-use efficient, curbing wastefulness, and conserving energy are steps all countries should take. In addition, we can accelerate the development of more economical solar, wind, and geothermal power--renewable energy sources that can have less significant global pollution impacts.

4. *Begin Now to Minimize our Economic Dependence on Energy Growth:* Try to decouple our economic system and its growth rate from heavy dependence on energy growth. Minimizing the economic consequences of slowed energy growth needs to be done as soon as possible. This step would reduce risks associated with growth of all sources of energy, and not just fossil fuel.

These suggestions are the barest outline of the kinds of steps we need to consider in response to the energy/climate problem. *We do not have ten years to wait before acting without significant increase in risks.* Ten years of delay will put us ten years closer to potentially irreversible changes. To decide to accept that risk is to make a value judgment, not to give an expert opinion.

Policymakers must realize that the tough decisions that have to be made generally are value judgments of how to weigh risks and benefits in the face of large uncertainties. In many cases, scientists cannot definitively assess the risk/benefit issues and thereby simplify the politicians' decisionmaking. Scientists are, of course, obligated to narrow these uncertainties as quickly as possible--which means more focused, interdisciplinary research. Narrowed uncertainties make choosing a course of action easier. But in the case of CO_2 we can't wait for research to turn up more technical certainty without some additional risk; we need political decisions today to weigh those risks versus hedges against them.

Weighing the risks of possible climatic changes against the benefits of continued and increased fossil fuel consumption is a process long overdue. The current energy debate does not address these issues sufficiently and the omission is serious. It is irresponsible to ignore them.

REFERENCES

Delwiche, C.C. (1977), Energy Relations in the Global Nitrogen Cycle, *Ambio*, 6, 2-3, 106-111.

Schneider, S.H., with L.E. Mesirow (1976), *The Genesis Strategy: Climate and Global Survival*, Plenum, New York.

ESTIMATES OF A COMBINED GREENHOUSE EFFECT AS BACKGROUND FOR A CLIMATE SCENARIO DURING GLOBAL WARMING

H. Flohn

Any comparison of past temperatures and the expected increase of the greenhouse effect must take into account that, in addition to CO_2 (Schneider, 1975), other (at least partially man-made) gases absorb terrestrial radiation, particularly in the window region between 7.5 and 12 µm just below the region of strong CO_2 absorption (12-18 µm: Ramanathan, 1975; Wang et al. 1976). The strongest absorber of infrared radiation is water vapor: the global amount of evaporation (and precipitation) has been estimated recently to be 496×10^3 km^3/a, equivalent to a water column of 973 mm/a (Baumgartner and Reichel, 1975). The man-made evaporation over land has been estimated as 1800 km^3/a for 1965 (Lvovich, 1969); this should probably rise to about 2500 km^3/a by 1980 (Flohn, 1977). This is equivalent to only 0.5% of the global value, which is certainly within limits of error, and can be neglected in global considerations.

While the future increase of the CO_2 concentration has been investigated by many authors, the role of trace gases has only recently been recognized.[1] Wang et al. (1976) have taken a one-dimensional radiative-convective model with fixed relative humidity. Cloudiness changes can be taken into account by assuming either a fixed cloud-top altitude (CTA) or a fixed cloud-top temperature (CTT). According to these investigations, the combined effect of the man-made trace gases is of the same order of magnitude as that of CO_2--any neglect of these processes could lead to a great underestimation of the total greenhouse effect. Table 1 gives a condensed form of Wang's table, together with the results of an (apparently similar) model for the CO_2-temperature relation presented by Augustsson and Ramanathan (1977). In contrast to the frequently quoted Manabe and Wetherald (1975) model, both the Wang and the Augustsson and Ramanathan models neglect atmospheric dynamics and transports. The radiation-cloud relation is only approximately included; any feedback between temperature and snow-ice albedo is excluded. Thus the results can only be taken as *representative for low and middle latitudes*, while in subpolar and

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[1] See the papers by K.Ya. Kondratyev and A.M. Bunakova, and by R. Reck, in these Proceedings.

Table 1. Greenhouse effects arising from changes of atmospheric constituents (after Wang et al., (1976), Augustsson and Ramanathan (1977), indicated as W and AR).

Constituents	Present Concentration	Increase in % 1)	Greenhouse Fixed Cloud-Top Alt. (CTA)	Effect Fixed Cloud-Top Temp. (CTT)	(°K) Source
CO_2	320 ppm	100	1.98	3.2	AR
CO_2	330 "	25	0.53	0.79	W
O_3	0.34 cm	- 25	-0.34	-0.47	
H_2O (strato-sphere)	3 μg/g	100	0.65	1.03	
N_2O	0.28 ppm	100	0.44	0.68	W
CH_4	1.6 "	100	0.20	0.28	
CCl_2F_2+ CCl_3F	0.2 ppb 2)	factor 20	0.36	0.54	
CCl_4 +CH_3Cl	0.6 ppb	100	0.01	0.02	W
NH_3	6 "	100	0.09	0.12	
C_2H_4	0.2 "	100	0.01	0.01	
SO_2	2 "	100	0.02	0.03	

1) All assumed growth rates in the Wang model are estimated for the year 2020; the AR model is independent of time.

2) ppb = 10^{-9} volume parts.

polar latitudes the temperature effect (as shown by Manabe and Wetherald 1975) must be amplified by a factor near 3. Estimates from the CTA model version of the Augustsson and Ramanathan model do not differ much from the results of Manabe and Wetherald (1975): with a doubling of the CO_2, the latter model yields for the latitude belt 0 to 30° a warming of 1.92 C, for lat. 0 to 50° of 2.20 C, since the albedo-temperature feedback is only effective poleward of lat. 55°. Recent investigations of the dependence of actual temperature fluctuations on latitude (Borzenkova et al., 1976) indicate that over the last 100 years the amplitudes in polar latitudes are amplified also by a factor near 3 when compared with those of middle and low latitudes.

Table 1 shows that the Wang and Augustsson-Ramanathan models coincide well in estimating the CO_2 greenhouse effect, with the assumption that the temperature increase up to the first doubling of CO_2 can be taken as nearly linear (Figure 1). Considering future changes of the stratospheric constituents due to increasing supersonic traffic, the changes in O_3 and H_2O content are probably too high, since it is doubtful that this traffic will reach the levels used by Wang in his calculations. While the sum of infrared absorption by a decrease of O_3 and an increase of stratospheric H_2O yields additional warming (Table 1), it is here assumed that the two effects tend to cancel each other.

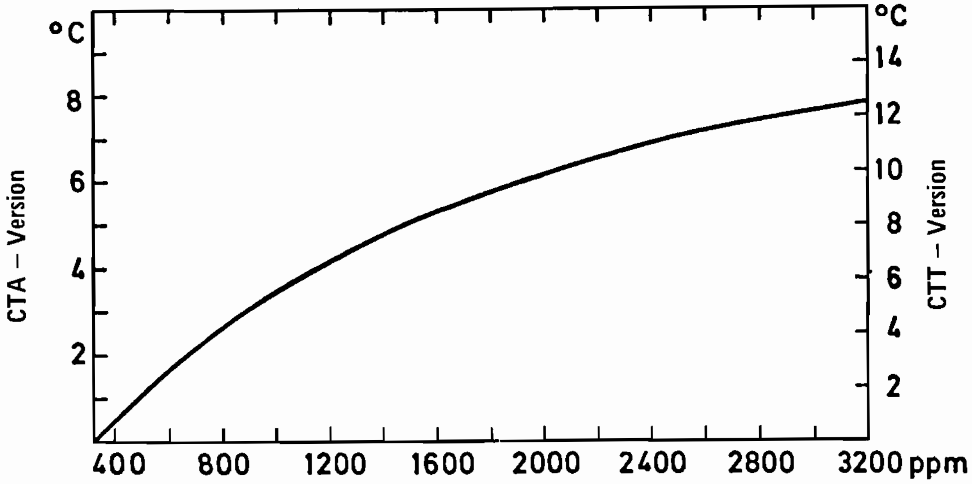


Figure 1. CO_2 concentration and equivalent surface temperature, Augustsson and Ramanathan model.

One of the most important trace constituents is N_2O, produced by the denitrification of fertilizers in the soil. In this case, a strong increase seems unavoidable, keeping in mind all uncertainties of the complex nitrogen cycle in the environment including the uncertainty as to atmospheric residence time of nearly 70 years (Söderlund and Svensson, 1976). During the period 1962-1974, the annual average increase in nitrogen fertilizers was as high as 10.7% (Pratt et al., 1977). Even with a linear growth rate of this order, one could expect by the year 2000 an increase of 170%, instead of 100% as assumed by Wang for 2020. Pratt estimates the increase from the 1974 level between 200 and

450%. The assumption of an exponential rise of 10% annually seems unrealistic. However, two of the absorption bands of N_2O (at 7.78 and 17.0 μm) are situated at the flanks of much stronger bands of H_2O and CO_2 respectively (see Figure 1, Wang et al., 1976). Thus the question of overlapping, taking into account the enormous differences in concentration, merits further investigation.

CH_4 is considered a conversion product of CO and thus strongly correlated with the burning of fossil fuel. The great contribution of the chlorofluoromethanes (CFMs) is derived from their chemical inertia and thus from their estimated residence time of 30 to 50 years in the atmosphere. Since there are now strong efforts to prohibit the use of these freons in refrigerators, aerosol sprays, etc., we may reduce their increase from factor 20 to factor 3, and will assume a linear reduction of the corresponding greenhouse effect. The greenhouse effect of all other gases is small compared with those discussed above.

One point for further discussion is the treatment of the cloud-top conditions, recognizing that the important cloud-radiation feedback cannot yet be handled adequately owing to our ignorance of several important parameters of these processes. While Augustsson and Ramanathan prefer to hold cloud top altitudes constant, Wang et al. consider the assumption of a constant temperature of cloud tops more plausible. The CTA version appears to be more consistent with the assumption of constant relative humidity. Table 1 shows that the CTA version is less sensitive than the CTT version. The author feels that it is more appropriate to remain on the conservative side and prefers to use the CTA version; comparison results from the CTT version are also given.

Taking the results from Wang's model, and assuming that his estimated growth rates are a reasonable first order assumption (except for O_3, stratospheric H_2O, and Freon, see above), one may start from an increase of CO_2 from 330 to 412 ppm, equivalent to a warming of 0.53°K (CTA) or 0.79°K (CTT). One has also to expect from N_2O, CH_4, CFMs, and other gases a warming of 0.81°K (CTA) to 1.19°K (CTT), i.e., in the two cases a 150% more warming than would be the case with CO_2 alone. Adding the full effects of supersonic transport (O_3 and H_2O) as indicated by Wang et al., this would give a further warming of 0.31°K (CTA) to 0.56°K (CTT)--in other words, an addition to the CO_2 greenhouse effect by 212 to 228%. The author prefers to disregard this possibility. Undoubtedly this conservative attitude could be unjustified: our estimates are *more probably too low than too high*. The role of the individual gases has been considered by Wang et al. to be independent of each other, thus an additive effect is given. In view of the manifold uncertainties, one need not take this result as necessarily representative; but it would be irresponsible to ignore it. All these constituents have weak absorbing bands in the infrared window between the strong absorption bands of H_2O and CO_2, similar to the well-known 9.6 μm band of ozone. The physical processes of trace gases in the window region 7.5 to 12 μm are similar to those of CO_2; together these gases act as venetian blinds attached to the atmospheric window.

To remain on the conservative side, the author proposes to add 50 or 100% to the increase in CO_2 content (above the 320 ppm base used by Wang), and to express this combined greenhouse effect (CGE) in units of a *virtual* CO_2 concentration to be given in ppm*. An increase of the real CO_2 content of 50 (100, 200)% is then equivalent to a contribution of 67 (50, 33)% of the real CO_2 increase to the virtual CO_2 content of CGE. That is, if we use the relation between CGE expressed in ppm* and temperature according to Figure 1, then the real CO_2 value at this same level is given in the right-hand column of Table 2. The first of these columns (in brackets) refers to an increase of CO_2 of 200% for trace gases, equivalent to a contribution of one third by the increase of CO_2, two thirds by the sum of other trace gas increases to the virtual CO_2 content. This assumption is taken as probably unrealistic, while the other two assumptions in columns two and three respectively--equivalent to a contribution of the trace gases of one half or one third to CGE--may serve as more realistic indicators for future development.

Table 2. Estimated increase of near-hemisperic temperatures and equivalent changes of the virtual (ppm*) and real (ppm) CO_2 content, both estimated from the Augustsson and Ramanathan model.

	Temperature increase 1)		Virtual CO_2 content	Contribution of real CO_2 to combined greenhouse effect (CGE) 33%	50%	67%
CTA	+ 0.5°K	(perception of warming)	400 ppm*	(346)	360	374 ppm
	+ 1.0°K	(Medieval warm phase)	490	(376)	405	432
	+ 1.5°K	(Holocene warm phase)	580	(406)	450	492
	+ 2.0°K	Eem interglacial period	670	(435)	495	555
	+ 2.5°K		760	(465)	540	615
	+ 4.0°K	Ice-free Arctic Ocean 2)	1150	(560)	740	878
CTT	+ 0.5°K		365 ppm*	(335)	342	350
	+ 1.0°K		420	(353)	370	386
	+ 1.5°K		475	(371)	398	422
	+ 2.0°K		530	(390)	426	458
	+ 2.5°K		590	(409)	455	498
	+ 4.0°K		780	(465)	555	630

1) Augustsson and Ramanathan model.

2) Budyko model.

COMBINED GREENHOUSE EFFECT AND ITS POSSIBLE TIME SCALE

Climatic fluctuations with a time scale of between one year (climatic "anomalies") and some centuries or longer have occurred from time immemorial. These irregular fluctuations are part of the mechanism of the climatic system with its many interacting subsystems and different time scales. In addition to these *internal* processes, some *external* events probably cause climatic fluctuations, such as possible changes of solar radiation in different parts of the spectrum, heavy volcanic eruptions, and possibly the little known surges of the West Antarctic ice-dome.

For our purposes such natural causes should be disregarded. At present they are unpredictable, and there is little hope that they will be predictable in the foreseeable future. Owing to the lack of sufficient knowledge of the interaction between radiation and cloudiness (GARP, 1975), it is also necessary to disregard possible changes of the cloudiness; some considerations (Cess, 1976, 1977) seem to indicate that this effect remains negligible. Most clouds, except inversion stratus, are produced by ascending motions of convective or advective scales and disappear with subsidence; owing to the conservation of mass the average cloudiness is expected to remain rather constant. These limiting assumptions should be borne in mind when discussing possible man-made or man-triggered climatic fluctuations. In this situation, only a "prediction of the second kind" is realistic, i.e., a prediction of what may happen after a change in the boundary conditions of the present climatic situation, all other effects being constant.

Under these conditions, a scenario of future climatic evolution in the case of man-made global warming must be based on some relationship of temperature and greenhouse effect. In our case we have to distinguish between the pure CO_2 greenhouse effect and the effective CGE (see Table 2). To outline typical paleoclimatic stages characterized by a representative temperature increase, the climate model of Augustsson and Ramanathan (Figure 1) can be used.

Table 2 considers the CTA version of the model as well as the more sensitive CTT version. The first threshold may be selected as the level of warming that can be derived unambiguously from current data sources (see for example van Loon and Williams, 1976, 1977; Borzenkova et al., 1976), taking into account the large gaps of the climate stations network and the unavoidable inhomogenities of individual temperature records. Since the Augustsson and Ramanathan model does not take into account the ice-snow-albedo-temperature feedback, the (annual) temperatures given here are only representative if one excludes polar and subpolar regions and limits the consideration to about 80% of the earth's surface. This "level of perception" for a quasiglobal warming can be estimated to be 0.4 to 0.5 C. Using the CTA version and the last two columns of Table 2, one finds a corresponding real CO_2 level of 360 to 375 ppm. Figure 2 gives a time scale for the expected temperature levels--derived from the CTA version of the Augustsson

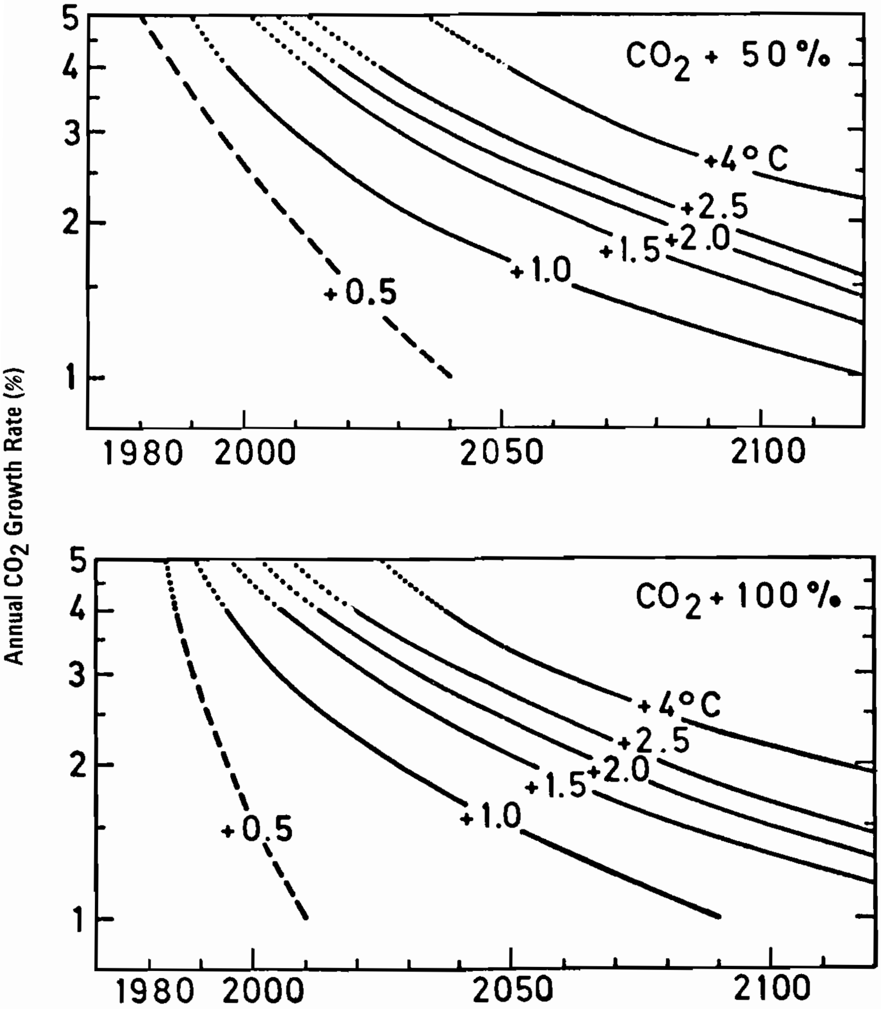


Figure 2. Sample of curves representing different temperature thresholds, derived from CTA version of the Augustsson and Ramanathan model, plotted as a function of time and the initial CO_2 growth rate for two values of the combined greenhouse effect (CGE), above and below.

and Ramanathan model (Figure 1)--using CGE (Table 2) and the Zimen CO_2 growth rate model (see Figure 3 in Morgan, 1977). In view of recent developments in the global carbon cycle modeling, a revision using more realistic models (e.g., Zimen 1977) seems necessary. Assuming that the more recent growth rates of 3.5 to 4%/a are continued, it can be concluded that this level will be reached between 1990 and 2000. Under the same assumption, the CTT version would yield a date between 1985-1990.

The other threshold values (Table 2) are estimates of the representative temperature changes over land areas during some characteristic paleoclimatic stages, starting from the early Middle Ages (ca. 900 to 1100 AD), the postglacial (Holocene) optimum (about 6500 to 5500 BP), and extending backwards to earlier interglacials. The next threshold is equivalent to the last interglacial period (the Eem stage), as described by Frenzel (1967, 1968), coinciding with stage 5e as defined by Emiliani and Shackleton (1974) (about 125,000 BP), which is now the object of a new global-scale investigation by members of the CLIMAP Program. The author has selected these stages as a background for a scenario for possible future climatic changes.

From the practical point of view, one of the most important questions is: *when* are these different temperature and CGE thresholds (and their possible climatic consequences) expected? The answer to this question depends on developments and decisions in the fields of economics and politics in a pluralistic, multilevelled society, which remain beyond any forecast based on physical sciences. It is only possible to outline the range within which these dates can vary, dependent on fairly realistic growth rates. At present such growth rates can at best be estimated for CO_2, but not for all other trace gases contributing to the CGE. While the present worldwide economic situation seems to tend, in the long run, to a lowering of the CO_2 growth rate, probably below 4%, the growth rates of other constituents (particularly N_2O) may remain higher (or even increase) in the future; thus the CGE growth rates could be somewhat higher. Apparently the growth rate of the world's population decreased in the most recent years, from its peak above 2%/a to slightly lower values; this may announce the transition from an exponential to a logistic (i.e. sigmoid) growth curve and, eventually, to a stabilization.

Lacking a sound scientific base for a realistic estimate of future CGE growth rates, two assumptions should be made:

- Since the infrared radiation processes in the window range are, in principle, similar to those in the CO_2 bands, the Augustsson and Ramanathan model (Figure 2) can be taken also as representative of the relationship of CGE and representative surface temperatures (excluding polar and subpolar latitudes).

- The development of CGE growth rates can be described, as a first approximation, by the logistic Zimen model given initial CO_2 growth rates varying between 1 and 4%/a. In the light of recent improvements in our knowledge of the CO_2 cycle--especially the exchange processes with the biosphere and the ocean (Bolin 1977; Woodwell 1978; the Report of Working Group I in these Proceedings)--the Zimen model could also be revised.

Until these revisions are available, only an approximation is possible. The logistic function, which is dependent on the gradual depletion of available resources, is primarily intended for the consumption of fossil fuel, while some other constituents of CGE are either renewable or far away from a depletion of their resources. The CGE concept is inherently complex.

This approximation is given in the last two columns of Table 2. The full weight of trace gases as suggested by Wang et al. would provide for a CO_2 contribution to CGE of only 33%. This would yield a dramatic acceleration of the expected processes; it should be taken only as an upper limit. Figure 2 gives, as a two-dimensional diagram as a function of the CO_2 growth rate of the real CO_2 (logarithmic scale) versus time, a sample of curves representing different temperature thresholds derived from the Augustsson and Ramanathan CTA model (Figure 1), using CGE values (in ppm* instead of ppm) as input.

With a CO_2 increase of 1%/a--which is utterly unrealistic, since it assumes a decrease of energy consumption per capita--the temperature rise would be quite slow and remains imperceptible until about 2010 or 2040. With an initial 4% growth rate (the current rate), the 1.5° threshold--equivalent to the Holocene climatic optimum--will be reached between 2005 and 2015, the 2.5° threshold between about 2020 and 2030. This latter level represents the warmest period in climatic history--the Eem stage--since the paleomagnetic Brunhes/Matuyama boundary at 700,000 BP. Taking into account less conservative model parameters, this level could be reached as early as 2010. However, it must be realized that these figures are taken from a small printed figure and are thus slightly uncertain.

Budyko (1969, 1972) suggested the possibility of a disappearance of the drift-ice from the Arctic Ocean--a situation which, according to most recent data (Herman, 1978), has not been observed over the past 2.3 million years, i.e., since the start of the Pleistocene epoch. More recently Budyko (1974) estimated the increase of summer temperature needed to cause this melting to be 4°C (see also Kellogg 1977, 1978). This value may be taken here as representative of the necessary change of the annual temperature (Table 2). Unfortunately, estimates with more sophisticated models are hitherto unavailable. If it is realistic, one could expect such an extreme change, with an annual growth rate between 3 and 4%, as early as between 2040 and 2075. Only with lower average growth rates could this event be delayed until the twenty-second century.

REFERENCES

Augustsson, T., and V. Ramanathan (1977), A Radiative-Convective Model Study of the CO_2-Climate Problem, *J. Atmos. Sci.*, 34, 448-451.

Baumgartner, A., and E. Reichel (1975), *The World Water Balance*, Oldenbourg, Munich.

Bolin, B. (1977), Chances of Land Biota and Their Importance for the Carbon Cycle, *Science*, 196, 613-615.

Borzenkova, I.I., et al. (1976), Fluctuations of Air Temperature at the Northern Hemisphere During the Period 1881-1975, *Meteor. i. Gidrol*, No. 7, 29-35 (in Russian).

Budyko, M.I. (1969), The Effect of Solar Radiation Variations on the Climate of the Earth, *Tellus*, 21, 611-619.

Budyko, M.I. (1972), The Future Climate, *Transact. Amer. Geophys. Union*, 53, 868-874.

Budyko, M.I. (1974), *Climatic Changes*, Hydrometeoizdat, Leningrad (in Russian).

Cess, R.D. (1976), Climatic Change: An Appraisal of Atmospheric Feedback Mechanism Employing Zonal Climatology, *J. Atmos. Sci.*, 33, 1831-1843; Discussion see *J. Atmos. Sci.*, 34 (1977), 1824-1827.

Emiliani, C., and N.J. Shackleton (1974), The Brunhes Epoch: Isotopic Paleotemperatures and Geochronology, *Science*, 183, 511-514.

Flohn, H. (1977), Some Aspects of Man-Made Climate Modification and Desertification, in H. Mensching and J. Honholz, eds., *Applied Science and Development*, Vol. 10, Institute of Scientific Cooperation, Tübingen.

Frenzel, B. (1967), *Die Klimaschwankungen des Eiszeitalters*, Vieweg, Braunschweig.

Frenzel, B. (1968), Grundzüge der pleistozänen Vegetationsgeschichte Nord-Eurasiens, in *Erdwissenschaftliche Forschung*, Vol. 1, Steiner, Wiesbaden.

GARP (1975), *The Physical Basis of Climate and Climate Modelling*, GARP Publications Series, No. 16, World Meteorological Organization, Geneva.

Herman, Y. (1978), personal communication.

Kellogg, W.W. (1977, 1978), Effect of Human Activities on Global Climate, Parts I and II, *WMO Bulletin*, 26 (1977), 229-240; 27 (1978), 3-10.

Lvovich, M.J. (1969), *Water Resources for the Future*, Posveshchenie, Moscow (in Russian).

Manabe, S., and R.T. Wetherald (1975), The Effects of Doubling the CO_2 Concentration on the Climate of a General Circulation Model, *J. Atmos. Sci.*, 32, 3-15.

Morgan, J.J., rapporteur (1977), Source Functions: Fossil Fuel Combustion Products, Radionuclides, Trace Metals, and Heat Group Report, in W. Stumm, ed., *Global Chemical Cycles and Their Alterations by Man*, Abakon Verlagsgesellschaft, Berlin.

Pratt, R.F., et al. (1977), Effect of Increased Nitrogen Fixation on Stratospheric Ozone, *Climatic Change*, 1, 109-135.

Ramanathan, V. (1975), Greenhouse Effect Due to Chlorofluorocarbons: Climatic Implications, *Science*, 190, 150-152.

Schneider, S.H. (1975), On the Carbon Dioxide-Climate Confusion, *J. Atmos. Sci.*, 32, 2060-2066.

Söderlund, R., and B.H. Svensson (1976), The Global Nitrogen Cycle, *Ecological Bulletin*, 22 (1976); SCOPE Report No, 7, Paris.

van Loon, H., and J. Williams (1976, 1977), The Connection Between Trends of Mean Temperature and Circulation at the Surface, Parts I-IV: *Monthly Weather Review*, 104 (1976), 365-380, 1003-1011, 1591-1596; 105 (1977), 636-647.

Wang, W.C., et al. (1976), Greenhouse Effects Due to Man-Made Perturbations of Trace Gases, *Science*, 194, 685-690.

Woodwell, G.M. (1978), The Carbon Dioxide Question, *Sci. Am.*, 238, 34-43.

Zimen, K.E., P. Offermann, and G. Hartmann (1977), Source Functions of CO_2 and Future CO_2 Burden in the Atmosphere, *Z. Naturforsch.*, 32a, 1544-1554.

THE EFFECTS OF DIFFERENT ENERGY STRATEGIES ON THE ATMOSPHERIC CO_2 CONCENTRATION AND CLIMATE

J. Williams

In order to assess the future atmospheric CO_2 concentration and its implications, three models are required. An energy model is used to estimate the future use of fossil fuels, and thus to estimate the input of fossil fuel CO_2 into the atmosphere. The amount of the fossil fuel CO_2 that remains in the atmosphere can then be given by a model of the carbon cycle, which considers the reservoirs of carbon and the transfers between them. The effects of the atmospheric CO_2 concentration on climate can then be assessed using a climate model. To the results of each of these models must be attached an uncertainty, such that the future use of fossil fuels and the implications thereof can not be predicted. The model results can only be used at the present time to assess the magnitude of the problem.

A preliminary assessment of the time scale of interaction between energy strategies and the atmospheric CO_2 concentration was made at IIASA by W. Häfele and W. Sassin (see Häfele et al., 1976). It was assumed that there would be a population growth from today's 4 billion to 12 billion and that provision must be made for an average per capita energy consumption of 5 kW. It was further assumed that oil and gas would be consumed at first and coal thereafter. Taking a scenario where 200% additional CO_2 is considered as a limit, the use of coal was found to be curtailed to 20% of the world's coal resources assumed at present. Figure 1 shows the implications of these assumptions when different energy growth rates are considered. At a growth rate of 4.5% the limit of 200% increase of CO_2 is reached just beyond 2030; at a growth rate of 2% the limit is reached only 42 years later. This result shows that, within the limits of the assumptions made, the reaching of some imposed limit on fossil fuel consumption is fairly insensitive to technological/economic considerations.

An example of the combined use of an energy model, a carbon model and the results of a climate model is given in the study of Niehaus and Williams (1977), which again shows the range of the CO_2 problem. The model of the carbon cycle has been described by Niehaus (1976, 1977). Exchange rates of carbon and 14 C are simulated between eight reservoirs. The global surface

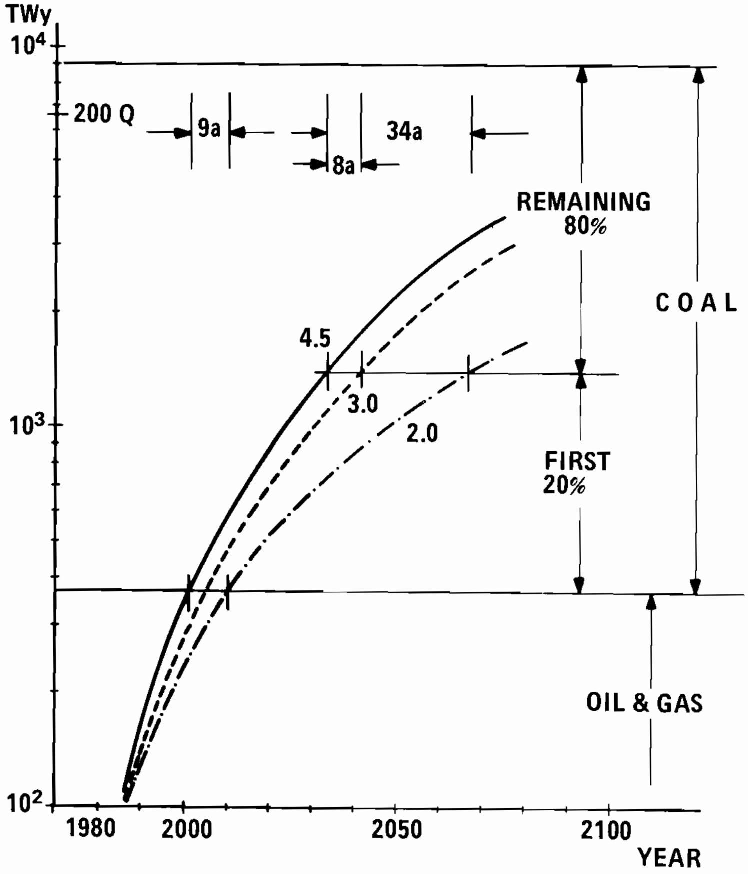


Figure 1. Fossil energy reserves and cumulated energy consumption.

Source: Häfele et al., 1976

temperature response to the increasing atmospheric CO_2 level was assumed from the study of Augustsson and Ramanathan (1977), which gives a best estimate of the average global temperature change of about 1.9°K for a doubling of atmospheric CO_2 concentration. Most of the scenarios for future energy consumption were derived using a global energy model developed by Voss (1977). The latter model considers the dynamics of population growth, interactions between investments, labor and industrial production, the process of capital stock growth, environmental costs, raw materials and the dynamics of substitution of primary energy carriers.

The verification of the carbon model has been described by Niehaus (1976) and Niehaus and Williams (1977). The model reproduced the observed increase of atmospheric CO_2 concentration from 1958 to the present. The Suess effect was simulated to be -1.9% in 1950 in agreement with recent estimates (Broecker, 1977) and the post-1962 decline in $^{14}C/^{12}C$ ratio of atmospheric CO_2 was also reproduced. For each of the scenarios studied an initial value of 298 ppmv for the preindustrial atmospheric CO_2 was assumed.

The results of three scenarios will be discussed here; others are described by Niehaus and Williams (1977). Figure 2 shows a scenario for energy consumption based on a "35 TW Reference Supply Scenario for 2030", which has been described by Häfele and Sassin (1977). The energy consumption in 1975 is assumed to be 7.5 TW of which 0.45 TW is used for non-energetic purposes. The growth rate in energy consumption is assumed to be 3.5% in 1975 decreasing smoothly to 1% by the year 2030 and thereafter. The consumption of oil and gas for non-energetic purposes is 6% of energy demand in 1975 increasing to 11% by 2030 and constant thereafter. It is assumed that the consumption of oil, coal and gas reaches a constant level in the year 2020, such that the annual consumption of coal is 8.06 TW, of gas is 3.52 TW and of oil is 3.47 TW.

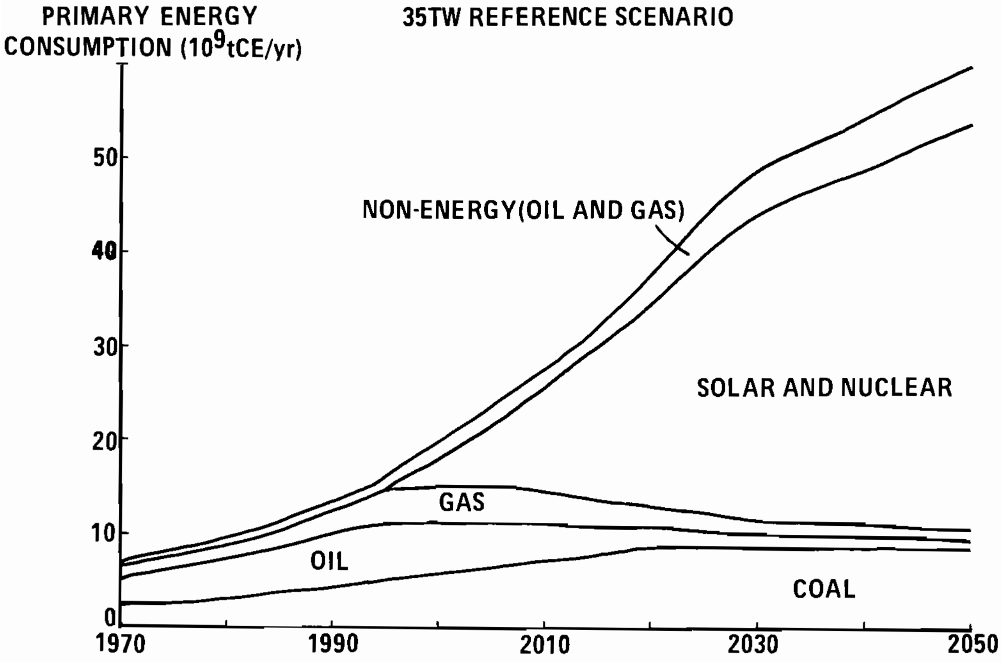


Figure 2. Energy strategy for the 35 TW Reference Scenario.

Figures 3 and 4 show energy strategies, in which the energy model of Voss was used to decide on the distribution of energy supply as a function of time while the total amount of energy was based on estimates given by Riedel (1977). In Figure 3 it is assumed, after Riedel (1977), that energy consumption levels out at 30 TW and that nuclear and solar energy contribute significantly to the energy supply. In Figure 4, the energy consumption is assumed to level out at 50 TW and no nuclear and solar energy are used. Table 1 shows the amounts of fossil fuels used in each of these scenarios for the period 1970-2050.

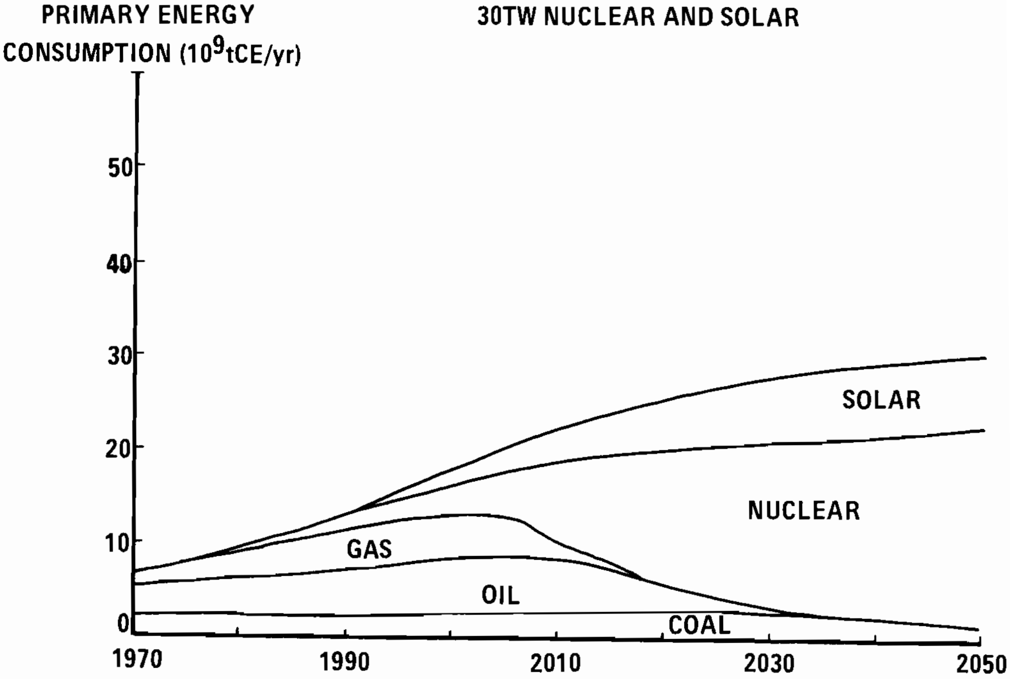


Figure 3. 30 TW energy strategy with nuclear and solar.

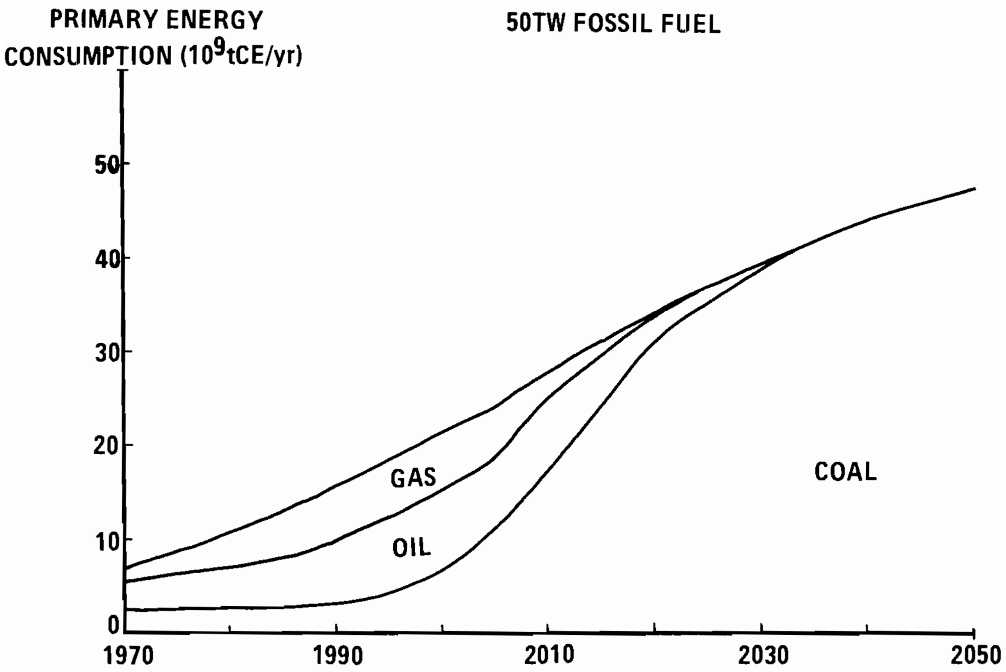


Figure 4. 50 TW fossil fuel energy strategy.

Table 1. Fossil fuel consumption (1970-2050) for three energy strategies and estimates of reserves.

(Figures in 10^9tCE)

Strategy	Coal	Oil	Gas
35 TW Reference Scenario	530	370	280
30 TW with nuclear and solar	210	250	150
50 TW with fossil fuels	1700	330	190
Reserves*	925**	330	245

*Riedel (1977)
**10% recovery rate

Figures 5, 6 and 7 show the atmospheric CO_2 concentrations given by the carbon model for the above three strategies together with the CO_2 emissions implied by the strategies and the estimate of global surface temperature change corresponding to the atmospheric CO_2 concentration.

For the 35 TW strategy (Figure 5) the emissions of CO_2 reach a constant level at about the year 2000; the atmospheric CO_2 concentration continues to increase, reaching a level of about 510 ppmv in 2050 and the corresponding mean temperature increase is about 1.7°C.

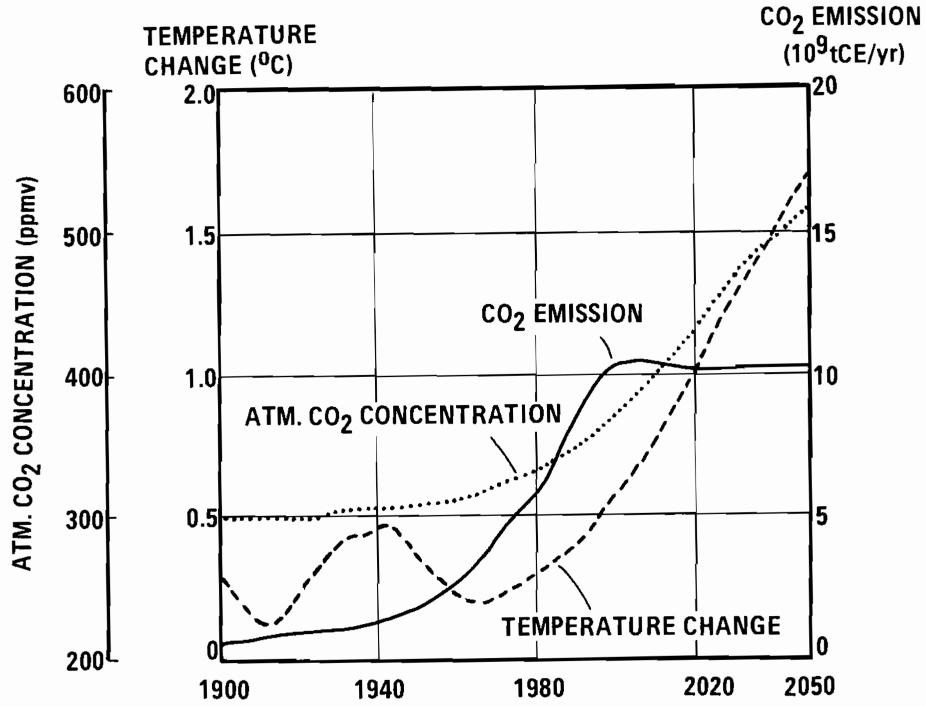


Figure 5. CO_2 emissions, atmospheric CO_2 concentration and temperature change for 35 TW Reference Scenario energy strategy.

For the 30 TW strategy with solar and nuclear energy, Figure 6 shows that the emissions of CO_2 peak at about 2000 and the concentration of atmospheric CO_2 reaches a maximum of 400 ppmv in about 2020. The largest mean surface temperature change associated with this strategy is therefore less than 1°C.

For the 50 TW strategy which considers only fossil fuel consumption the emissions of CO_2 increase until 2050, reaching a value 3.5 times as large as that in the 35 TW Reference Scenario by the year 2050. The atmospheric CO_2 concentration reaches about 800 ppmv in 2050, implying a mean surface temperature increase of about 4°C.

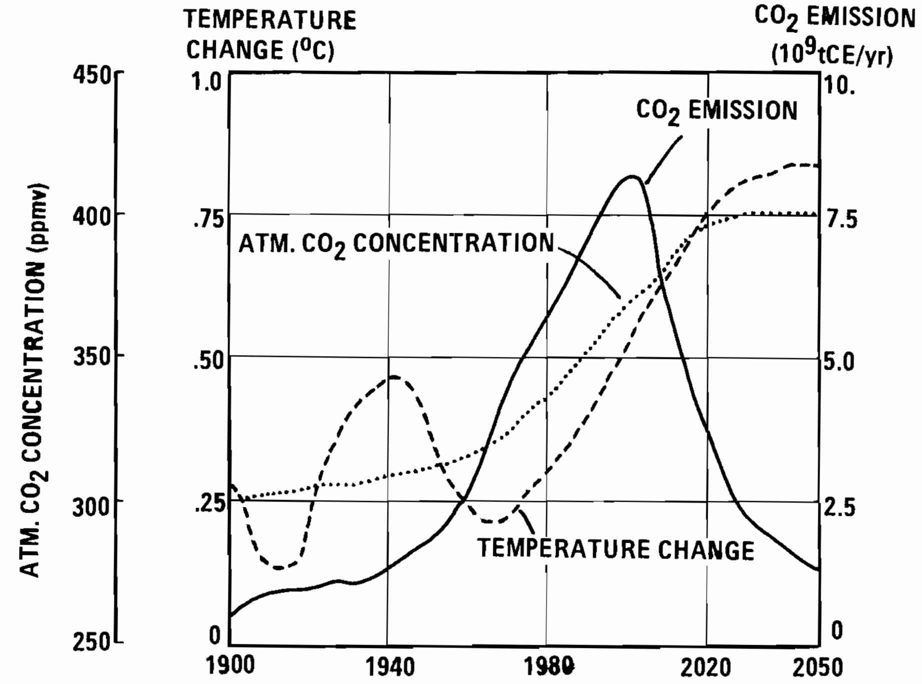


Figure 6. CO_2 emissions, atmospheric CO_2 concentration and temperature change for 30 TW solar and nuclear energy strategy.

The results of the models have many limitations. For example, we have only considered the mean surface temperature change as derived from a one-dimensional radiative-convective model, whereas we know that the climate system is highly complex and that the surface temperature changes in the year 2050 as shown in Figures 5-7 are only indicators of the scale of response to the change in atmospheric CO_2 concentration. Likewise, the carbon model has considered that the biosphere acts as a sink for CO_2, being allowed to grow to 110% of its initial size as a result of the increasing atmospheric CO_2 concentration. As pointed out above, because of such uncertainties in the model results, the latter can only be used at the present to indicate the possible magnitude of the problem. In this regard, the results of the three energy strategies described above show that, if the ultimate level of energy consumption is limited to 30 TW and nuclear and solar energy conversion are relied on,

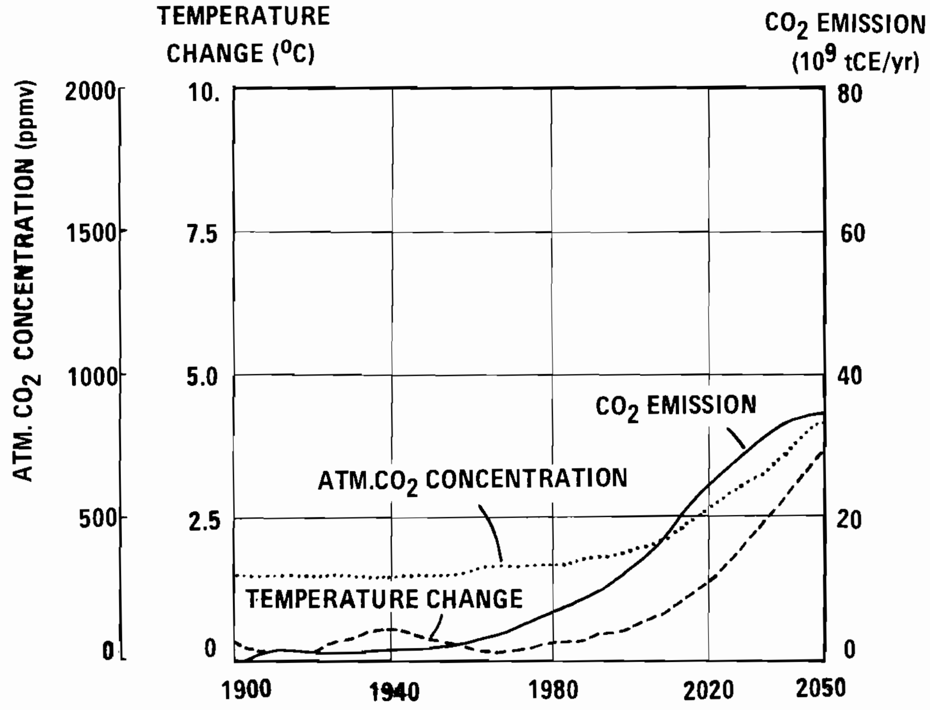


Figure 7. CO_2 emissions, atmospheric CO_2 concentration and temperature change for 50 TW fossil fuel energy strategy.

the climatic effects are small since the mean surface temperature change was computed to be less than 1°C. If the use of fossil fuels increases to levels as shown in the 35 TW Reference Scenario, then the climate effect increases, with a mean surface temperature change of more than 1.5°C. If only fossil fuels are used and if the ultimate level of energy consumption is assumed to be 50 TW, then the climate change by 2050 is considerably larger, with a mean surface temperature change of about 4°C.

Referring to the curves showing the emission of CO_2 corresponding to each strategy it should be noted that each of the three has a different shape. The strategy which results in the smallest climatic effect shows a peak in CO_2 emissions in 2000 and a rapid decline thereafter, while the strategy resulting in the largest climatic effect shows continually increasing CO_2 emissions. An important point which must be considered in the light of these comparisons is that the dynamics of substitution between primary energy carriers, which depends on economic and technical constraints, has a magnitude of decades.

REFERENCES

Augustsson, T., and V. Ramanathan (1977), A Radiative-Convective Study of the CO_2 Climate Problem, *J. Atmos. Sci.*, 34, 448-451.

Broecker, W.S. (1977), *The Fate of Fossil Fuel CO_2: A Research Strategy*, Report of the Scientific Workshop on Atmospheric Carbon Dioxide, WMO-No. 474, WMO, Geneva.

Häfele, W., et al. (1976), *Second Status Report of the IIASA Project on Energy Systems*, RR-76-1, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Häfele, W., and W. Sassin (1977), *A Future Energy Scenario*, paper presented at 10th World Energy Conference, September 19-23, Istanbul.

Niehaus, F. (1976), *A Non-Linear Tandem Model to Calculate the Future CO_2 and C^{14} Burden to the Atmosphere*, RM-76-35, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Niehaus, F. (1977), *Computersimulation langfristiger Umweltbelastung durch Energieerzeugung: Kohlendioxid, Tritium, Radiokohlenstoff*, ISR41, Birkhäuser Verlag, Basel.

Niehaus, F., and J. Williams (1977), *Studies of Different Energy Strategies in Terms of Their Effects on the Atmospheric* CO_2 *Concentration*, paper presented at the Session on the Carbon Dioxide Cycle of the Joint IAGA/IAMAP Assembly, August 17-31, Seattle, Washington, USA.

Riedel, C. (1977), *Zero Order Evaluation of the Supply/Demand Situation in the Various World Regions (1975-2025)*, discussion paper, IIASA Workshop on Energy Strategies: Conception and Embedding, May 17-18, Laxenburg, Austria.

Voss, A. (1977), *Ansätze zur Gesamtanalyse des Systems Mensch-Energie-Umwelt*, ISR30, Birkhäuser Verlag, Basel.

SCIENTIFIC INFORMATION REQUIRED BY POLICYMAKERS AND REGULATING DECISIONMAKERS

H.L. Wiser

I speak as one concerned with protecting human health and welfare and all life on earth. The answers to the questions I pose will be valuable for all decisionmakers. Research to date on global models is an important initial step. However, it is not enough for the scientific community to be able to inform policy- and decisionmakers that the global average temperature will increase a few degrees C. What are the consequences? This question must be answered.

When considering a problem, decisionmakers examine many options. For example, the supply of oil will be depleted early in the next century and that of coal sometime later. Assuming that energy demand continues its present trend, we see that most readily available fossil fuel will be exhausted by the year 2100. The exact date is not important for my scenario. What climatic change would these CO_2 concentrations in the atmosphere produce? The effects for this extreme case would be a global average temperature increase of about 10°C.

Assume, for example, the case of a 10°C increase. What will be the effect on climate, precipitation, sea level, biota, agricultural production, energy demand, and so forth? Solutions must be sought not only globally but also on a regional climate basis, because regions are affected differently. More regional climate modeling studies are therefore needed.

Another important question concerns reversibility. If CO_2 emissions are reduced drastically, will ambient CO_2 concentrations decrease? To what level? Over what time period?

After the necessary predictive models have been developed, then one can ask whether the climate predictions for the next century or two look like anything in our past historical climate data? What is the natural variability of climate and are changes expected to be induced by increasing CO_2 emissions within or outside the natural variability band? Or will it create a drastic perturbation? Could your models have predicted past changes or trends?

We must know not only about the changes in climate, but also the effects of a changing climate. What climate perturbations can the biosphere, or segments of the biosphere, tolerate? On a regional basis we would like to know the impact of climate and energy-use changes on:

- Food production--quantitative changes and what types of crops will be affected and where;
- Energy demand changes for personal comfort (heating and air conditioning);
- Forestation or deforestation;
- Water quality;
- Land use, availability, and changing quality.

In fact, I hope your models will be able to determine which regions will be at risk and which will benefit, and to quantify this.

I would like to suggest some questions for your consideration at the Workshop:

- If you were in a position to make a decision to control CO_2 emissions, what information would you want to have?
- How much of this information is now available? How much may be within X years? What is the value of X?
- Can the uncertainties in data and models be quantified? There are, in general, two kinds of uncertainty: that which we can assess and assign numbers to; and our lack of confidence in the correctness of the basic structure of the model--that something important may have been omitted.
- When will we have, or expect to have, sufficient knowledge to know whether CO_2 induced climate changes are bad or good, and be able to specify on a regional basis?
- What key parameters should we be watching to alert us that a critical phase is almost upon us?

There are some socioeconomic factors that should also be considered. Assume that we are able to establish eventually the amount of global reduction of atmospheric CO_2 required. How is the reduced CO_2 emission to be divided among regions, among nations? Can, or should, that nation (or region) that stands to gain by climate warming and better precipitation patterns be forced to forego those gains in order to "protect" the rest of the world?

Research on other technological areas to counteract climate changes is essential such as the development of other forms of "clean energy", methods to prevent CO_2 from entering the atmosphere, improved food production techniques, and improved irrigation practices to counteract decreased precipitation.

FOSSIL FUEL UTILIZATION POLICY ASSESSMENT AND CO_2 INDUCED CLIMATIC CHANGE

J.A. Laurmann

The potential for climate change resulting from heightened levels of atmospheric CO_2 has long been recognized as a possible consequence of the increasing use of fossil fuel as a primary energy source. Projections, albeit very tentative, gave leeways ranging from several decades to a century for the onset of significant climatic disturbances. Recently Häfele and Sassin (1976) recognized that, if in fact a global reorientation of energy resource utilization was necessary to avoid climatic catastrophe, a half century would be needed to effect a smooth transition to the predominant use of a new energy source. In order to assess the policy implications of the growing acceptance of the reality of this CO_2 threat to the environment, a judgement is required as to the likelihood not only of the occurrence of the environmental insult but also of governmental actions that might be taken to avoid it. As a consequence, in developing the arguments contained herein, we find that our considerations are dominated by uncertainties, the sources of which range from the strictly scientific to the geopolitical. The following is a summary of an attempt to quantify the former, thereby leading to recommendations for steps needed to prepare for the succeeding evaluation of the interregional social and political problems that will have to be addressed if global remedial measures are indeed found to be necessary. We have formulated the analysis in terms of projections that assume continuity of present energy resource usages. The importance of the various sources of prediction uncertainty need to be reconsidered when evaluating strategies of amended fossil fuel use.

GLOBAL ENERGY USE AND CO_2 PRODUCTION

Figure 1 assembles the latest econometric projections of world energy consumption for the next 60 years. Most of these predict a reduced rate of growth (mostly between 3 and 4% per annum) compared with the pre-1973 rate of 5.5% per annum and earlier estimates such as Darmstadter's (1972). Recent fossil fuel utilization rate predictions, as illustrated in Figure 2, are similarly reduced, between 2 and 4% per annum, depending upon whether the short-falls between demand and supply are made up by coal or by other forms of energy (usually nuclear).

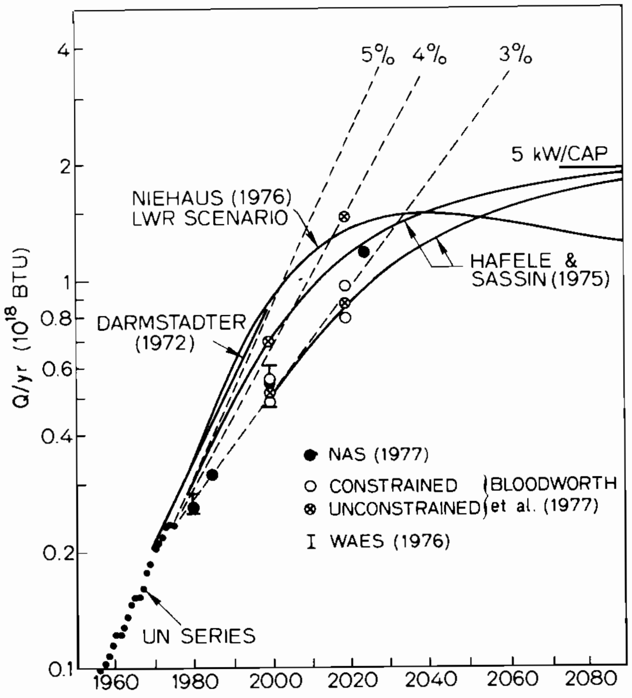


Figure 1. Global energy consumption.

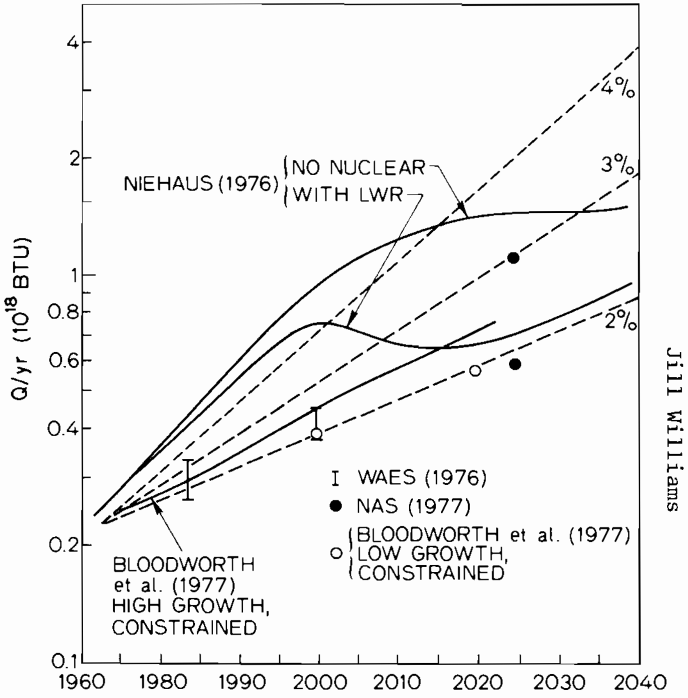


Figure 2. World fossil fuel use predictions.

PROJECTED ATMOSPHERIC CO_2 LEVELS

The projections of a number of carbon cycle models are shown in Figure 3, being plotted as relative increments of atmospheric CO_2 above the preindustrial, 1860, value, and include allowances for resource depletion effects for the model inputs. The projections show close to exponential growth at the same rate as the CO_2 release rate well beyond the dates for doubling of the CO_2 concentration above the preindustrial value, when the ordinate is unity. (This can be seen by comparing the model projections with the fixed exponential growth curves shown in the figure as dashed lines.) The exception is the Revelle-Munk prediction (NAS 1977), which includes a substantial initial contribution (about 44%) of CO_2 release from forest clearing and

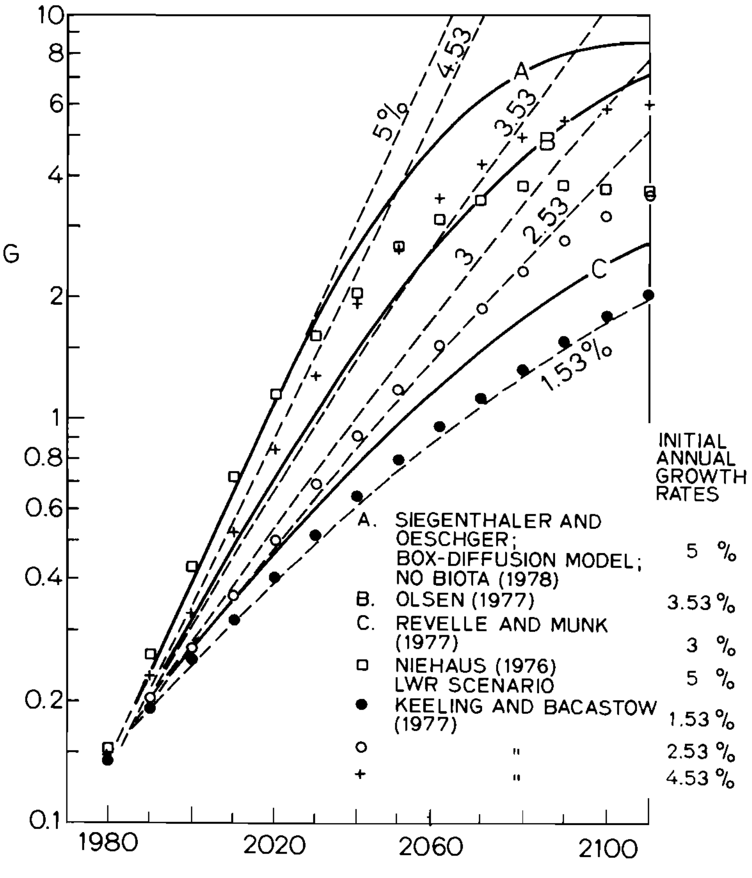


Figure 3. Fractional atmospheric CO_2 increase above 1860 level.

burning, the rapid depletion of which drops their atmospheric CO_2 growth rate below a constant 3% value. The other models show very little effects of fossil fuel resource depletion in this time frame. The simplicity of these results is a consequence of model linearity and of fitting empirical constants in the models to the same twenty year period of observational data on atmospheric CO_2 levels. Thus the current intense controversy on the relative roles of the oceans and the biosphere as sinks for atmospheric CO_2 excess does not appear to affect projections for the next fifty years or so, which we may assume encompasses the time period relevant to current policy concerns.

TEMPERATURE RESPONSE

We assume the relationship $\Delta T = 2.8 \ln (1+G) + .78 G$ between the global temperature rise ΔT resulting from a fractional increase G of atmospheric CO_2 concentration relative to the preindustrial value. This equation is based upon the latest radiative-convective one-dimensional climate models (Schneider, 1975; Kellogg, 1977), as well as the only three-dimensional model predictions of Manabe and Wetherald (1975). It gives a 2.5°C rise of temperature in the year 2038 with a 3% per annum growth rate of atmospheric CO_2, corresponding to a doubling of the preindustrial concentration. Although this change at first sight may seem small, it is, in fact, extremely important, since it also implies much larger interregional effects, as indicated by the Manabe-Wetherald results and by paleoclimatological evidence of the Altithermal period 4000-7000 years ago--which was the last time the earth experienced such high temperatures (Kellogg, 1977). Then precipitation patterns and hence agricultural zones were much different than today, and a re-accommodation to that climate would involve drastic redistribution of the world economic order. However, there is a large degree of uncertainty in these predictions of climatic change, due in large measure to the omission of important climatic feedback mechanisms (see NAS 1977); we shall in fact assume the temperature response relationship to be in error by a factor of two, as suggested by the WMO panel on CO_2 and climate change (1977).

PREDICTION UNCERTAINTIES

Figure 4 illustrates the effect on global temperature rise of changing the assumed fossil fuel consumption rates. A 1% change from a 3% per annum rate shifts the doubling time (i.e., the time to elevate temperatures by 2.5°C) by about a decade. A return to the pre-1973 energy growth advances this date by some twenty years.

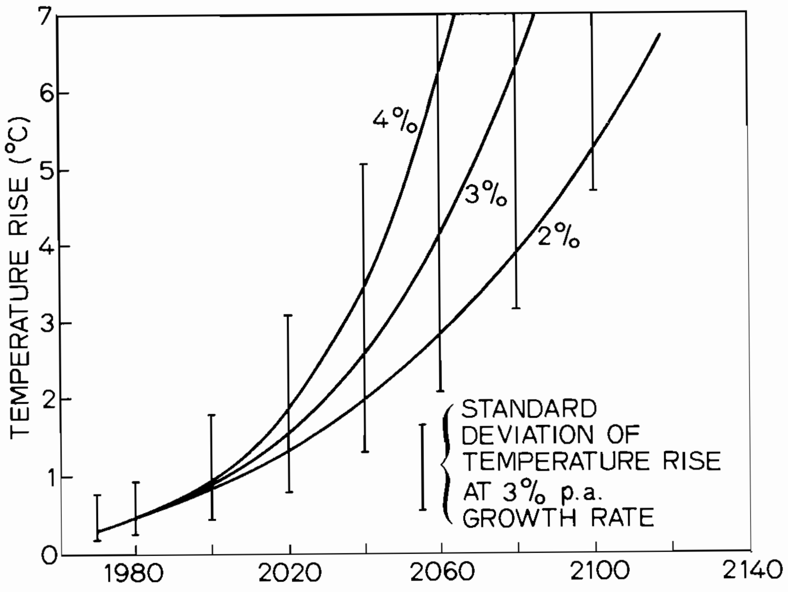


Figure 4. Global temperature increase for 2%, 3% and 4% per annum atmospheric CO_2 growth rates.

As seen from the carbon cycle model predictions shown in Figure 3, the error in taking the annual atmospheric CO_2 growth rate to be the same as the release rate is negligible well beyond the doubling time. Departure from this conclusion can occur if the biospheric source for atmospheric CO_2 is much larger than assumed in any of these calculations and if its depletion is sufficiently rapid.

By far the largest error arises from inadequacies in climate modeling. Figure 5 plots the cumulative probability of reaching at least a 2.5°C global temperature rise by a given date, assuming the curves of Figure 4 to have a ln-normal error of 2. The same assumption was made in deriving the probability estimates shown in Figure 6, these now being all for a 3% per annum growth rate. Note that these calculations indicate a probability of 1 in 4 that the temperature rise will be at least 2.5°C by the year 2012, as compared with the most likely date (the 50% curve) of 2029.

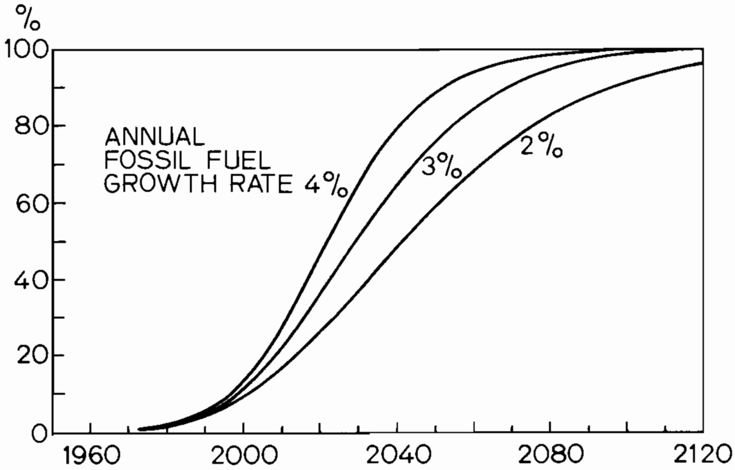


Figure 5. Cumulative probability of a 2.5°C global temperature rise.

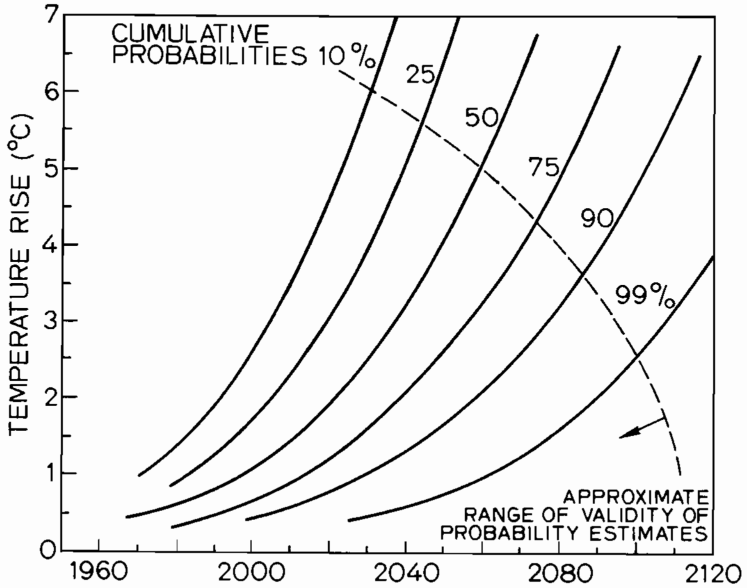


Figure 6. Cumulative probability of global temperature change; 3% per annum fossil fuel growth rate.

POLICY IMPLICATIONS

The most likely date for reaching at least 2.5°C, 2029, suggests the need for immediate remedial measures in the form of global reduction of fossil fuel use. However, uncertainties confuse the issue, since this critical date may be either considerably advanced, or, to the contrary, may never occur. One possible method for dealing with this situation appears to be with the aid of probabilistic techniques employed in decision analyses. Such an approach has to include discounting of future costs and benefits as an important feature. An example is shown in Figure 7, which illustrates how discounting reduces the time taken to encounter maximum (discounted) costs; with a 4% per annum discount factor and taking the cost of a 2.5°C temperature rise to vary in proportion to the probability of its occurrence, the figure shows that 80% of the maximum discounted costs is reached by the end of the present century. However, since the estimates are not given in absolute dollar measure, we cannot tell whether this striking result worsens the situation; perhaps present day absolute discounted costs are too small to be of concern. We note that analogous calculations by Nordhaus (1977) have not taken this important aspect of prediction uncertainty into account in the consideration of fossil fuel reduction strategies.

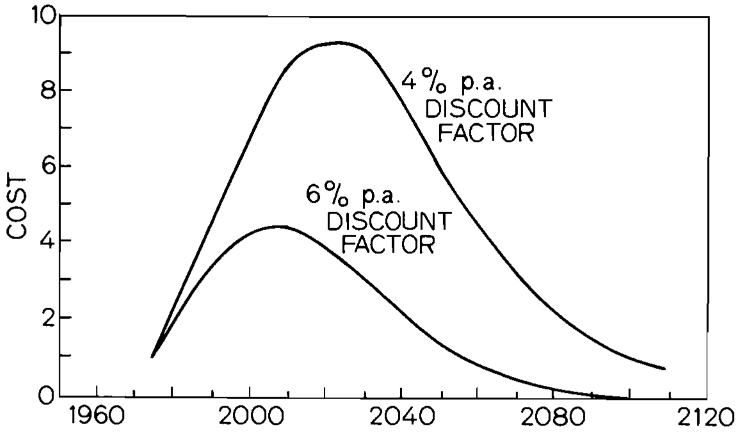


Figure 7. Discounted cost relative to 1975 norm (0.68% probability of a 2.5° C temperature rise by 1975).

RECOMMENDATIONS

We see the primary scientific tasks to be as follows:

1) To eliminate uncertainty in projections arising from the possibility of a large contribution to atmospheric CO_2 release from deforestation. A worldwide census would be the most straightforward way of achieving this goal.

2) To do a cost/benefit analysis, using a probablistic decision theory approach, to determine whether we can afford to postpone the introduction of remedial measures, in anticipation of improvements in climate change prediction capability that will reduce present day uncertainties.

3) To confirm that the world is indeed following the reduced global energy use growth rates currently being forecast, contrary to long-term historical trends.

Once these matters, and especially item 2), are resolved, and if indeed the criticality of the situation is confirmed, the major source of uncertainty leaves the scientific and enters the geopolitical arena. The task then is to convince the international community of the reality of the threat and the need for action.

Acknowledgement

The point of view expressed here was developed as a by-product of a review on the CO_2-climate question prepared for the Electric Power Research Institute, but should not be taken to reflect the attitude of that organization. Elaboration on the brief description given above is available in the above mentioned review report (Laurmann, 1978).

REFERENCES

Bloodworth, I.J., E. Bossanyi, D.S. Bowers, E.A.C. Crouch, R.J. Eden, C.W. Hope, W.S. Humphrey, J.V. Pullin, and J.A. Stanislaw (1977), *World Energy Demand to 2020*, presented at the Tenth World Energy Conference, Istanbul, September.

Darmstadter, J. (1972), Energy Consumption: Trends and Patterns, in S.H. Schurr, ed., *Energy, Economic Growth and the Environment*, Resources for the Future, Inc., Washington, DC.

Häfele, W., and W. Sassin (1976), *Energy Strategies*, presented at the European Physical Society Third General Conference on Energy and Physics, Bucharest, September 1975; also RR-76-8, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Keeling, C.D., and R. Bacastow (1977), Impact of Industrial Gases on Climate, in *Energy and Climate*, National Academy of Sciences, Washington, DC.

Kellogg, W.W. (1977), *Effect of Human Activities on Global Climate*, World Meteorological Organization, Geneva (draft).

Laurmann, J.A. (1978), *Climatic Change from Carbon Dioxide Released by Fossil Fuel Combustion*, Electric Power Research Institute, Palo Alto, California (draft).

Manabe, S., and R.T. Wetherald (1975), The Effects of Doubling the CO_2 Concentration on the Climate of a General Circulation Model, *J. Atmos. Sci.*, 32, 3-15.

National Academy of Sciences (1977), *Energy and Climate*, Washington, DC.

Niehaus, F. (1976), *A Non-Linear Tandem Model to Calculate Future* CO_2 *and* C^{14} *Burden to the Atmosphere*, RM-76-35, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Nordhaus, W.D. (1977), *Strategies for the Control of Carbon Dioxide*, Discussion Paper #443, Cowles Foundation, Yale University, New Haven, Conn.

Olsen, J.S. (1977), personal communication.

Revelle, R., and W. Munk (1977), The Carbon Dioxide Cycle and the Biosphere, in *Energy and Climate*, National Academy of Sciences, Washington, DC.

Schneider, S.H. (1975), On the Carbon Dioxide-Climate Confusion, *J. Atmos. Sci.*, 32, 2060-2066.

Siegenthaler, U., and H. Oeschger (1978), Predicting Future Atmospheric CO_2 Levels, *Science*, 199, 388-395.

United Nations (1976), *World Energy Supplies 1950-1974, Satistical Papers*, Series J, #19, New York.

World Meteorological Organization (1977), *Report of the Scientific Workshop on Atmospheric Carbon Dioxide*, WMO Report #474, Geneva.

Workshop on Alternative Energy Strategies (WAES) (1976), *Energy: Global Prospects 1985-2000*, Mcgraw-Hill, New York.

THE ATMOSPHERIC CO_2 CONSEQUENCES OF HEAVY DEPENDENCE ON COAL

R.M. Rotty

Carbon dioxide (CO_2) emissions from fossil fuels have been calculated from United Nations fuel production data given in World Energy Supplies (Keeling, 1973; Rotty, 1973, 1977a). In 1973, Keeling estimated the amount of carbon released by fossil fuel burning. Annual values for the global emission of CO_2 from fossil fuel sources (adding a small contribution from the manufacture of cement--about 2% of that from fossil fuels--and including estimates from flared natural gas) have subsequently been calculated for the period 1860-1976 by Rotty (1973 and 1977a) (Figure 1).

The exponential trend in CO_2 production is quite evident (Figure 1). Except during the period of the two world wars and the great economic depression of the 1930s, a growth rate of 4.3% per year provides an excellent fit to the data. While it might be suspected that the rate of growth might now be leveling off, an examination of the current decade offers little encouragement for such optimism.

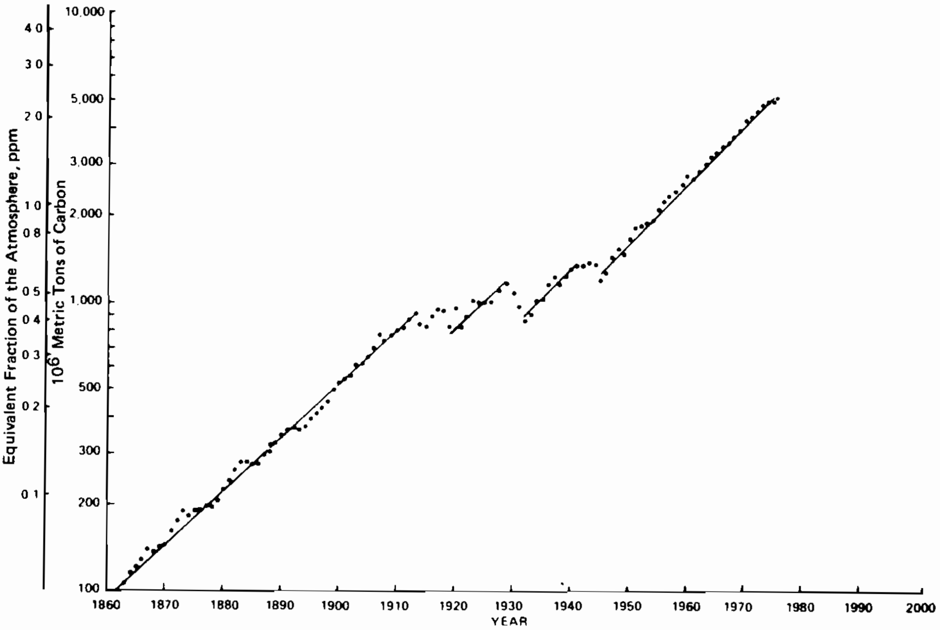


Figure 1. Global production of CO_2 from fossil fuels and cement, 1860-1976.

The upper part of Figure 2 shows global CO_2 production rates, and the lower shows the annual rate of energy use in the USA. The relatively sharp decline in US energy use in 1974 and 1975 was accompanied by a proportionally much smaller decrease in global CO_2 production. This suggests that conservation in the USA cannot be counted on to arrest the growing CO_2 production on a global scale.

Can we predict when the CO_2 concentration might reach alarming levels? The definition of "alarming levels" will depend on greater climatological knowledge than we now have; also the time when a given concentration of CO_2 in the atmosphere will be reached depends on fossil fuel use (and on resiliency of the natural carbon cycle).

Keeling (1973) has estimated the amount of carbon that is released as CO_2 for each unit of fossil fuel removed from the ground. Using Keeling's values (which assume a global average value for the carbon content of each fossil fuel), it is possible to estimate the amount of CO_2 released per unit of energy obtained by simply assuming similar average values for the energy content of each fuel. The results of such calculations are given in Table 1, and these factors make it relatively easy to estimate the amount of CO_2 released into the atmosphere for a given energy scenario, whether the energy demand (and the CO_2 produced) is for the USA or for the world.

Table 1. CO_2 produced from fossil fuels per million Btu.

After: Keeling (1973).

Fuel	Kg C/10^6 Btu	Ratio to Natural Gas
Coal	25.4	1.74
Oil	19.0-21.7	1.32-1.51
Methanol	(~16-18)	(~1.11-1.25)
Natural Gas	14.4	1.0
Synthetic Fuel from Coal (75% efficient conversion)	33.8	2.35

Of even greater consequence is the probable growth in fossil fuel use in the rest of the world. I have attempted a rough assessment of the energy demands of various segments of the world

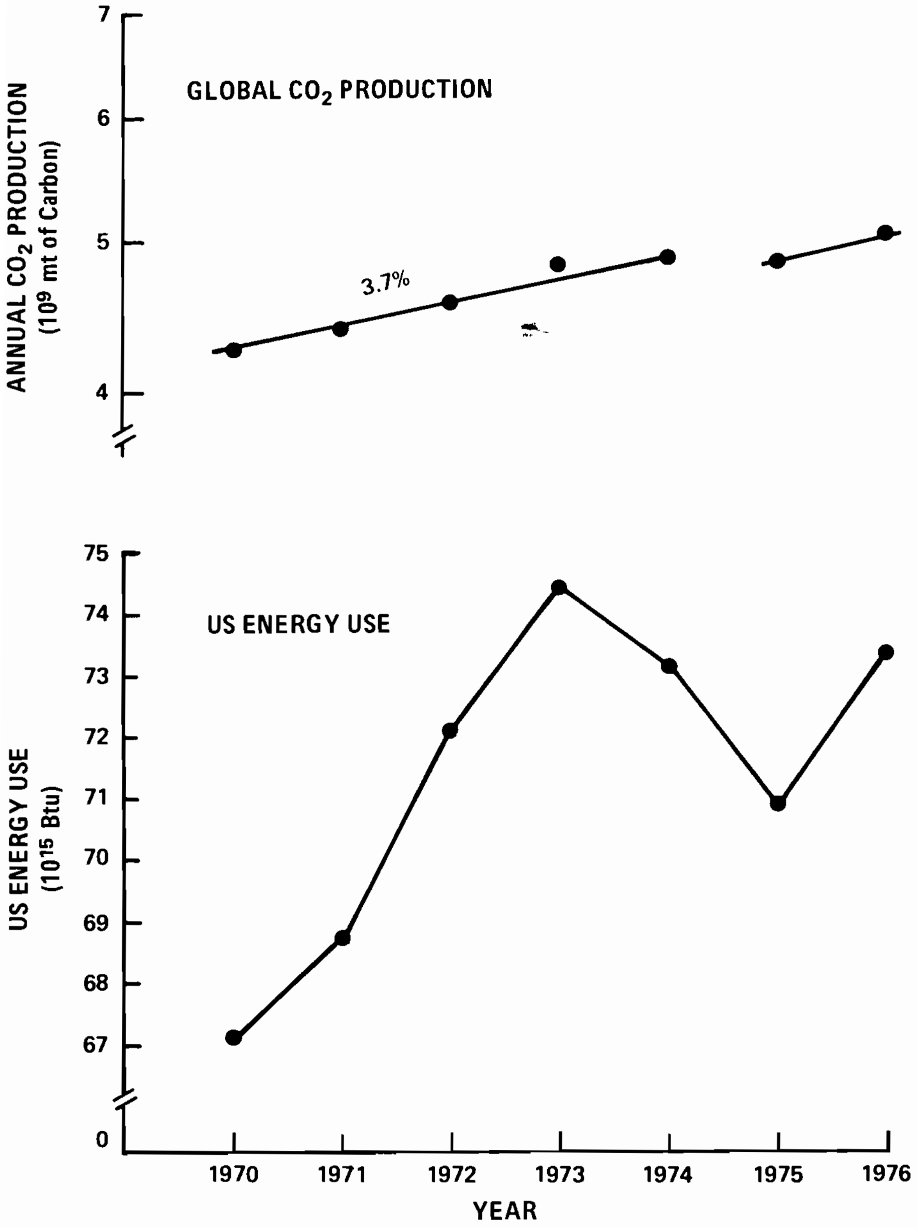


Figure 2. Global CO_2 production, and US energy use, 1970-1976.

as they are now and could be 50 years hence. Figure 3a shows the global CO_2 production as it is apportioned among the indicated 12 political-economic sectors (Rotty, 1977b). Clearly North America, Western Europe, and centrally planned Europe (including the USSR) are responsible for nearly three fourths of the global total fossil fuel CO_2--the USA, alone, for over one quarter.

To develop a scenario for 50 years from now, the world was divided into six sectors--corresponding to combinations of the 12 sectors used in the present time analysis. The results of Figure 3b are based on the following assumptions for the period 1974-2025:

- The US energy requirements will be 125 quads with 15% nonfossil.
- Western Europe's energy use will grow at 2% per year, and 15% will be nonfossil.
- Centrally planned Europe (including the USSR) will grow in energy use by 4%, with 15% nonfossil.
- Japan and Australia will experience a similar 2% annual growth as Western Europe, with 15% nonfossil.
- Centrally planned Asia (largely China) will expand with an energy growth of 4.5%, nearly all fossil.
- The developing world will have an average population growth rate of 1.5% and an increase in the per capita energy use to 53×10^6 Btu per year--the 1970 global average. (Although this requires a 5% average growth for 50 years, these countries have achieved an 8% annual growth during the past decade or so.)

Based on these assumptions, the calculations result in an annual fossil fuel CO_2 release containing 23×10^9 t of carbon for this period. This total is 4.5 times the 1974 amount, and represents a global energy dependence of fossil fuel equivalent to 1090 quads. The sizes of the circles in Figure 3b (1974 and 2025) are proportioned so that the areas on the figure represent the total quantity of carbon released from fossil fuel.

Others have estimated global energy demand for the future in a variety of ways and frequently for specific times other than the year 2025. In such cases, I have extrapolated and interpolated to obtain an estimate for 2025. The resulting values are given in Table 2.

The previous analysis leads to the conclusion that the problem of avoiding CO_2-triggered climate change becomes that of

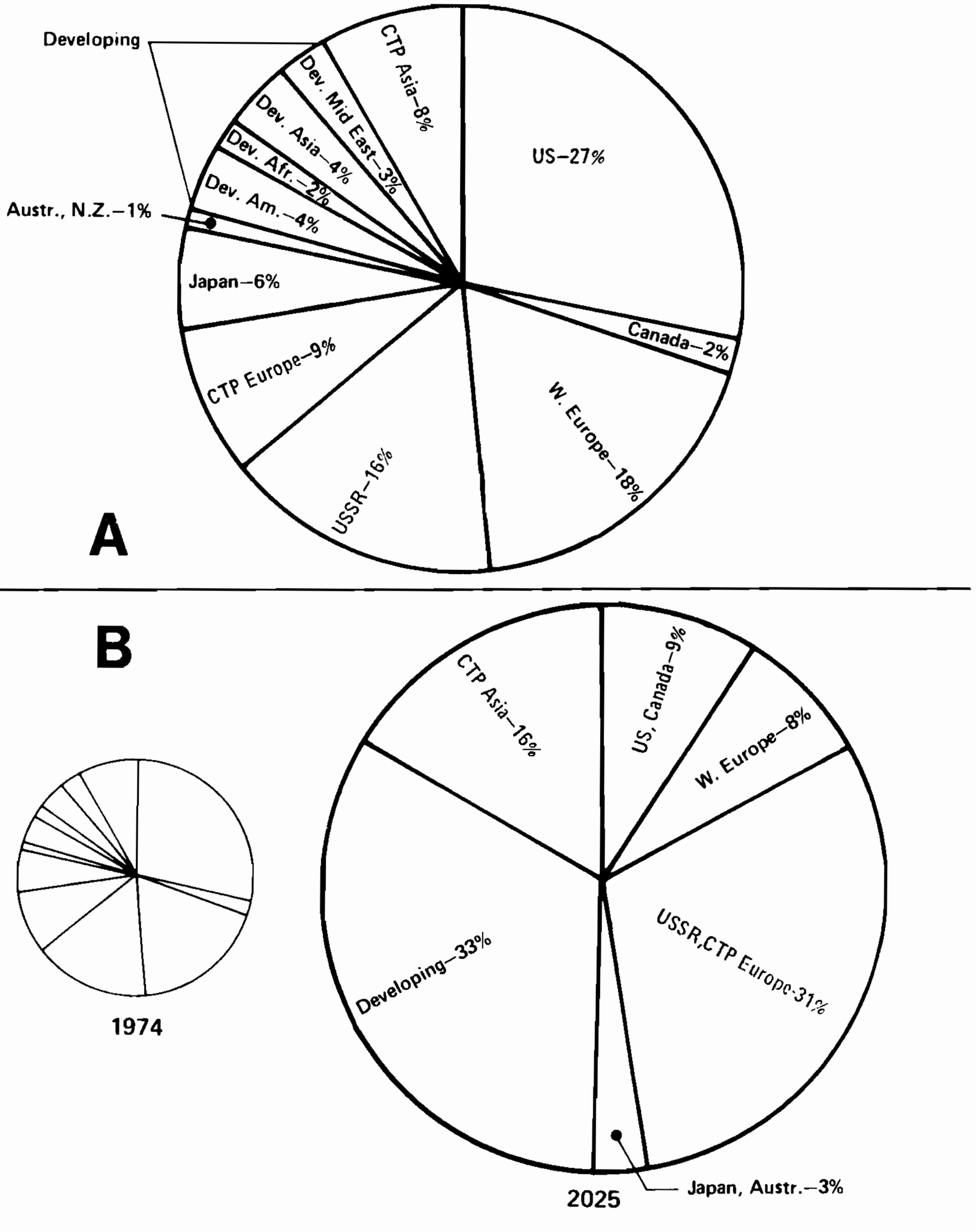


Figure 3. Global CO_2 production by world segments. (A) 1974, (B) 2025 scenario.

Table 2. Estimated global energy demand in the year 2025.

Source (Reference)	Demand (10^{15} Btu)	TW
Perry and Landsberg (1977)	1173	39.2
WAES (1977) (extrapolated from the year 2000)	710-1000	23.7-33.4
Chesshire and Paritt (1977) (interpolation)	550-1500	18.4-50.2
Houthakker (1977) (personal communication)	>1000	>33.4
Bloodworth et al. (extrapolated from the year 2020) (World Energy Conference, 1977)	815-1110	27.3-37.1
Rotty (this paper)	1090 (+nonfossil ~100)	36.5 (or 39.8)
IIASA (for the year 2030) (see W. Häfele, these Proceedings)		35

providing fuel for the developing countries to assure their progress without such heavy dependence on fossil fuels.

One might suspect that growth to 1090 quads (or 23 × 10^9 t of carbon) for the year 2025 will heavily tax the fossil fuel reserves of the world. This is simply not true; recoverable fossil fuels (and shale oil) contain 7.3 × 10^{12} t of carbon.

Several possible patterns for future CO_2 production from fossil fuel may be represented by the mathematical expression

$$\frac{1}{N}\frac{dN}{dt} = 0.043\left(1 - \frac{N}{A}\right)^{x}$$

where

N is a function of time t and represents the total cumulative amount of CO_2 produced from fossil fuel use up to that time;

A is the quantity of CO_2 that would be produced from all of the fossil fuel ultimately recoverable (~7.3 × 10^{12} t C); and

x is the parameter used to vary the emphasis on price, availability, etc., as the fraction of recoverable fossil fuels remaining is reduced.

The quantity $(1 - \frac{N}{A})^x$, which is always between zero and one, enables the cumulative use function to reflect a reduced rate of use as the resource approaches depletion and the costs rise. In Figure 4, the historical fossil fuel use to the present is indicated by the open circles; the curve with x = 1 might represent "free and easy" access to remaining reserves along with early exhaustion of those readily available; the curve with x = 4 might represent lowered demand scenarios for fossil fuels resulting from high prices and low availability stimulating early extensive reliance on solar, nuclear, and other sources. In each case the total area under the curve (carried to infinite time) is the same and represents the total recoverable fossil fuel--mostly coal. The circle at the year 2025 corresponds to the quantity calculated in the previous paragraphs ($23{,}000 \times 10^6$ t C or 10.9 ppm). The curves x = 1 and x = 4 can be regarded as error limits on the projections for future global fossil fuel use; they approximately bound the estimates of the scenarios of Table 2.

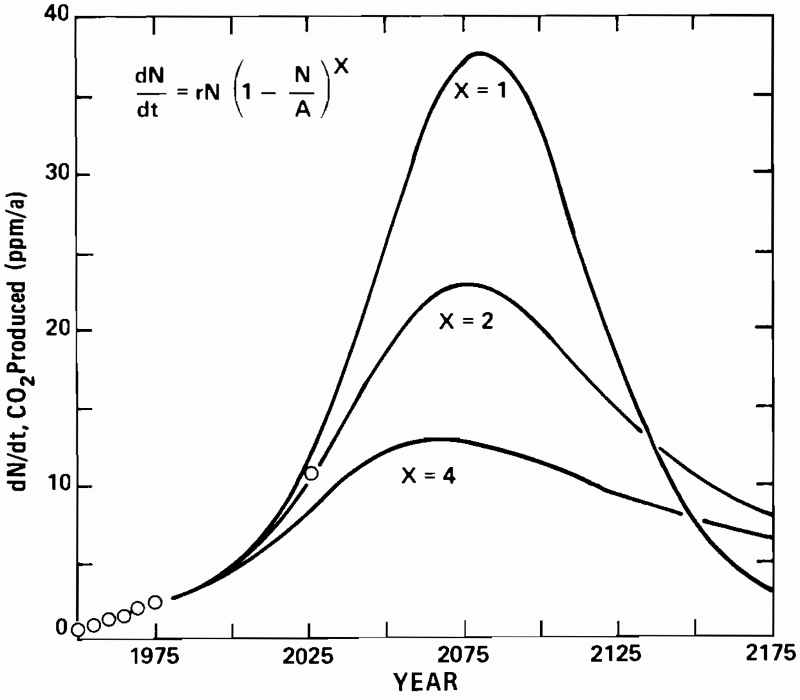


Figure 4. Global production of CO_2 from fossil fuels.

In Figure 5, cumulative production of CO_2 since 1958 (as calculated above) is shown by the series of solid circles, and the projections along the lines x = 1, x = 2 and x = 4 correspond to the fuel-use curves of Figure 4. The projected atmospheric concentration of CO_2 starting with observations represented by the open circles, is based on 53% of the cumulative production remaining in the atmosphere. The atmospheric concentration increases rapidly after the year 2000 and, for the 1090 quad scenario developed here for 2025, it approaches a 150 ppm increase (over 1958) by 2025, a 220 ppm increase by about 2035, and a 300 ppm increase around 2050. Even low growth scenarios (such as x = 4) are likely to result in observable climate change during the first half of the next century.

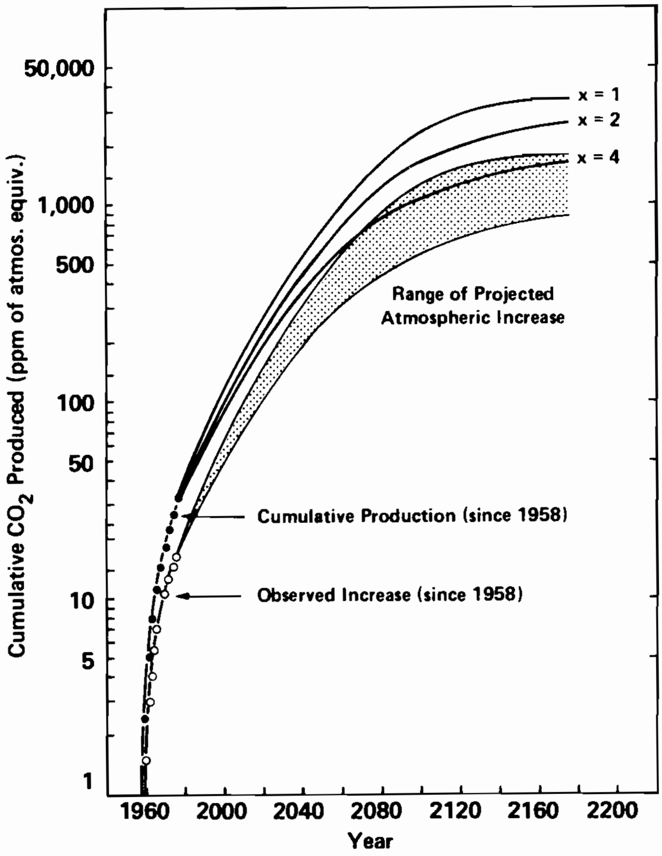


Figure 5. Projected cumulative CO_2 production and atmospheric CO_2 decreases.

Of course, even lower fossil fuel-use scenarios are conceivable if the global society recognizes the potential environmental changes soon enough. Greater reliance on solar energy, even though more expensive, and on nuclear energy, even with its attendant risks, may become much more attractive; the fossil fuel use curve could thus be brought even lower, and the magnitude of the potential climate change reduced.

The central question which ultimately must be addressed is: At what rate can we use the coal reserves before the resulting increased concentration of CO_2 in the atmosphere will cause an unacceptable climate change? This question probably oversimplifies the case since there are degrees of unacceptability and tradeoffs of economic growth, social stability, etc., as well as serious impacts of climate change. As suggested before in this paper and in many recent articles and papers on the subject, four principal areas of inquiry require serious consideration.

Rates of fossil fuel use are critical. If all of the fossil resources were to be burned at a steady rate over a 10,000 to 100,000-year period, the atmospheric concentration would probably never rise to an unacceptable level. At such a low rate of utilization there would be enough time to sequester the carbon in the deep sea, and the problem would be nonexistent. Controlling the rate of fossil fuel use while maintaining hope within the impoverished masses of the world will require extremely careful planning and ability to deploy so-called inexhaustible energy sources effectively. A better understanding of the future energy requirements of the developing world and the alternatives for meeting these requirements are both essential in determining and possibly controlling rates of fossil fuel use.

The distribution of the CO_2 produced from fossil fuel combustion and from other anthropogenic sources among the several reservoirs in the carbon cycle must be known. Without better information on the behavior of the terrestrial biosphere, we cannot say whether the biosphere is a source or a sink of CO_2. If the biosphere is supplying more CO_2 than it is absorbing, then the behavior of the oceans must be different from what we believe. The ability of the ocean to act as a CO_2 sink is large, but the *rate* of possible sequestering of carbon is the important factor. Before we can estimate with confidence what fraction of the CO_2 from fossil fuels remains in the atmosphere, we must understand better the roles of both the biosphere and the oceans in the carbon cycle.

Even if the concentration of CO_2 in the atmosphere could be accurately predicted for some given future time, there would remain vast uncertainty as to the effects on climate. The evidence is strong that additional atmospheric CO_2 will cause global warming;

the "best guesses" are in the range of 2 to 4°C average temperature rise for a doubling of the CO_2 concentration. Of even greater uncertainty are the changes that will occur in the local climates of critical areas of the world. Will the areas of good agricultural soils continue to have climates conducive to good production? Since past major global climate shifts--e.g., glacials to interglacials--have occurred with temperature changes of about 5°C over many centuries, climate changes associated with a doubling of CO_2 concentration will be significant, and the rate with which they occur may be too great to allow for easy adjustment.

We have little conception of how the world might manage a substantial climate change without drastic social dislocation. Granted that currently there is still uncertainty as to the magnitude of the CO_2-induced climate change, I believe it is not premature to examine possible global responses to such an eventuality that would preserve the stability of our social-political order.

REFERENCES

Bloodworth, I.J., E. Bossanyi, D.S. Bowers, E.A.C. Crouch, R.J. Eden, C.W. Hope, W.S. Humphrey, J.V. Mitchell, D.J. Pullin, and J.A. Stanislaw (1977), *World Energy Demand to 2020*, discussion paper prepared for the Conservation Commission of the World Energy Conference by the Energy Research Group, Cavendish Laboratory, University of Cambridge, England.

Chesshire, J., and K. Paritt (1977), *Social and Technological Alternatives for the Future*, Energy Science Policy Research Unit, Sussex University, England.

Houthakker, H.S. (1977), personal communication.

Keeling, C.D. (1973), Industrial Production of Carbon Dioxide From Fossil Fuels and Limestone, *Tellus*, 25, 2, 174-198.

Perry, H., and H.H. Landsberg (1977), Projected World Energy Consumption, in *Energy and Climate*, National Academy of Sciences, Washington, DC.

Rotty, R.M. (1973), Commentary on and Extension of Calculative Procedure for CO_2 Production, *Tellus*, 25, 5, 508-517.

Rotty, R.M. (1977a), Global Carbon Dioxide Production from Fossil Fuels and Cement, A.D. 1950-A.D. 2000, in N.R. Andersen and A. Malahoff, eds., *The Fate of Fossil Fuel CO_2 in the Oceans*, Plenum, New York.

Rotty, R.M. (1977b), *Present and Future Production of CO_2 from Fossil Fuels - A Global Appraisal*, IEA-0-77-15, Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee; also presented at the ERDA Workshop on Environmental Effects of Carbon Dioxide from Fossil Fuel Combustion, Miami, Florida, March 7-11, 1977.

WAES (1977), *Energy Supply Demand Integrations to the Year 2000*, Report of the Workshop on Alternative Energy Strategies, MIT Press, Cambridge, Massachusetts.

WILL HYPOTHESES ABOUT PROPERTIES OF CO_2 AFFECT ENERGY CONCEPTIONS?

G. Zimmermeyer

INTRODUCTION

There are a number of publications, which rapidly increased after the Policy Declaration of President Carter, on the presumed global impacts of CO_2 on our climate due to the so-called greenhouse effect. Carter's energy program, essentially based on the use of coal for electricity generation, induced the proponents of energy to point out all the possible adverse environmental influences of the use of other sources of energy.

A list of the anticipated effects of CO_2 on climate can be found in [1]. That report states the hypothesis that an increase in temperature of 6°C can be expected by the year 2150 or 2200, due to the physical property of CO_2 of being transparent to shortwave radiation (visible light) but absorbing and reradiating longwave radiation. Prerequisites for this temperature increase would be, inter alia, a steady growth in energy consumption, the demand being met largely by fossil fuel energy conversion. This climatic change would presumably have the following consequences:

- The heating up of the sea water, with a consequent increase in its volume and thus a sea level rise of about 1 m;
- The melting of the West Antarctic ice sheet, raising the sea level by another 5 m over a period of 300 years, so that most of the coastal areas would be flooded;
- The devastation of fertile lands and transformation of woodland into steppe.

The report [1] also describes the natural cycles of CO_2 as far as they are known today and have been investigated. These include a *biological cycle* (essentially the assimilation of plants), the *physical cycle* (processes of solution in water), and the *chemical cycle* (sedimentation in the form of calcium carbonate).

THE "CO_2 PROBLEM"

The various facets of the CO_2 problem are listed below, each followed by some qualifying factors.

- The predicted increase in energy consumption: forecasts vary between a slight reduction in consumption and an annual increase of 7%.
- The meeting of energy demand by fossil fuels: as the consequences of a moratorium on nuclear energy are made to look serious, this prediction is based on the assumption that the entire energy demand is to be met by fossil fuels, which probably will not be the case.
- The calculated CO_2 emission during energy conversion per MWh: estimates may vary by ± 10%, according to statements in [1].
- There are no technical installations for a reduction of CO_2 emission: this is correct; and it seems unreasonable to take the second step before the first--namely, to carry out research and development work with the aim of reducing CO_2 emission, and to lay down conditions involving high costs for the operation of power plants, before the effects of increased CO_2 concentrations have been clearly determined.
- About 40% of the CO_2 released by man's activities remains in the atmosphere, while part of the remaining 60% has been dissolved in water and other parts in the biomass: this assumption has simply been extrapolated for the CO_2 emitted in the future, without considering that a higher CO_2 concentration could cause a quicker conversion of CO_2 into oxygen and carbon by means of assimilation in the increased biomass; also, the water courses of the earth could have a much higher solution capacity than supposed so far.
- The greenhouse effect: the physical effect of CO_2, to transmit shortwave rays of light but to absorb longwave radiation from the earth's surface, has not been confirmed, at least not in a global way; the permeability or reflectivity of the atmosphere as a function of concentrations and the thickness of layers have yet to be observed.
- Heat balance and climate: for a presumed heat balance, the change of climate and temperature is based only on a supposition (an increase of 6°C in the period 2150 to

2200); the temperature distribution on the earth is also doubtful.

- Effects of climatic changes: predictions on a transformation of woodland into steppe, a drying out and dislocation of fertile regions, the melting of the polar ice masses and the thermal expansion of the volume of water, thus raising the sea level by about 6 m and causing coastal flooding, could be correct from a calculatory viewpoint (required quantities of heat to melt a certain mass of ice), but will not necessarily materialize, owing to inhomogeneous temperature distribution.

The effects of CO_2 predicted in [1] would occur only if all the above statements--and possibly others still--were true; but at the moment, none of them is scientifically founded.

CONCLUSIONS AND ARGUMENTATION

We have no answers to the points raised above. If we assume a certain truth of some of them, the predicted effects would take place over the next 200 years. In other words, sensible and measurable consequences of a much increased CO_2 emission are expected at the earliest by the second half of the twenty-first century. Changes in CO_2 concentration and the climate measured today are within the climatic noise level. A trend cannot yet be proved, at least for temperature changes. Some experts even predict a gradual decrease in global or zonal temperature on the basis of natural climatic variation. But perhaps a CO_2 "armor" prevents a decrease in temperature that would have even greater ill effects on life on earth.

The foregoing makes it clear that it could be premature to derive arguments based on the points discussed for the present energy-political discussion. The actual need at present is to plan power plants to meet our energy demand during the ensuing years. These power plants, to be put up in the medium term, will not affect the CO_2 level to such an extent that we need expect any effects on our climate. Rather, it is necessary and sufficient--in view of the long periods required to introduce new energy carriers and the speculative character of the problem--to obtain precise knowledge within the next five or ten years on the effects of CO_2. Only when we have obtained this knowledge will conclusions for the deployment of energy systems be possible.

For decisions to be practical, they would have to be applied on a worldwide scale. Ecologically and economically, it would be of no use if only some of the industrial countries took steps. Where, however, is the institution that could impose restrictions on CO_2 emissions, perhaps by rationing the use of fuel or by forbidding certain technical processes, that would be valid for all countries, especially those still in development where the availability of fossil fuel energy is vital for man and his health? It would be more appropriate to look first for other practical methods of solving the CO_2 problem, e.g., the prevention of tropical deforestation which increases CO_2 concentrations either directly, by combustion, or indirectly, by removing the possibility of assimilation.

REFERENCE

[1] National Academy of Sciences, *Energy and Climate*, Washington, DC, 1977.

STANDARD SETTING FOR CARBON DIOXIDE

E. Höpfinger

Since the effects of increased shares of CO_2 in the atmosphere are not well known, there exist rather contradictory conjectures. A continuous increase of CO_2 in the atmosphere from fossil fuel combustion beyond an unknown critical value will lead to irreversible large-scale changes in the earth's climate. This paper deals with the modeling of the decision problem, taking into account different interest groups.

The problem of how to determine and adapt an emission standard for CO_2 is treated within the framework of a three-person infinite-stage game; the players are called regulator, producer, and impactee.

The set of states of the game may be expressed as

$$\{(C,L)\,|\,C \geq 0,\ L \geq 0\} \cup \{k \geq 0\}$$

where

C is the amount of CO_2 in the atmosphere;

L is the upper bound of emission of CO_2 during the period;

k is the critical value for catastrophe.

Let (C_o,L_o) denote the first state.

The choices of the players in the case of state (C,L) are as follows. The regulator chooses $0 \leq l \leq L$ where l denotes the upper bound for the emission of CO_2 by the producer. The producer choses $o \leq a \leq l$, the amount of CO_2 to be emitted. The impactee choses the degree $o \leq p \leq 1$ of pressure he wants to exert on the regulator. p can denote the probability of a vote to suspend the government or of an aggression against institutions. With probability pv, the bound L is replaced by $\frac{L}{2}$, where $o < v < 1$ is a fixed number.

Those choices of the players in the case of state k are:

$$l = o,\ a = o,\ p = o.$$

Assume that the critical value is not known and that additional information is not available. Hence all three players may have different conjectures which are denoted by C_I, C_P, and C_R. For simplicity $C_P := \infty$.

Given state (C,L) and the choices (l,a,p), the following states are possible at the next stage:

$$(C + \beta a, L) \quad , \quad (C + \beta a, \tfrac{L}{2}) \quad , \quad \{k \geq C\} \quad ,$$

βa denoting that part of the emitted CO_2 remaining in the atmosphere. β is assumed to be constant.

The subjective probabilities P_R, P_P, P_I for the new states are shown in Table 1. State k cannot be changed.

Table 1. Probabilities for new states.

New State	P_R	P_P	P_I
$(C + \beta a, L)$	0 if $C \leq C_R < C + \beta a$ $1 - pv$ if $C + \beta a \leq C_R$	$1 - pv$	0 if $C \leq C_I < C + \beta a$ $1 - pv$ if $C + \beta a \leq C_I$
$(C + \beta a, \frac{L}{2})$	0 if $C \leq C_R$ $C + \beta a$ pv if $C + \beta a \leq C_R$	pv	0 if $C \leq C_I \leq C + \beta a$ pv if $C + \beta a \leq C_I$
C_R	1 if $C \leq C_R < C + \beta a$		
C_I			1 if $C \leq C_I < C + \beta a$

The transition from state s to state t has the following utility:

U_j (s; l,a,p; t) for player = j = R,P,I.

$$U_R\ (C,L;\ l,a,p;\ C + \beta a, M) = c_1\, l + c_2 a + c_3 p \quad (M = L, \tfrac{L}{2})$$

$$U_R\ (C,L;\ l,a,p;\ k) = c_1\, l + c_2 \frac{k - C}{\beta} + c_3 p + c_R$$

$$U_R\ (k;\ o,o,o;\ k) = 0$$

$$U_P\ (C,L;\ 1,a,p;\ C + \beta a,M) = c_4 a \qquad (M = L,\tfrac{L}{2})$$

$$U_P\ (C,L;\ 1,a,p;\ k) = c_4 \frac{k - c}{\beta} + c_P$$

$$U_P\ (k;\ o,o,o;\ k) = 0$$

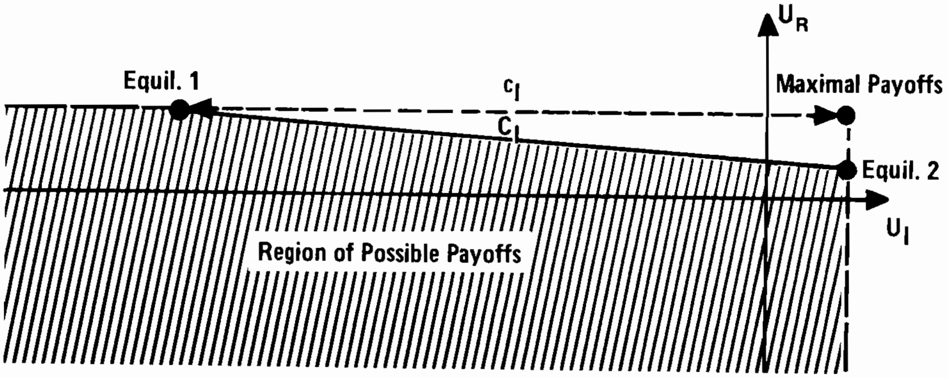
$$U_I\ (C,L;\ 1,a,p;\ C + \beta a,M) = c_5 a + c_6 p \qquad (M = L,\tfrac{L}{2})$$

$$U_I\ (C,L;\ 1,a,p;\ k) = c_5 \frac{k - C}{\beta} + c_6 p + c_I$$

$$U_I\ (k;\ o,o,o;\ k) = 0$$

We admit only stationary strategies, which are maps depending on the state and not on the number of the stage. Given a strategy-three-tuple, the payoff to each player is the sum of his "transition utilities".

The parameters are assumed to have the following signs: $c_1 \geq o$, $c_2 > o$, $c_3 < o$, $c_4 > o$, $c_5 > o$, $c_6 < o$; whereas c_R, c_P, c_I are large negative payoffs. These assumptions are essential for the shape of the range of payoffs as shown in Figure 1. We use the following solution concepts: equilibrium point, Pareto optimality, distance of the point of maximal possible payoffs.



Equil. 1: $\left(c_2 \frac{C_R - C_o}{\beta}\ ,\ c_5 \frac{C_R - C_o}{\beta} + c_I\right)$

Equil. 2: $\left(c_2 \frac{C_I - C_o}{\beta}\ ,\ c_5 \frac{C_I - C_o}{\beta}\right)$

Figure 1. Payoff for regulator and impactee ($C_R > C_I$).

An equilibrium point if a three-tuple of strategies such that no player can get a better payoff if he alone applies a different strategy. A point (U_R, U_P, U_I) of payoffs is called Pareto-optimal if no single payoff can be increased without decreasing the payoff of another player.

Then in the case of $C_I < C_R$, the strategies given by

$$l(C,L) = \min\left(L, \max\left(0, \frac{C_I - C}{\beta}\right)\right), \qquad l(k) = o$$

$$a(C,L,l) = 1, \; a(k,l) = o$$

$$p(C,L,l,a): = \begin{cases} 0 \text{ if } l = \min\left(L, \max\left(o, \frac{C_I - C}{\beta}\right)\right) \\ \qquad \text{and } C \le C_I \\ 1 \text{ if } l \neq \min\left(L, \max\left(o, \frac{C_I - C}{\beta}\right)\right) \\ \qquad \text{or } C > C_I \end{cases}$$

$$p(k,l,a) = o$$

form an equilibrium point; the payoffs are Pareto-optimal and about maximally close to the point of maximal possible payoffs. The payoffs are given by

$$\left((c_1 + c_2)\frac{C_I - C_o}{\beta}, \; c_4 \frac{C_I - C_o}{\beta}, \; c_5 \frac{C_I - C_o}{\beta}\right) \quad ;$$

they are shown as equil. 2 in Figure 1.

As an example let $C_o: = 6 \times 10^{16}$ g, $C_I = 18 \times 10^{16}$ g, $L_o: = 0.2 \times 10^{16}$ g, $\beta = 0.3$, $c_1 = 0$, $c_2 = 0.002\$/g$, $c_4: = 10^{-4} c_2$, $c_5 = 0.7\, c_2$

Then production is possible for 200 years and the payoffs equal ($8 \times 10^{14}\$$; $8 \times 10^{10}\$$, $5.6 \times 10^{14}\$$).

For comparison $3.6 \times 10^{12}\$$ is an estimate of the gross world product of 1970.

A detailed description of this subject, along with a discussion of the framework for the dynamic aspects, is contained in a forthcoming report for the Volkswagen Foundation, FRG.

CARBON DIOXIDE DISPOSAL IN THE OCEAN

C. Mustacchi, P. Armenante, and V. Cena

INTRODUCTION

Disposal of CO_2 from power station flue gas involves:

- Finding a system that can receive the amounts of CO_2 in question without major ecological alterations;
- Choosing a suitable strategy and the relevant technology to transfer the CO_2 from the source (power plant stack) to the acceptor system.

With these aims in mind, a feasibility study was carried out to obtain orders of magnitude of the marginal cost of CO_2 removal and compare it with the production cost of fossil fuel electricity. This can help in assessing the impact on the energy system of a decision to limit the enrichment of the atmosphere so as to avert a major disaster.

CO_2 SOURCES

The flue gas composition of a power station changes only slightly with the specific fuel and air excess used in combustion. With an excess around 10%, Table 1 shows typical fuel and flue compositions. Table 2 indicates some figures relevant to a typical 1 GW(e) power station. Assuming an average production of 800 t/h of CO_2 per GW(e) and a global power consumption at the present rate of 7 TW, the atmosphere weighing 5×10^{15} t, each year receives 2×10^{10} t of CO_2. This, barring dissolution into the sea, would imply an increase in CO_2 concentration of the order of 1% per year.

A number of estimates have been made as to the flux of CO_2 back into the sea (Craig 1957; Keeling 1973). The conclusions so far indicate that dissolution is a slow process, and that in several seas in the equatorial belt the actual overall flux is from the sea to the atmosphere whereas whenever sea temperature is lower than about $20^{0}C$ in the surface, CO_2 is dissolved. In any case, the macroscopic effect is an increase of around 10% per century of CO_2 concentration in the troposphere.

Table 1. Typical fuel and flue compositions.

Fuel	Coal	Oil	Gas
Carbon (wt%)	66.6	87.3	72.2
Hydrogen	3.3	10.5	23.6
Sulfur	.5	.8	-
Nitrogen	1.4	.3	4.2
Water	19.0	.6	-
Ashes	9.2	.5	-
Net Heating value (kcal/kg)	7000	10,000	12,000
Flue gas (mol %)			
CO_2	15.67	12.81	8.03
CO	.03	.02	.01
SO_2	.04	.04	-
H_2O	7.63	11.78	15.06
N_2	74.81	73.47	75.34
O_2	1.82	1.88	1.56

Table 2. 1 GW(e) power station.

	Coal	Fuel Oil	Gas
Fuel consumption (mt/a)	2.56	1.81	1.51
Flue gas (t/h)	3820	5150	4420
Flue (m^3/h,m)	2.86	3.87	3.16
CO_2 (t/h)	880	778	508

CO_2 SINKS

CO_2 sinks can be visualized as either temporary holdup storages or ultimate disposals. The first category includes essentially all the chemicals that contain CO_2 (sodium carbonate, urea, etc.) except, possibly, some hard-to-destroy polymeric material such as polycarbonates.

Broadly speaking, these chemicals may also include all the carbohydrates (sugars, starches, cellulose) making up the biomass, which gradually return CO_2 to the biosphere after a cycle time lasting, typically, one to ten years. Thus, an increase of the terrestrial biomass cannot be counted upon as an ultimate sink since the various enzymatic degradations of the protoplasm oxidize living matter back to CO_2 and water, except in the special case of major upheavals where, by burying large amounts of biomass, anaerobic transformations are initiated that again generate a stock of fossil fuels.

The ultimate sink is thus apparently only the ocean, which through the equilibrium

$$2\ HCO_3 \rightarrow CO_3 + CO_2 + H_2O$$

may still absorb sizeable amounts of CO_2 without changing its composition too much.

A theoretical possibility that could provide an alternate disposal facility would be to prevent a return of CO_2 from the biomass into the ecosphere. For instance, through photosynthetic fixation of CO_2, carbohydrates could be obtained (such as sugar) and pumped back into the underground reservoirs where fermentation would at most be anaerobic. Thus a 1 GW(e) power station, which uses about 2 Mt of fuel per year, would have to return roughly 5 Mt of sugar to the oil wells. This is clearly not possible, unless a closed circuit is established using the hydro-carbohydrate loop (photosynthesis and anaerobic fermentation) as a solar energy converter--with the well-known poor conversion efficiency 2 or 3% at most, requiring 100 m^2 of forest per kW).

Lastly, another way of attacking the problem could be to give up altogether the dangerous habit of exploiting the complete oxidation of fossil fuels for energy. Instead of obtaining 10,000 kcal per kg of hydrocarbon and turning it into CO_2 and water, one could stop at 5000 kcal per kg and obtain alcohols, aldehydes, acids, etc., as combustion products. This would halve the fossil energy reserves, but would yield a liquid by-product that could (in part) be dumped into the sea or returned to the oil wells with much less difficulty than returning CO_2. However, large-scale applications of such possibilities require more careful appraisals; we shall concern ourselves, for the time being, with CO_2 disposal into the sea.

MODES OF CO_2 DISPOSAL INTO THE OCEAN

Basically, CO_2 can be disposed of into the ocean in three alternative ways:

(a) By bubbling and dissolution of untreated flue gases;

(b) By dissolution of separated CO_2 in the gaseous or liquid phase;

(c) By abatement with sea water of CO_2 in the power plant and return of the solution to the ocean.

Solution (a) requires cooling and compressing the flue gases, and venting through a diffuser resting at a suitable distance below surface level. An estimate was carried out for average environmental conditions (horizontal water velocity 0.01 m/s, mean bubble diameter 5 mm). It appears that 95% of CO_2 can be absorbed if released at a depth of 240 m, which would require compression to 25 kg/cm^2. This would entail using about 45% of the energy produced by the power plant just for compression. The compressor, piping, and other accessories would cost about 0.3¢ per kWh produced. The result would be roughly a doubling of the cost of electrical power. An assessment should be made, however, for the siting of the power plant along the shore, compatible with finding the required depth within a reasonable distance (perhaps 10 km).

Approach (b) follows the same outline as (a), except that the gaseous CO_2 is now pure, and that with a depth of 160 m, i.e., a compression to 17 kg/cm^2, over 99% of CO_2 can be dissolved. In this case the energy required for compression is about one tenth of that of (a), less than 5% of the electrical power produced. The difference in cost can be invested in the construction and operation of the CO_2 separation plant, which will be discussed later.

Pumping CO_2 in the liquid phase into the sea must be discarded on technical and economic grounds. In fact, the very high pressures (56 kg/cm^2 at 20°C) required to retain CO_2 in the liquid phase along the whole downcomer tube would cause a tremendous energy waste. This solution should be considered only if the distance from the power plant to the seashore is so high that pumping liquid CO_2 is more convenient.

Approach (c) involves dissolving the CO_2 in seawater in a pressurized absorber. The solution is pumped back into the ocean at a depth such as to guarantee a sufficient stability in solution of CO_2: around 10 m, which will require pumping the solution to little over 1 kg/cm^2.

CO_2 DISPOSAL PLANTS

Let us again examine the three former approaches. In the case of the dissolution of untreated flue gas, the plant will consist of a battery of cooling towers, a series of multistage compressors with intercoolers (possibly up to 30 kg/cm^2), and a downcomer flue gas pipe some 10 km long. The cost of depreciating this equipment, as previously mentioned, is negligible compared with the cost of compression energy.

In the case of CO_2 separation and disposal in the gaseous phase, the plant will consist of a cooling tower to take the flue gases down to 40°C, and an absorber-stripper system whereby CO_2 is selectively adsorbed or absorbed and separated again.

Solid absorbers were evaluated and discarded. Liquid solutions were also examined: sodium and potassium hydroxides and carbonates. Mono-, di-, and triethanolamines were also evaluated, as were water, propylene carbonate, glycerine triacetate, etc. The amines appeared to be the best choice: highly selective for CO_2, low cost (0.7 $/kg), easy to regenerate.

With mono- or diethanolamines the absorption step can be carried out at atmospheric pressure. If monoethanolamines are used, the solution is 15% wt and the absorption column has a cross-section of about 800 m^2/GW. The stripping column where the solution is regenerated can be conveniently operated under pressure (10 to 30 kg/cm^2), and it will have a cross-section of about 20 m^2/GW. The bottom temperature is kept around 200°C with a steam reboiler. Heat exchange is provided between the lean solution from the stripper bottom and the rich solution flowing toward the stripper feed. With a higher operating pressure in the stripper, no compressor is required to pump the CO_2 to the ocean.

The process heat requirements will be, in an optimized plant, 20% of the heat duty of the power plant.

Electrical power consumption of this process unit, mainly due to the pumps from the absorber to the stripper, will constitute about 5% of the electrical power generation of the plant. Investment costs for the process unit are estimated to be $70 per kW(e), about one third of which is the cost of heat exchange surface.

Altogether, this approach to separating CO_2 from the flue gases would, at present prices, increase the cost of 1 kWh by about 0.8¢, 0.6 of it for the energy expenditure and 0.2 for the plant.

The last approach considered, direct abatement with seawater in the plant, requires multistage compression of the flue gases. The intercoolers are direct-contact heat exchange units fed with seawater. For a final absorption pressure of 20 kg/cm^2, nine stages and a power of 0.35 kW per kW(e) of the power station are required. However, about one half of this power is recovered by expanding the CO_2-free flue gas from 20 kg/cm^2 to ambient pressure. Thus, the overall power expenditure is around 17% cf the electrical power produced. Investment costs are estimated to be $110 per kW(e). The cost of this solution is thus about 0.8¢ per kWh, of which two thirds is due to compression energy.

Table 3 summarizes these results.

Table 3. CO_2 disposal plants.

	Investment ($ per kW(e))	Operation and Depreciation ($ per kWh)
Whole flue gas bubbling	130	.03
Amine absorption	70	0.8
Seawater absorption	110	0.8

CONCLUSIONS

It appears that if and when it is acknowledged that CO_2 cumulation in the troposphere can be dangerous, no major difficulty and only moderate cost will be involved in its removal. The processes to be preferred are those involving a separation of

CO_2 by absorption stripping in the plant. By optimizing the process detail, the additional cost per electric kWh is expected to be not higher than 20%.

The equipment is conventional chemical engineering process units, operated in very conservative design conditions. If anything, our estimates are oversafe inasmuch as they were based upon a detailed design for a 1 GW(e) power station. Assuming a one-order-of-magnitude increase in the unit size of power stations, a sizeable economy of scale is in order, and removing the CO_2 to the ocean can entail an increase price per kWh of barely 12 to 15%.

Some small verification effort should be devoted to the dissolution aspects where most of the uncertainties lie. Sinking a number of CO_2 bottles at depth 150 to 200 m and monitoring pH at various distances and times is a minor undertaking for oceanographers and should be considered at this time.

REFERENCES

Craig, H. (1957), The Natural Distribution of Radiocarbon and the Exchange Time of Carbon Dioxide Between Atmosphere and Sea, *Tellus*, 9, 1-17.

Keeling, C.D. (1973), The Carbon Dioxide Cycle, Reservoir Models to Depict the Exchange of Atmospheric Carbon Dioxide with the Oceans and Land Plants, in S.I. Rasool, ed., *Chemistry of the Lower Atmosphere*, Plenum, New York.

DEEP SEAS: CLIMATE AND ECONOMIC DEVELOPMENT

R.Gibrat

Man fears that his economic activity may become limited by the exhaustion of the possibilities of the atmosphere (Gibrat, 1978). Recently attention has focused on the use of the mass of the oceans and particularly that of the deep seas. Two approaches have been proposed, almost simultaneously though independently, by Marchetti (1977) to solve problems raised by the discharge of industrial CO_2 and by Gibrat (1974, 1976a, 1976b) to solve those raised by the thermal discharges from electric power stations.

CARBON DIOXIDE

The mass of the oceans is such that, if the atmospheric CO_2 from industrial discharges could be dissolved in the ocean water throughout its entire depth, the equilibrium content would be practically the natural level of the past and the corresponding problems would be eliminated. However, only the surface layer participates partially, whence Marchetti's idea of introducing the CO_2 forcefully into the deep seas. His "gigamixer" is based upon the use of the current of 1 to 2×10^6 m^3/s which, at the bottom of the Strait of Gibraltar, moves from the Mediterranean toward the Atlantic while, on the surface, a reverse current reestablishes roughly the equilibrium. The first waters are heavy and warm, the second are light and cold. The water from the Mediterranean thus sinks, in principle, into the deep layers of the ocean, reaches a depth of 1500 m along a course of a few hundred kilometers, and then mixes with the other masses forming the deep-sea water of the oceans. Marchetti has shown that the orders of magnitude involved are suitable, particularly for CO_2 contents acceptable by marine life.

THERMAL DISCHARGES

Two-thirds of all oceanic water, representing over 1000×10^6 km^3, have common temperature and salinity properties. They are related by surface phenomena taking place at locations of very small dimensions (a few percent of the surface area of the oceans) and for a very small number of months per year--which is the present belief.

The oceans are in fact naturally stable along the vertical: cold waters at the bottom, warmer waters on the surface. And this stability with respect to density is disturbed only in certain rare places by surface variations in the budget of heat exchanges with the atmosphere or in salinity, the consequence being density variations of the order of 10 ppm in the vertical column giving rise to vertical movements at speeds of a few tenths of a millimeter per second but corresponding to flows of several million cubic meters per second (Lacombe, 1968, 1974, 1977).

Three oceanic surfaces appear to provide, by themselves, almost all the supply of the deep seas, the main one being the Weddell Sea in the Antarctic, and those of Labrador and Norway.

The rises take place especially in the North Atlantic at the location of fisheries after covering a long distance in depth requiring several tens of thousands of years. The rise rate is extremely slow, representing a few tenths of a millimeter per hour.

Comparisons will be made of the mass of these deep-sea waters at an average temperature of 1.5°C (1000×10^6 km^3), with the annual consumption of a nuclear power unit, as well as the sink rate in the Weddell Sea (several million cubic meters per second) to that of a nuclear power unit 50 m^3/s). This gives extraordinary theoretical cold-source possibilities especially as thousands of years will elapse between the downflow and the moment a surface modification is felt (when the upflow occurs). But how can these possibilities be used? This does not appear to be easy because, even if it is possible to solve the problems relative to the set-up of power plants in downflow areas of very difficult access (the Antarctic for example) and those relative to utilization for only a few months of the year, thermal discharges will have an opposite effect on density, heating the water and reducing its density. It is possible to consider charging the effluent water with marine salt in order to compensate the effects of temperature on density, but the idea appears farfetched.

If we add to these ideas on CO_2 and thermal discharges current plans for using the thermal gradient of the oceans (thermal energy of the seas), it will be seen how important it is to understand very thoroughly the oceanographic mechanisms involved. These mechanisms are very poorly understood and surely very complex.

VARIABILITY OF OCEANS

Practically unknown 20 years ago, the concept of ocean variability has become quite current and is a dominant problem throughout the world.

We shall take as a first example the sill of Gibraltar. The two upper and lower currents must compensate for the negative water balance (river inflow smaller than evaporation) while maintaining the total amount of salt since there is no secular variation in salinity and level. The *average* value of the incoming surface current is about 1 × 10^6 m^3/s (about 36.2% salt water). The outgoing bottom current must consequently always have an average of 5% less water and 5% more salt, representing 0.95 km^3/s and 38.2‰. However, only averages are involved. There are of course the periodic tidal currents (12 to 24 hours) so that, at certain points and for certain depths, the current is sometimes incoming and sometimes outgoing. Then, the conditions of atmospheric pressures in the western part of the Mediterranean play the very important role: roughly, when the pressure rises, the water is driven toward the ocean and vice versa. The average current, calculated over a tidal period, can thus exhibit variations of 100% from one period to another. Finally, the tide creates, on the very sill, significant vertical oscillations of the interface between the two currents. Furthermore, new measurement techniques make it possible to almost simultaneously measure the temperatures on a vertical. And, waves of short periods (15 minutes) corresponding to great increases in surface current have been revealed. For Gascard (1977), the present major problem regarding flows in the Strait of Gibraltar is to determine the origin of the water of the bottom current. In fact, Atlantic water forms two branches which remain on the surface after having gone through the Strait on the surface: one in the direction of Sardinia and Corsica, describing a cyclone movement, and then extending in the east-west direction along southern France and Spain; the other running closely against North Africa in the direction of the eastern Mediterranean and increasing in salinity as it approaches the coasts of Asia Minor.

In the autumn and winter, toward Cyprus and Rhodes, the cold and dry continental winds cause evaporation and cooling with stirring movements in the first 150 or 200 m, creating the "levantine" water (T = 15.7°C, S = 39.1%) which moves slowly westward, crosses the canal of Sicily (14°C, 38.75%) and provides the "intermediate" water in the entire western Mediterranean. There is also the classical three-layer system, adding the deep Mediterranean water formed south of Toulon through the downflow of the mixture of the first two layers.

Is the outgoing water "levantine" or "deep" or a mixture of the two and in what proportion? The question is fascinating from the theoretical standpoint but also, quite evidently, from the technological standpoint as regards the storage of CO_2.

Unfortunately, the very great turbulence of the Strait due to tides makes the problem very difficult. A calculation of fluid dynamics on the basis of salinities and temperatures appeared to show, in 1973, that deep-sea water is capable of rising over the sill either by itself or mixed with levantine water by upwelling. What is the process? Is it stable? Two German scientists from the Institut für Umweltphysik at Heidelberg are presently undertaking, with the Museum of Paris, tritium measurements and a study of the ratio of its content to that of helium 3 on the sill and in the different formation basins of the waters.

This "variability" is of a general nature and some historical information is necessary. In fact, until about 1960, oceanographers believed that ocean movements were essentially permanent and dominated especially by the Coriolis force. Explanation for the general circulation patterns of the oceans, and in particular for the surprising concentration of currents on the western coasts, was the major subject of that time. However, gradually, investigation facilities were improved, the possibility of almost instantaneous measurements appeared and it was quickly found that the properties (temperature, salinity, density, and so forth) of the real surface currents varied with respect to time and space in a manner "totally incompatible" with the general models of earlier authors. The equivalent of the well-known atmospheric variability was gradually found in the ocean to the scale of the day, week, or season.

The first discovery was the variability due to the action of the thermal atmosphere with evaporation, the passage of sensible heat, infrared radiation and mechanically with the action of winds and waves. Then came the recent discovery of variability due to the internal dynamics of the oceans themselves, owing to the technique of floats with neutral floatability.

The following was thus observed, under the action of the atmosphere:

- "Inertial" horizontal oscillations according to the Coriolis period and in the anticyclone direction, under the action of a gust of wind and bringing about *vertical* oscillations in the thermocline with the same period.
- Vertical oscillations which can go down to the bottom and are referred to as *stability* oscillations with the frequency of Brunt-Väisälä related to the variation in density with depth.
- Waves of a special nature on the continental plateaus as well as at great depths.
- Meteorological depressions having, in general, a speed higher than those of the waves of the schematic ocean with two layers and thus dragging complex wakes behind them.

The internal dynamics, i.e. concerning the entire depth of the ocean, are surprising. As early as 1950 the discovery was made of the existence of meanders of the Gulf Stream giving five to six cold water cyclone rings on the right off the coasts of the United States, and, on the left, as many hot water anticyclone rings, all directed toward the southwest and then reabsorbed by the current.

Today, whirlpools are discovered everywhere and it has been written that the ocean is a mosaic of whirlpools (from 10 to 200 km in diameter) even at depths of 5000 m and greater. These are essential because they concentrate over 90% of the kinetic energy of marine currents.

At the end of April 1977, a meeting of experts in the United States issued recommendations for the program of oceanographic experiments, to be carried out during the decade beginning in 1980, for the purpose of climatological research in connection with the Global Atmospheric Research Program (GARP). They estimate that the real processes of ocean heat transfer are not known today: are they deep, permanent or variable with time, extensive on the surface, etc.? What is their origin? This is all essential information for founding climatology on a scientific basis, and for engineers wishing to use these phenomena; it provides food for thought for the many people throughout the world who would like to use the thermal energy of the seas. Long and costly measurement programs must be implemented before the actual utilization can begin.

THE FORMATION OF DEEP SEAS

We recently reread five articles devoted to the Weddell Sea in the volume *Research on the Antarctic* (1971), then 29 papers presented at the 1972 Conference of the Centre National de la Recherche Scientifique (CNRS) in Paris on the formation of deep seas and, finally, Gascard's recent thesis (1977) on the western Mediterranean. Considering the many explanations, often in agreement and sometimes contradictory, and in any case very difficult for the nonprofessional to follow, and in view of the very few facts available (except as regards the western Mediterranean), we are reproducing below a small table published in the Proceedings of the CNRS Conference. The table represents an inventory of the conditions prevailing in known sink zones.

It is very important to comment on this matter because only more in-depth knowledge of the mechanisms forming the deep waters will allow us to use them, for example for introducing CO_2 or for disposing of thermal wastes. This will also make it possible to determine the locations and periods during which sink movements may have been observed, because they have been hitherto sought only on the continental shelves or in their vicinity. They must also exist on the open sea. It is also important not to destroy the phenomenon while using it, and perhaps to produce it wherever necessary.

Table 1. Conditions in known sink zones.

Source: CNRS (1972), p. 272

	Weddell Sea and Antarctic	Norwegian and Greenland Seas	Labrador Sea	Red Sea	Mediterranean	
					East	West
Cyclone circulation	+	+	+	?	+	+
Cold low-salinity water	+	+	+		+	+
Warm salt water	+	+	+		+	+
Cold salt water	+			+		
Cyclone wind	+	+	?		+	+
Continental shelf						
Real	+			+		+
Virtual	+		+		+	+
Double diffusion	+	+	+		+	+
Nonlinearity	+	+	+			
Convection on continental shelf	?	+	?	?	+	+
Convection on the open sea	+			+	+	?

The studies were conducted mainly upon French initiative, owing to the considerable data obtained through international measurement campaigns carried out since 1969 in the north-western Mediterranean. (The observation center is located at 42° N, 5° E, about 100 km S of Toulon.) In 1977, Gascard provided an overall explanation which, though very general, does not appear to cover the entire question. We are citing it here in the hope of not distorting his ideas:

> The dense deep waters are in fact formed from the lighter surface or subsurface waters which undergo an increase in density through the effect of cooling, evaporation or freezing... However, this increase in the density of the surface waters must be very great and must reach the point where they are then caused to sink...

This entails a certain number of conditions.

> Firstly, the presence of meteorological conditions which produce a definite cooling and an internal evaporation (or with freezing) of the surface waters... Then, the presence of a large quantity of salt... This source of salt is in general constituted by relatively very warm and very saline water circulating at an intermediate depth between the surface layer of low-salinity and cold in winter and the cold, very dense and saline deep layers resulting from the mixing and the transformation of the two underlying layers in winter... Finally, a situation of dynamic preconditioning of the surface and intermediate waters is necessary for initiating the process of their transformation into deep water... There are two special cases: in shallow water--hence having a low thermal content (around the Antarctic); in deep water when the water masses are driven in a cyclone circulation while keeping the more dense waters toward the center of circulation and the lighter waters toward the periphery (the case of the northwestern Mediterranean).

Gascard's explanation is not sufficient, and he details the process by introducing "purely convective phenomena" and turbulent mixing phenomena involving the breaking of internal waves--which we mentioned in an earlier paragraph relative to oceanic variability (inertial waves, Brunt-Väisälä waves).

We have seen that the first seven lines of the table appear in this general description. However, the Arctic seas of Norway, Greenland, and Labrador have only two layers in the table; the Red Sea has only one; and, by contrast, the western Mediterranean has both the "real" and "virtual" forms of the continental shelf. The last four lines still remain to be considered.

Double diffusion, i.e. heat and salinity, is regarded by certain investigators as an important sink mechanism. The ratio of the coefficients of heat and salt diffusion is high, of the order of 10^0 in the molecular scale, but, owing to turbulence, it is taken as equal to unity for the oceanic processes which are of a very large scale. Anati (1972) believes that there is a transition zone to medium scales (greater than a few kilometers) and the ratio is greater than unity. A horizontal flux of "floatability" could apparently be generated under certain conditions, with the resulting appearance of surface water sinking in depth.

The *nonlinearity* of the state equation of seawater has often been put forward since 1960 for the Antarctic: it occurs when waters of different temperature and salinity, but of the same density, are mixed. Such nonlinear changes would make it possible to explain how the water coming from the continental shelf can act to maintain a bottom water with a greater salinity attained through a linear exchange.

We shall simply say a few words regarding the last two lines of the table. The problems of *convection* were brought up by Foster (1972). He assumed that a dense boundary layer begins to develop on the surface of the ocean by diffusion. It becomes unstable and a "convective flux" is established, which greatly increases the effectiveness of the downward transport of the denser fluid. The stopping of the phenomenon, then the return to a deep instability, would explain the sinking to great depth.

The major originality of Gascard's thesis lies in the demonstration of the importance of *barocline instability*, i.e. the primary role of an even small inclination on the horizontal of the surface of the densities (isopycnics). This is said to generate small whirlpools with a period of two to three days associated in cyclone-anticyclone pairs. This has been observed in the Gulf of Lion and also in the Labrador Sea. The phenomena observed in the Mediterranean are thus very similar, with a similarity ratio of 1 to 100, to the classical ones of the troposphere, "generating, at the level of the polar front, the cyclone and anticyclone disturbances which are a characteristic of the climatology of the temperature regions..."

Owing to these phenomena, the waters undergo a transformation which enables them to sink at rates of the order of 1 mm/s. This leads to tens of millions of cubic kilometers per year, i.e., within the same order of magnitude as the outgoing flows at the sill of Gibraltar.

Summarizing, the mechanisms underlying the formation of deep-sea waters provide an exceptional wealth of suggestions which man should continue to investigate if, one day, he is to use the deep waters for any reason whatever. Today, oceanographers are still endeavoring to understand these phenomena, making the best use of the still rare existing data. They are beginning to obtain increasingly satisfactory patterns from fluid dynamics and are working toward an explanation of what is taking place. However, engineers must begin to think about the practical utilization of this immense mass of cold water and, for this purpose, must propose precise research orientations for oceanographers. For the moment, too little is known. Cooperation is absolutely necessary in this area. This paper is a modest attempt in that direction.

REFERENCES

[1] Anati, D.A. (1972), Double diffusion à échelle moyenne et formation d'eaux profondes, in P. Lacombe, ed., *Processus de formation des eaux océanographiques profondes en particulier en Méditerranée occidentale*, Internat. No. 215, Centre National de la Recherche Scientifique Colloques, Paris.

[2] Foster, T.D. (1972), The Hierarchy of Convection, in P. Lacombe, ed., *Processus de formation des eaux océanographiques profondes en particulier en Mediterranée occidentale*, Internat. No. 215, Centre National de la Recherche Scientifique Colloques, Paris.

[3] Gascard, J.C. (1977), *Quelques éléments de la dynamique de formation des eaux profondes*, Thèse Université de Paris VII, Paris.

[4] Gibrat, R. (1974), L'énergie en l'an 2000, communication faite le 12 Mars 1974 à l'Académie des Sciences Morales et Politiques, *Revue Sciences et Techniques*, 14 (15 May).

[5] Gibrat, R. (1976a), Energie et environnement après l'an 2000, *Revue Sciences et Techniques*, 36 (November).

[6] Gibrat, R. (1976b), in *RIO (Reshaping the International Order)*, Dutton and Co., New York, Chapter 13 and Appendix 5.

[7] Gibrat, R. (1978), L'influence du développement économique sur le climat (Réflexions d'un ingénieur), *La Météorologie* (forthcoming).

[8] Lacombe, H. (1968), *Les énergies de la mer*, Coll. Que Sais-Je?, PUF, Paris.

[9] Lacombe, H. (1974), *Deep Effect of Energy Transfers Across the Sea Surface*, Melbourne Scientific Program.

[10] Lacombe, H. (1977), *Méchanismes océaniques et environnement physique*, Assoc. Inter. de recherches hydrauliques, presented at the Congrès de Baden-Baden.

[11] Lacombe, P., ed. (1972), *Processus de formation des eaux océonographiques profondes en particulier en Méditerranée*, Internat. No. 215, Centre National de la Recherche Scientifique Colloques, Paris.

[12] Marchetti, C. (1977), On Geoengineering and the CO_2 Problem, *Climatic Change*, 1, 59-68.

REPORTS OF THE WORKING GROUPS

WORKING GROUP I: THE CARBON CYCLE

GENERAL REMARKS

The carbon dioxide (CO_2) resident in the atmosphere at any one time represents a small part of the total carbon circulated among the atmospheric, the biospheric, and the oceanic reservoirs. The carbon content of the reservoirs is reasonably well known. However, it is the net exchange between the reservoirs that determines the rate of accumulation of carbon in the atmosphere and these exchanges are not at all well known. Since we cannot measure the exchanges directly, it is necessary to formulate biogeophysical models of the carbon cycle to represent the exchanges and to test these models against observations of as many kinds as possible.

The key question in the CO_2-climate discussion is: how much confidence do we have in existing carbon cycle models? Unfortunately, ten years ago we had considerably more confidence in the models than we have in 1978. This is not to say that we have no powers of prediction. Past fossil fuel injection rates are well known and we have two decades of observations on the proportion of CO_2 that has remained in the atmosphere (~50%). It is most unlikely that biogeochemical conditions will change significantly during the next two to three decades, so that reasonable predictions over that time period should be possibly by simple extrapolation, given an approximately exponential growth rate in fossil fuel usage. The existing models do not disagree significantly from predictions based on extrapolations over such time scales. However, beyond the next 30 years the uncertainties in predictions increase rapidly.

The role of the oceans is not the major uncertainty in these predictions. There is now fair agreement about how much CO_2 the oceans can and can not partition from the atmosphere. Recent improvements in ocean models have given differences in the partitioning of about 10%, and such differences are small compared to the uncertainties that exist in predictions of the role of the biosphere in the future. Further refinements in ocean modeling--in particular greater cognizance of the role of advective transport--are not expected to markedly increase the capacity of the model oceans to take up CO_2.

Therefore this Working Group concentrated on the recent conflicts in opinion concerning the net fluxes between the biosphere and the atmosphere. It was a highly topical aspect of the carbon cycle, because many recent papers have been published dealing with the subject.

EVIDENCE OF DECREASING BIOSPHERE

Data were presented indicating the apparent insignificance of forest fires and a number of changing land-use practices as sources of carbon. Further support was given to the idea that tropical forest clearing could represent a significant source. The discussion touched on the great difficulties of using observations of tropical forest clearing to estimate global inputs of CO_2, which are reflected in the order of magnitude range of estimates in the recent literature.

The difficulty of dispersing this carbon in the oceans was reiterated and the possibility was raised that, given the growing concensus is that there probably has been net global deforestation during the past century up until the present, this may have been in part compensated for by regrowth patterns in areas recovering from cutting in earlier decades.

It was considered unlikely that reliable inventories of global biospheric carbon could be obtained in the near future with sufficient precision to observe trends. This pointed to the need for independent indicators of significant interreservoir exchanges, such as isotopic studies.

TREE RING OBSERVATIONS

Three organizations presently making stable carbon isotopic measurements of tree rings were represented in the Group. A discussion of their data indicated the variability of $^{13}C/^{12}C$ measurements, with evidence of variations in ratios in single rings which exceed the magnitude of the trends already reported in the literature. Nevertheless, in the more extensive German data set, there was some evidence of consistent patterns emerging from the records. The need for many records indicates the dangers of drawing conclusions from data published for single trees.

The short-term (year-to-year) variability of ratios presumably reflects direct environmental influences on fractionation and/or the imperfect siting of trees as indicators of background atmospheric conditions.

The general feeling seemed to be that these measurements of stable carbon isotopes in tree rings must continue, and there was optimism that once sufficient experience is gained in tree selection and the number of records is increased, a complete past record of atmospheric $^{13}C/^{12}C$ trends would be obtained.

DIRECT AIR MEASUREMENTS

The Group recognized the need for the immediate initiation of direct measurement of atmospheric stable carbon isotope ratios, with due consideration to obtaining data uninfluenced by local or regional effects. The use of existing baseline monitoring stations would be a suitable approach.

INTERPRETATION OF ISOTOPIC TRENDS WITH MODELS

Given existing isotopic trends published in the literature, or those which may be subsequently derived from expanded tree ring studies or direct atmospheric measurement, the interpretation of how these reflect interreservoir exchanges will depend on the way one models the partitioning of carbon between the various reservoirs to reproduce the observed atmospheric CO_2 concentration trend. Papers were presented which discussed this problem. Little attention was given to alternative treatments of the ocean uptake, the emphasis being mainly on the difficulty of modeling the biosphere. The biospheric reservoir is composed of material in many different forms, e.g., leaves, stems, roots, soil organic matter, and peat. Each of these subcompartments possesses its own characteristics, e.g., chemical composition, carbon residence time. The matter is further complicated by the fact that the subcompartments are different in each biome and the biomes are heterogeneously distributed geographically. Generally the biosphere appears to offer greater modeling difficulties than the somewhat more homogeneous oceans.

Discussions centered on the use of the growth factor concept where some functional relationship is assumed between the growth of the global biosphere and the atmospheric CO_2 concentration. In view of the complexity of the biosphere, present relationships do not adequately describe the possible CO_2 fertilization feedback effects on the biosphere. The possible feedback due to effects on the climate has been almost ignored thus far.

The complexity of the situation led to a discussion of the likelihood of success in modeling with mechanistic models and whether empirical techniques will prove necessary. While no firm conclusions were obtained, it appears at this stage that the mechanistic approach should be pursued.

WORKING GROUP II: THE IMPACT ON CLIMATE AND ENVIRONMENT OF INCREASING ATMOSPHERIC CO_2 CONCENTRATIONS

CLIMATE MODELING STRATEGY

While it is now virtually impossible to predict weather and climate a month, a year, or a decade ahead, we may have success in a second kind of prediction--that is, a prediction by which we deduce a climatic change due to an anticipated change in some boundary conditions of the climate system. Such a prediction is only reliable to the extent that we can predict the boundary condition change (notably atmospheric CO_2 content) and to the extent that our climate system models respond like the real atmosphere.

Climatologists have developed a hierarchy of climate models ranging from one-dimensional or single-column models, to two-dimensional latitudinally dependent models, to three-dimensional and time-dependent models where the only limit to the physical detail of the simulation of the climate system is human ingenuity and computer power. We will refer to the latter as general circulation models (GCMs). To date almost all model experiments to test the effects of doubling CO_2 have used the simpler one- or two-dimensional models, and the only three-dimensional or GCM-type model used has been that of Manabe and Wetherald (1975) that included one continent, fixed cloud amount, and an ocean with the characteristics of a swamp.

Among the major model-related questions discussed by the Working Group are the following:

a. What have our models revealed so far about the CO_2-climate interaction and to what extent can we believe the modeling simulations?

b. What can we learn from one-dimensional (or quasi-two-dimensional) models which admittedly do not include some feedback loops already existing in the real world?

c. Is it worthwhile to experiment with the more elaborate (and more expensive) GCM-type models?

The response of the Working Group to these questions is summarized below.

A variety of one-dimensional, globally averaged models has been used to determine the *purely radiational effect* of a CO_2

doubling on vertical temperature distribution, the tropospheric lapse rate being constrained (the convective adjustment), the relative humidity remaining constant and all other factors (except clouds) remaining constant. It can be assumed that clouds respond by keeping their cloud tops at either a constant altitude or a constant temperature (cloud amount being fixed). This kind of calculation has now been repeated and refined to the point where there can be little doubt about the result, if we are willing to accept a 25% uncertainty. For a doubling of CO_2 we calculate:

- \+ 2.0°C mean surface temperature change, fixed cloud top height;
- \+ 3.2°C mean surface temperature change, fixed cloud top temperature.

Unfortunately, we cannot decide which assumption about clouds is better, though there are some hand waving arguments in favor of the fixed cloud top height and the smaller response.

The figures for a change of mean surface temperature with a CO_2 doubling are calculated under carefully specified constraints on the behavior of the rest of the climate system, and are given to demonstrate that our knowledge of the purely radiative effects of CO_2 are fairly well understood. When other feedback mechanisms are taken into account, the result will not necessarily lie between the two figures given--i.e., they are not to be considered as limiting values.

The Working Group heard and discussed two papers reporting on original one-dimensional model results, by Ruth Reck and Peter R. Rowntree and Julie Walker; reviews of modeling results by Wilfred Bach and Hermann Flohn had been previously heard. Since these papers are in the Proceedings, their conclusions will not be repeated here. The main insights to be gained from such model experiments are an appreciation of the sensitivity of the modeling results to a variety of physical assumptions or boundary conditions, and it is likely that the real climate system would display about the same sensitivity. For example, Reck's experiments showed that a 1% increase in global average surface albedo (now taken to be 0.14) would result in a surface temperature increase (ΔT_s) of -0.14°C; she also showed how the temperature would respond to the addition of other infrared absorbing gases; and Rowntree and Walker showed the importance of treating moisture in the convective parameterization, since different treatments result in different lapse rates and distributions of water vapor and therefore a different model sensitivity. Thus, even though such relatively simple models cannot be thought of as providing a "complete" simulation of reality, their flexibility and relatively modest computer requirements make them suitable for answering specific questions about the climate system. Furthermore, these insights are needed for the design of more complex models.

As for the advantages of expensive GCM-type modeling experiments, *GCMs of the atmosphere* have evolved to a fairly high level of sophistication. They now include realistic topography, generate their own clouds and rain (though crudely), and determine whether there is snow on land and (less well) where there is sea ice, and so forth. However, an equally important component of the climate system is the ocean, and ocean modeling has lagged for a number of reasons. The ultimate GCM-type climate model will have a fully coupled and interactive *atmosphere and ocean*, and also an improved simulation of the cryosphere of the polar regions.

Those involved in GCM development are aware of the deficiencies of their atmospheric models, be they ever so complex, and are doubtful that there will be a completely satisfactory ocean model for many years. Nevertheless, the Working Group heard that there are some possible interim solutions to the problem of including an ocean in a GCM-type model, such as the use of a model of the upper mixed layer of the ocean (neglecting the deep ocean), and a technique for adjusting present sea surface temperature distribution to maintain an overall thermal balance with a warmer (or colder) atmosphere. Neither of these has been tried so far, but we understand that plans for CO_2 experiments with such interim models are well advanced.

Why do we feel such expensive experiments are worth the effort?

On the *scientific side* of the question is the conviction that only such complex models can hope to include some of the important feedback mechanisms that exist in the real climate system. One feedback of obvious importance is the snow-and-ice-albedo-temperature. Another feedback about which we are still uncertain is the response of cloudiness to a climatic change. Other feedbacks whose importance remain to be investigated are the response of vegetation, of oceans currents, and of Arctic and Antarctic pack ice to climatic change. There are undoubtedly others. We will probably not have sufficient confidence in our climate models until we are satisfied that they include the important feedback mechanisms.

On the *practical side* of the question, we recognize the need for enough spatial resolution and physical realism to simulate *regional climate change*, and to be able to specify these changes in terms of *seasonal temperature and precipitation* patterns. Statements about global average temperature trends are of little value to planners or policymakers, for the important considerations are the changing distribution of sources of food and fiber, of water resources, of energy requirements, and so forth, in various parts of the globe.

Of course, the addition of CO_2 to the atmosphere is not the only influence of mankind on climate. There are other infrared-absorbing trace gases that can cause a greenhouse effect, such as the chlorofluoromethanes, nitrous oxide, and methane. Also, patterns of land use that result in desertification, deforestation, irrigation, or creation of new bodies of water can change the albedo and hydrological properties of large areas, and GCM-type models with good spatial resolution are needed to determine their impacts on global climate.

Until we have achieved these GCM-type modeling experiments there are only a few generalizations that can be made about the regional climate changes that will result from an increase of CO_2. One is that some regional changes will be much greater than the global average, and they will be both positive and negative with regard to temperature and precipitation. Our models already tell us that there will generally be more rainfall as the warmer atmosphere causes more evaporation from the oceans, and that this extra rainfall will probably show up in areas affected by monsoonal circulations and probably in some mid-latitude regions. A study of paleoclimatic records of the periods when it was warmer than now also reveals that there will probably be places where rainfall decreases as a result of altered large-scale circulation patterns.

In summary, climatic change will bring with it both gains and losses, winners and losers. Unfortunately, climatologists still cannot say *where* these will be.

THE SIGNAL-TO-NOISE PROBLEM

Monitoring of the climate has many objectives, and one that is frequently stated and used to justify a monitoring effort is that it will detect a climatic change as soon as it occurs. The Working Group recognized that the detection of climatic change is far from simple, since any such change (or *signal*) must be distinguished from the *noise* of natural climatic fluctuations.

There are a variety of techniques for discriminating a signal from a noisy background, techniques well known to both information theorists and climatologists. These techniques work especially well when the signal is harmonic or has some characteristic shape that is known ahead of time. However, the CO_2 induced trend is going to be much harder to detect. A simple approach is to say that it will be identifiable when the global mean surface temperature change (averaged over a five to ten year period) becomes equal to or larger than the natural temperature fluctuations of the past several centuries (again, using averages over five to ten year periods). These past temperatures have had a range of about 1 °C, so this signal-to-noise exceeding unity could occur before the year 2000, according to our present estimates.

Other possibilities were discussed, generally based on the belief that there must be certain parts of the climate system that will respond more sensitively than the global average surface temperature. Perhaps it will turn out to be the polar regions, or the middle stratosphere, or the alpine glaciers of the world. These are possibilities that should be considered in plans for climate monitoring.

In any case, the first true recognition of a climate change due to CO_2 increase will have to result from a *combination* of climatic observations, CO_2 monitoring, and theory. If our models are correct, they should allow us to draw a consistent picture of what is happening, including the natural causes of climate change that may be operating at the same time.

DATA FOR CLIMATE RESEARCH AND APPLICATIONS

The United Nations Environment Programme (UNEP), in cooperation with the World Meteorological Organization (WMO), has just completed a comprehensive review of data requirements for climatic research and applications to planning, and C.C. Wallén reviewed the report for the benefit of the Working Group. (The report will hopefully be available through the national weather services. It will be reviewed by a meeting of government experts in April 1978.)

It is Wallén's belief that a major advance in climatic data availability would be to have a survey and up-dated catalogue of the data that are being gathered at some 140,000 climatic stations around the world (in addition to the 9000 synoptic weather stations whose data are transmitted and archived already). It is currently difficult to get access to much of this large mass of data because many countries do not have a systematic way of assembling it.

The Working Group was also concerned that climatic data be adequately applied to practical problems of society. The climatic and environmental data that are now available, or will be within the next five to ten years, should be applied to the resolution of various key questions concerning possible climatic impacts on the overall global food and energy system. These include the relationships between basic environmental conditions and snow/ice conditions, length of growing season, and water resources. Other environmental parameters of possible importance are solar radiation, atmospheric turbidity, atmospheric trace gases, wind, ocean currents, and so forth, which may relate to food and energy considerations.

LESSONS FROM PALEOCLIMATOLOGY AND THE CLIMATIC RECORD

We have already referred to the inferences that can be drawn about a warmer earth from studies of warm periods of the past, and there are clearly many other questions that can best be answered by referring to the past record. For example, we need such a record to determine the statistics of natural climatic fluctuations, to determine correlations between temperature, pressure, and rainfall, to understand the effects of natural events such as volcanic eruptions and changing of solar activity and so forth.

There is an even more fundamental value in studies of past climatic regimes, namely the identification of important interactions that we may have overlooked in our models. The process of geophysical research has traditionally begun with a description of the system to be studied, since that is the way to learn which parts seem most important and which parts may be neglected--at least, for the first development of a theoretical framework. The climate system is indeed so complex that we could not hope to develop a model of it entirely from first principles, and some parts may have to remain largely empirical. Examples of some of the complex interactions that may have to be treated empirically, based on inferences from the past, are the influences of equatorial upwelling in the ocean on the Hadley circulation of the atmosphere (probably changing greatly between ice ages and interglacials), behavior of the monsoonal circulation in its extensions over Africa and Southeast Asia, variations in the oceanic boundary currents with wind stress, and so forth. Even though these interactions may eventually yield to the first principle approach, we will always have to check our results against reality.

In fact, a major use of the climatic record is to test our models against past climatic changes. We are only beginning to understand how to do this, but it is a potentially useful way to verify the sensitivity of our models to real climate change--in short, to *validate* the models.

WHAT DECISIONMAKERS NEED

A recurring theme, one to which we have referred at the end of the modeling section, is the requirements that politicians (in the broadest sense of the word) have for climatic change predictions. Even more important, in fact, is their need for predictions of the consequences of these climatic changes. Dr. Herbert Wiser posed some more-or-less rhetorical but important questions to the Working Groups.

Suppose, for example, we imagine a kind of "worst case" in which we burn up most of our economically recoverable fossil fuel by the year 2100, and this results in an 8^0 to 10^0C global average warming. What will this mean in terms of food, fisheries, water resources, transportation, and so forth? Is this process reversible? Are there any precedents in historical data for such a climatic change?

Referring to the planning process, if we were in a position to control CO_2 emissions, at a cost, what data or predictions would we need? When would we decide to take action?

Since climatologists apparently cannot provide adequate predictions for the planners yet, it is natural for them to ask: When *will* you be able to give us your predictions? What are your uncertainties now and in the future? Can these uncertainties be quantified?

And then there are the ultimate and agonizing questions for which the climatologist cannot be expected to have any expertise. For example, can a country that expects to gain from climate change be persuaded to pay for the losers? Would it, perhaps, be better not to have any predictions at all?

REFERENCE

Manabe, S., and R.T. Wetherald (1975), The Effects of Doubling the CO_2 Concentration on the Climate of a General Circulation Model, *J. Atmos. Sci.*, 32, 1, 3-15.

WORKING GROUP III: THE INTERACTION BETWEEN ENERGY STRATEGIES AND THE CO_2 QUESTION

The Workshop Group heard several papers on subjects ranging from the setting of standards for emissions and atmospheric concentration limits, through the possibilities of geoengineering the oceans to "embed" major amounts of CO_2 directly into the oceans, to the concepts of decisionmaking in the face of limited knowledge. It was evident throughout the discussion that in almost every aspect of the CO_2 issue we are confronted with uncertainties. The implications of significant climate changes may be so serious that establishment of energy policies that recognize these potentialities and maintain flexibility is the only prudent course of action. It was judged that mankind needs and can afford a time window of between five and ten years for vigorous research and planning to narrow the uncertainties sufficiently so as to justify a major change in energy policies to those that are more responsive to the CO_2 problem from those that allow the continued reliance on abundant and inexpensive fossil fuels.

Specifically, we face four major problem areas demanding progress if a rational course of action can be determined (and accepted by society) by the end of this time window:

a. What are the tolerable rates of burning fossil fuel? Maintaining a rate of fossil fuel use at or below such tolerable values while maintaining hope within the impoverished masses of the world will require extremely careful planning and the ability to deploy inexhaustible energy sources effectively. A better understanding of the aspirations and energy requirements of the developing world are essential in determining rates of fossil fuel use on a global scale.

b. The distribution of the CO_2 produced from fossil fuel concentration among the several reservoirs in the carbon cycle must be known. Before we can estimate with confidence what fraction of the CO_2 from fossil fuels remains in the atmosphere, we must better understand the roles of both the biosphere and the oceans in the global carbon cycle. This is a necessary input to establishing the tolerable rates discussed below.

c. The evidence is strong that substantial additional atmospheric CO_2 will cause significant climate changes; quantitative values are difficult to assign with confidence.

Even greater uncertainty is evident in attempting to define the potential changes in regional climates. Definition of the tolerable rates of fossil fuel use requires a better understanding of climate changes, their effects and acceptabilities.

d. We have not yet identified the whole range of adjustments the world would or could make to a substantial climate change. It is not premature to examine possible global and regional responses to the eventuality of such changes and the consequences the responses to the changes can cause on the well-being of the global society.

Within these broad areas, we interpreted our workshop assignment as being centered on point (a), but total separation among the areas is impossible when cost versus benefit quantitative tradeoffs are made. In attempting to address the problem of supplying energy in sufficient quantities to assure global economic, political, and social well-being and yet remain within "acceptable" bounds of CO_2 emissions, five policy statements evolved. Each statement reflects the importance of flexibility in determination of energy policies.

Quantitative estimates on the rates of increase in CO_2 and other infrared absorbing molecules in the atmosphere and resulting global and regional climate changes are not only uncertain, but are likely to remain so for most of the next decade. We therefore stress that *it is premature to implement at this time policy measures which require the reduction in use of coal and other fossil fuels. We believe that present knowledge is sufficient to require both broad and deep study of many alternative energy supply systems, but does not yet warrant a policy of curtailment of fossil fuel use.*

Policies to emphasize the use of coal because of its great abundance in preference to nonfossil (non CO_2-producing) energy supply systems are equally unjustified. Such policy decisions can become difficult and very costly to reverse because of the evolving technologies required in each energy supply system. Emphasis on coal at the expense of either hard or soft solar, nuclear (including the breeder), nuclear- and/or solar-methanol systems appears to be unreasonable in view of the possible CO_2 consequences. *We urge the maintenance of great flexibility in energy supply policies at this time.*

Environmental impact assessments of escalating energy use must be performed with greater depth than in the past and on a scale commensurate with the potential importance of the problem. In particular increased long-term basic research must be adequately conducted in and across those areas of the natural sciences dealing with the fundamental global cycles of those key elements that give the earth its life supporting characteristics, e.g., plant physiology, biochemistry, oceanography, meteorology, and dynamics (both fluid and solid). To assure the social well-being of the global community, basic research must also be conducted in and across several areas of the social sciences.

It would be highly desirable to devise energy supply systems that allow ready environmental amelioration. This would make energy policy decisions much easier. The concept requires either one of two conditions:

- The energy system must be nonpolluting (or very nearly so); or
- Any undesirable environmental effects must be easily mitigated (at acceptable cost and energy expenditure).

In the first of these categories we consider such possibilities as a solar or a hydroelectric hydrogen economy; the IIASA 35 TW scenario fueled largely by synthetic methanol manufactured at large central facilities with a basic nuclear (breeder) or solar energy supply located on remote islands in the world's oceans or desert areas, respectively; and a very highly decentralized solar energy supply system--although the exclusive use of these technologies is highly unlikely to provide sufficient energy to maintain the global economy at a satisfactory level.

In the second category we envisioned such systems employing a short-time recycling of carbon through the atmosphere. Biomass as fuel with prompt and rapid regrowth is only one example. Stripping CO_2 from exhaust stack systems and even from the atmosphere is now technically feasible, and the manufacture of synthetic methane or methanol (as in the IIASA system) from the carbon thus obtained would be an effective "short recycling time" system.

Augmented carbon storage in reservoirs other than the atmosphere can relieve some of the burden. We suggest that additional carbon can be stored in the living biomass by planting more trees, and more could be stored in the deep oceans by locating and using areas of sinking ocean waters, and by pumping CO_2 into old oil and gas wells. These techniques may prove costly in either money or time, but quantitative tradeoffs may prove either favorable or necessary.

Another possibility is in the area of climate modification or control, e.g., controlled modification of the albedo, control of the solar input by use of directed mirrors in space, etc. Such schemes appear to be "far out", but we believe the stakes to be so high as to justify careful systems analysis and economic, political, and institutional studies of such schemes. Active control measures of this type can be effective in resolving other energy related environmental problems, e.g., waste heat disposal.

No less important than efforts to maintain an appropriate energy supply are those to reduce energy demands. We believe that with carefully developed procedures energy demands can be reduced on a global scale without causing unacceptable changes in the global economic well-being.

APPENDIX

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