Assistant Secretary for Environment
Office of Health and Environmental Research

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Carbon Dioxide Effects Research and Assessment Program

Carbon Dioxide Research Progress Report

Fiscal Year 1979

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Assistant Secretary for Environment
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Washington, D.C. 20545

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Carbon Dioxide Effects Research and Assessment Program

Carbon Dioxide Research Progress Report

Fiscal Year 1979

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Preface

The consideration of the carbon dioxide issue in this report is largely limited to questions surrounding the global carbon cycle and the effect of increased carbon dioxide on the global climate system. While the Department of Energy feels great satisfaction in having sponsored this work, it has far to go before the comprehensive program it envisioned is fully in place. Consideration of the effects of a change in the climate system coupled with increasing atmospheric carbon dioxide concentrations on agriculture, on the unmanaged biosphere, and on the oceans and cryosphere is just beginning. The potential for possibly profound environmental dislocations affecting social, political, and economic systems has yet to be determined. Methods to ameliorate or adapt to undesirable effects remain largely unconsidered. The extraordinary task of assessing the costs or benefits of the carbon dioxide issue in terms useful to the many policy-oriented sectors of the national and international community remains intellectually virgin territory. The Department of Energy is currently working with literally hundreds of environmental and social scientists to define the questions in these new and difficult areas. We admit to being surprised but very pleased by the enthusiasm with which these tasks are being attacked.

Under the aegis of the National Climate Program Office, the Department of Energy is broadening its effort to include the participation of other Federal agencies with a capability or interest in the carbon dioxide issue. The current version of what will eventually be a National Program on Carbon Dioxide, Environment and Society appears on the following two pages. It is expected that the outstanding contributions of the National Oceanic and Atmospheric Administration and the National Science Foundation in the past years will be matched, albeit in different areas, by other agencies in the future.

David H. Slade, Manager
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A NATIONAL PROGRAM ON CARBON DIOXIDE, ENVIRONMENT AND SOCIETY

<u>RESEARCH CATEGORY</u>	<u>RESEARCH SUBCATEGORY</u>	<u>RESEARCH ISSUE</u>
I RESEARCH ON THE CARBON CYCLE	A. Net Sources of Atmospheric CO ₂	<ul style="list-style-type: none"> 1. Industrial Sources 2. Terrestrial (Biospheric Sources) 3. Oceanic and Cryospheric Sources
	B. Atmospheric Storage	1. Observations of Atmospheric CO ₂
	C. Sinks for CO ₂	<ul style="list-style-type: none"> 1. Transfer Across the Air-Sea Boundary 2. CO₂ Exchange Between the Upper and Deep Oceans 3. Carbonate Dissolution and Biological Transport 4. Biospheric Sinks
	D. Historical Records of CO ₂	1. Same
	E. Models of the Carbon Cycle	1. Same
II RESEARCH ON CO ₂ AND CLIMATE	A. Modelling the Effects of CO ₂ Increase	<ul style="list-style-type: none"> 1. Model Improvement and Modification 2. Model Verification Studies 3. Model Sensitivity Studies 4. CO₂ Perturbation Studies
	B. Reconstruction of Past Climates	<ul style="list-style-type: none"> 1. Reconstruction of Paleoclimates 2. Reconstruction of Historical Climates
	C. Climate Scenario Development	1. Same
	D. Evidence of Climate Change	1. Same
III RESEARCH ON THE EFFECTS OF CLIMATE CHANGE AND CO ₂ INCREASE ON THE REMAINDER OF THE ENVIRONMENT	A. Effects on the Oceans	<ul style="list-style-type: none"> 1. Effects on Oceanic Circulation 2. Effects on Marine Biota
	B. Effects on the Cryosphere	<ul style="list-style-type: none"> 1. Effects on the West Antarctic Ice Sheet 2. Effects on Arctic Sea Ice 3. Physical and Hydrological Effects on Permafrost
	C. Effects on the Less-Managed Biosphere	<ul style="list-style-type: none"> 1. Carbon Balance in Northern Ecosystems and Effects of Climate Change 2. Effects on Grazing Lands, Wildlife and Animal Husbandry 3. Paleoclimatic Data as a Predictive Tool for Biospheric Effects 4. Effects on Forest Ecosystems 5. Effects on Freshwater Ecosystems 6. Effects on Human and Animal Health 7. Ecosystem Response to CO₂ Enrichment
	D. Effects on Agriculture and the Managed Biosphere	<ul style="list-style-type: none"> 1. Effects of Increased CO₂ on Photosynthesis and Agricultural Productivity 2. Alleviation of Environmental Stress on Renewable Resource Productivity 3. Effects on Managed Forests and Range Lands 4. Effects on Crop Use Water Efficiency and Water Requirements 5. Effects on Plant Pests 6. Effects on Food Crops in LDCS 7. Effects on Animal Agriculture and Livestock Production

A NATIONAL PROGRAM ON CARBON DIOXIDE, ENVIRONMENT AND SOCIETY (Cont'd)

Acknowledgments

Information summarized in this report was provided by many scientists and research groups (see Section 6). Without their contributions and timely responses, the report could not have been prepared. The help and cooperation of principal investigators and their staffs and students are gratefully acknowledged.

The authors thank their respective office staffs, in particular Patricia Grimes, Deborah Moser, Betty Wells, and Floy Weichel, for assistance with draft manuscripts, and Cynthia Barber for help with proposals and contracts. The editorial assistance of Ruth Haas made the final report eminently more readable. Technical assistance with the final preparation of the report by Chester Cooper and Susan Kincade enabled us to distribute the report to original contributors prior to the Department of Energy's first research progress meeting. We are indebted to everyone who helped.

Accomplishments since the program's inception in 1978 are in large part due to the assistance from technical representatives of other Department of Energy programs. Individuals who helped the Carbon Dioxide Program review, evaluate and implement new research are Robert Beadle, Joseph Blair, Paul Gerhardt, Gerry Goldstein, Arnold Joseph, Harry Moses, William Osburn, Charles Osterberg, Robert Rabson, Herbert Volchok, and Fred Witmer. These scientists have our special thanks and appreciation.

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1 Introduction

Roger C. Dahlman

Executive Summary

The historic growth rate in the release of industrially produced CO₂ is about 4 percent annually. Provisional figures indicate a leveling off of CO₂ production between 1977 and 1978. It is too early to determine whether this is a temporary aberration or the beginning of a significant worldwide slowdown in burning fossil fuel in response to fuel price increases.

It is still unclear how much CO₂ is contributed to the atmosphere from deforestation and other changes in land use. Direct sensing of secular forest changes will be attempted, but it will be some time before it can be determined if the proposed methods meet the required standards of accuracy. Use of stable carbon isotopes in tree rings as records of historical carbon sources has encountered difficulties, although this technique still might indirectly reveal the historical extent of deforestation. The possibility of using changes in the atmosphere's oxygen content to detect changes in the global biomass is being investigated to determine if measurement techniques with the required accuracy can be developed.

Preliminary data suggest that temperate forests may act as a sink for CO₂. Information about the slash-and-burn agriculture of the tropics indicates that some storage of carbon in refractory charcoal may be occurring. None of these studies is as yet definitive, but they do indicate that it is too early to accept the hypothesis that land-use practices contribute a significant amount of CO₂ to the air.

The worldwide atmospheric CO₂ monitoring network has expanded from 10 stations to about 20 and 5 more will be added in the near future,

providing increased coverage for interpretation of patterns of sources and sinks, seasonal variability, and documentation of the global growth of CO₂.

Modeling studies emphasized that knowledge of the transport and mixing of surface ocean waters is important in understanding deep oceanic circulation. Initial studies in the equatorial Pacific are helping quantify estimates of the amount of outgassing CO₂ from tropical waters. Plans have been made for a large-scale, multiyear study that will use tracers to follow water transport and mixing in the North Atlantic to determine the rate of CO₂ penetration into deeper waters. Observations will start in 1980.

During fiscal year 1979, there was a substantial increase in appreciation of the role of the ocean in controlling not only atmospheric CO₂ concentrations but also the climatic response to changes in concentration. Model simulations of the effect of doubled CO₂ concentration carried out with fixed ocean temperatures, a situation that is possible during perhaps the next 20 years, showed relatively small summer heating over land areas. On the other hand, simulations in which the oceanic temperatures could come into instantaneous equilibrium with atmospheric conditions continued to show global temperature increases of $3 \pm 1.5^{\circ}\text{C}$, accentuated at high latitudes. Clearly, estimating the transition from the relatively constant present climate to the evolving one that will prevail during the next century will require substantial improvements in the models' representations of the ocean's heat capacity and response time. Plans to make such improvements are being implemented and models with interactive oceans should begin to be available in 1981.

To improve understanding of possible regional climate changes, there were increased efforts to reconstruct regional climatic patterns prevailing during past warm periods that might serve as analogs of future climatic conditions. Particular attention was directed to

the climates of the United States and other countries bordering the North Atlantic Ocean during the warm period 5,000 to 7,000 years ago. Work during 1980 will expand these efforts and augment on-going work in Great Britain to look at warm years during this century.

The Carbon Dioxide Issue

The perception that accumulations of atmospheric CO₂ may result in serious problems stems from the following.

- o There has been a well-documented worldwide increase in atmospheric CO₂ concentrations since 1957; this growth has probably been occurring since the middle of the past century.
- o During the past few decades, the CO₂ increase in the atmosphere has equaled about 50 percent of the total fossil fuel CO₂ released to the atmosphere.
- o CO₂ transmits solar radiation but absorbs some of the outgoing long wave radiation from the earth and reradiates part of it back to warm the surface of the earth, creating the so-called "greenhouse" effect. Thus, qualitatively, CO₂ should warm the lower atmosphere and cool the stratosphere.
- o Different calculations of the greenhouse warming indicate that a doubling of the CO₂ content of the air could result in a $3 \pm 1.5^{\circ}\text{C}$ warming of the lower temperature. This global warming would be a significant alteration of the present climate, to a degree unprecedented in historical times.
- o While such climatic effects would be worldwide, they would likely not be geographically uniform: some regions of the globe would experience greater changes than others.
- o The doubling of atmospheric CO₂ is likely to occur during the middle of the next century if use of fossil fuel continues to grow. There are sufficient fossil-fuel reserves to raise the atmospheric CO₂ manyfold if they are used.

- o After reaching some anthropogenically induced high CO₂ concentrations in the atmosphere, the natural removal mechanisms are such that it will likely take many centuries before atmospheric CO₂ levels return to "normal" after the additions cease.
- o Present-day concepts of environmental control technology of CO₂ do not appear economically or energetically feasible.

At this time, few responsible scientists or political leaders will positively assert that significant climate changes will occur if the burning of fossil fuel continues or that the predicted climate change would be adverse. On the other hand, we cannot ignore the possibility of undesirable climate changes. It is imperative that society be able to anticipate the consequences of fossil fuel consumption and CO₂ release at current or increased rates.

Answers to the following questions should be obtained in order to evaluate possible courses of action.

1. What will be the future atmospheric concentrations of CO₂ for various scenarios of carbon dioxide releases to the air?
2. What will be the climatic response to these elevated CO₂ concentrations?
3. How will these climate changes, along with the increased CO₂ concentrations, affect the biological and physical environments?
4. What, if any, will be the effects of these changes on human societies?
5. In the event these changes are undesirable, what actions can be taken to prevent or counteract them? Or to improve adaptation to them?

Goal and Strategy

In recognition of the potential importance of the carbon dioxide issue to the energy policy requirements outlined in the National Energy

Organization Act of 1977, a program to research and assess the effects of carbon dioxide was initiated in the Office of the Assistant Secretary for Environment, the Department of Energy, in 1978. Comprehensive reviews, analyses, and assessments are scheduled for 1984 and 1989. The goal of this national effort is to develop the ability to predict future global environmental, agricultural, and societal consequences of increasing atmospheric concentrations of carbon dioxide with sufficient confidence to permit informed policy decisions to be made on the use and development of energy and other resources.

There are three initial approaches to carrying out this program: (1) providing a national focus for the carbon dioxide issue, (2) encouraging a vigorous national and international research program, and (3) organizing and conducting the comprehensive syntheses and analyses required to predict consequences of CO₂ accumulations, and their policy implications, and to develop means for increasing confidence in the predictions. This comprehensive strategy devotes attention to research, impact assessment, ameliorative-adaptive measures, and energy policy. However, the priority during the program's first few years is to develop a more factual understanding of the scientific issues. The research program is designed to provide answers to the questions listed in the preceding section, with an initial focus on the first two questions. Thus, in fiscal year 1979, major attention was devoted to research on carbon cycle and climate.

Research Planning

Research plans were developed by using workshops to define important questions requiring further study and building on the research of established projects. The first workshop in 1977 (Elliott and Machta, 1979) focused on the carbon cycle and climate impacts of increasing

CO₂. Research issues identified by workshop participants, who were drawn from scientific institutions and government agencies, were evaluated in more detail by leading scientists; their analyses were used to prepare the Part I plan, "The Global Carbon Cycle and Climatic Effects of Increasing Carbon Dioxide" (1978). This plan has been widely reviewed and distributed, and it is the primary reference for implementing new research and expanding current work on this topic.

The second major workshop (held in April, 1979) dealt with the environmental and societal consequences of a carbon dioxide-induced climate change. A draft report of the second workshop has been completed, but detailed research plans on environmental and societal consequences of a carbon dioxide-induced climate change have not yet been developed.

Carbon Cycle

Carbon cycle studies represent research related to questions of future scenarios of CO₂ accumulation; specific objectives, including a discussion of rationale and priority, are described elsewhere (DOE 1978 report); the general objectives are:

Quantification of net sources of CO₂ contributions to the atmosphere.

This includes estimates of industrial (including synthetics, shale), terrestrial biospheric, oceanic, and cryospheric sources of CO₂. Sources influenced by man's activities are emphasized.

Documentation of changes in atmospheric CO₂. Precise measurement of atmospheric CO₂ is emphasized. Measurement of carbon isotope ratios provides some insight about biospheric source/sink relationships.

Determination of sinks for CO₂. Major sinks are identified, magnitudes estimated, flux or exchanges among major reservoirs are estimated. Ocean circulation and fertilization of the terrestrial biosphere are emphasized.

Modeling the carbon cycle. Data on carbon fluxes, sources, and sinks are integrated into global carbon cycle models. The models can indicate future atmospheric CO₂ concentrations based on scenarios of fossil fuel use and land management practices.

Determination of historical CO₂ concentrations. Solar spectra data are being examined for the period 1900 to 1957. The atmospheric CO₂ concentration during earlier times is being reconstructed by an analysis of ice cores.

Climate Effects

Research on climatic responses is directed toward resolving effects and uncertainties of increasing CO₂ on climate. Specific objectives are discussed in the DOE draft report and general objectives are given below.

Development of plausible scenario(s) of CO₂-induced climate conditions. Scenarios will attempt to describe a regional and seasonal variations in temperature and moisture. These may be used in ecological, social, and economic analyses.

Reconstruction of past climates. The aim is to document historic and paleoclimate records of climate analogs warmer than the present, and to try to understand future climate conditions based on similarities with warmer past climates.

Modeling the effect of CO₂ on climate. The main thrust of this program is to improve existing climate models and apply them to estimate climatic effects of increasing CO₂. Sensitivity studies will be used to estimate the climate's response to CO₂, as well as other physical variables. Model improvements are expected to involve refinements in the treatment of radiation, oceans, clouds, and the cryosphere.

Documentation of evidence of climate change. Evidence of climate change in the concurrent observational record will ultimately confirm (or reject) model predictions. If present model calculations are correct, initial evidence of potential climate change should appear in the next few decades.

Environmental and Societal Effects

A cascade of environmental effects may occur should climate changes result from increased atmospheric CO_2 , i.e., the antarctic ice sheet may melt, with a consequent rise in sea level and effects on sea chemistry and marine food productivity. Climate change and increased CO_2 could affect the terrestrial biosphere in terms of water supply and its efficient use, forest growth, and increased soil and peat oxidation. Very high levels of CO_2 may affect human health. This research effort includes studies of potential political and societal impacts of climate changes as well as the development of methodologies for dealing with complex future societal issues. The planning effort will examine scenarios and strategies for societal adaptation to major environmental perturbations, e.g., changes in water resources, altered flow of goods, services, and capital. Specific objectives of research on these environmental and societal effects will be defined from activities following the April 1979 workshop.

Amelioration and Adaption

Two types of ameliorative or adaptive investigations consider: (1) potential environmental control technologies for minimizing emissions of CO_2 , and, (2) strategies or technological initiatives for adapting the global societal system to a new environmental state.

The objectives of the ameliorative type are to:

- Evaluate options for removal and disposal of CO_2 from stationary sources.

- Analyze advanced control technologies for restricting CO_2 emissions.

Examine "natural" removal processes which may be optimized for either diffuse or centralized sources.

Specific objectives for adaptive types of investigations have not yet been developed.

Research Implementation and Coordination

The first significant implementation of the CO₂ research program was carried out in 1979. The initial strategy was to expand existing research already explicitly related to high priority objectives. Monitoring and measurement of atmospheric CO₂, climate modeling, climate reconstruction, and carbon geochemistry in oceans are selected examples. Top priority was devoted to startup of the Transient Tracers in the Ocean (TTO) project. This research, jointly funded with the National Science Foundation, is a four-year multi-million dollar project to investigate the distribution of transient tracers (¹⁴C, ³H, ³He, ⁸⁵Kr, ³⁹Ar) in the North Atlantic Ocean. The results will document oceanic mixing processes, which are essential to understanding the rate at which surface water CO₂ is mixed into the deep ocean.

In all, about 40 projects on carbon cycle and climate topics were either expanded or started at about 25 different institutions. A number of projects are jointly supported with other agencies.

The role of other agencies cannot be overemphasized in this comprehensive CO₂ program. Much substantive research is carried out either through extramural support of academic scientists or by scientists in agencies other than DOE. It is important for such efforts to continue if research plans and objectives are to be achieved. Time and logistics, unfortunately, did not permit including in this

report results from non-DOE-supported research. These efforts are acknowledged here, and possibly can be included in future progress reports of CO₂ research.

The extreme breadth and complexity of the CO₂ issue requires resources, capabilities, and management not found in any one agency. The National Climate Program Office is helping with multiagency coordination. This enables coordinated planning, review, and execution of CO₂-related research according to guidelines of the comprehensive plan prepared by DOE. As members of the research planning and coordination committee, representatives of other agencies are collaborating with DOE to carry out the coordinated program.

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2 Carbon Cycle Research

Lester Machta and William Elliott

Introduction

The goal of the carbon cycle portion of the CO₂ research program is to produce better estimates of future concentrations of atmospheric CO₂ and their uncertainties. This will be accomplished by devising and validating a model of the carbon cycle and inserting industrial releases and other significant net sources of CO₂ into it. The model will also have to include the sinks for atmospheric carbon. Some of these sinks depend upon the state of the biosphere and the oceans. But the ability of these sinks to absorb CO₂ depends to some extent on the prevailing climate. Hence, the ultimate model of the carbon cycle will have to be coupled to a model predicting the future climate. Scientists are now a long way from satisfactorily achieving such a definitive integration.

Besides providing a forecast of future atmospheric CO₂ concentrations, a model of the carbon cycle will be useful in deciding on how to manage the fossil fuels, forests, and other sources of CO₂. If it is decided that man-produced CO₂ emissions should be curtailed, a valid carbon cycle model would indicate the rate at which CO₂ could be produced to ensure that the atmospheric concentration did not exceed some desired quantity. In addition, such a model could be studied for sensitivities to natural changes.

This report treats only those components of the world's research effort that have been funded, sometimes jointly with other agencies, by the U.S. Department of Energy. Most of the research has just begun, so definitive results are few. The following section will sketch briefly some of the major problems to be solved. Succeeding sections will describe progress through fiscal year 1979. Sources, sinks, atmospheric concentrations, as illustrated in Figure 2-1, including past concentrations of CO₂ and carbon cycle modeling will be covered.

Figure 2.1 Exchangeable components of the global carbon cycle.

In addition, one section deals specifically with ocean research and one with biospheric research.

Problems, Research Questions and Issues

Sources of Atmospheric CO₂

Industrial activity is a source of CO₂ in the air, perhaps the dominant one in recent years. Statistics on current and past production of CO₂ are available. The numbers usually quoted are not strictly releases, but rather worldwide production values based on national estimates of the amount of coal mined, oil and natural gas drawn from the earth, etc. The real problem is forecasting future production. Future energy usage depends on a variety of economic factors and technological developments that are themselves difficult to forecast. Scenarios for future energy usage will have to include specific usage of fossil fuels, by types as well as amounts, because different fossil fuels produce differing amounts of CO₂ per unit of usable energy.

There is also the difficult problem of assessing the amount, if any, of net biomass oxidation. Global deforestation and virgin soil disturbance, particularly in the tropics, may be contributing significantly to the observed CO₂ increase. On the other hand, regrowth and reforestation in other regions may be compensating for the destruction of some forests. If the deforestation is contributing large extra amounts of CO₂ to the air, then there must be additional sinks for this CO₂ not now known. If the oceans are absorbing the excess CO₂ produced by disturbances of the land, then it is possible that they could absorb more industrial CO₂ if these disturbances should cease. It is also not known whether increases in atmospheric CO₂ could increase the rate at which the forests sequester CO₂ and possibly retard the growth of atmospheric CO₂.

Atmospheric Storage

The global increase in atmospheric CO₂ over the past 20 years is not disputed. The annual increase has averaged about 55 percent of the annual industrial releases. The percentage varies considerably from year to year for reasons only partially understood; it may be affected by the interannual variations of climate, particularly the tropical ocean surface temperatures.

The confidence that can be put in a model of the carbon cycle will depend heavily on its ability to reproduce observed trends and variations. There appears to be a latitudinal gradient in the amplitude of the annual cycle of CO₂ concentrations as well as in the concentration itself. How much longitudinal gradient exists in "clean" air is imperfectly known. The verification of carbon cycle models can be helped by constraining the models to reproduce the recent global distribution of CO₂ and its annual cycles. Thus, any increase in the data for model verification is desirable.

Accurate measurements of atmospheric CO₂ are available only since 1957. Since models will have to project CO₂ concentrations a century or more into the future, it would be desirable to extend the CO₂ record backward in time to provide more points for verification. An accepted value of CO₂ concentration at the beginning of large-scale industrialization, about the mid-nineteenth century, would be particularly useful. On longer time scales, climatic response to higher or lower CO₂ concentrations in the historical or geological past would be valuable.

Sinks for Atmospheric CO₂

The ocean is surely the main repository for most of the excess CO₂ that has not remained in the air. Its ability to act as a sink in the future will depend upon the rate at which the CO₂ absorbed in

the surface waters is transferred to deeper layers, as well as any changes in ocean chemistry that accompany an increase in dissolved CO_2 or climate alterations.

Future absorptive capacity of the oceans should depend upon the interactions of the waters with the sediments; in the short term the shallow water sediments could be important but in the long term (thousands of years), the deeper water sediments will come into play. Oceanic circulation and its changes could influence the capacity of the oceans to absorb excess CO_2 . If these circulation changes influence biological productivity, the ocean's biomass could also affect the role of the oceans as a CO_2 reservoir. The size of other possible sinks must be determined. For example, the land biota may grow in response to increased CO_2 by increasing their net carbon fixation. Calcareous soils could be another possible sink.

Historic CO_2

Uncertainties in CO_2 sources and sinks exhibit themselves clearly in the estimates of preindustrial levels of CO_2 air concentrations. Models without net biospheric source suggest a concentration of 290 to 300 parts per million by volume (ppm) whereas those with a significant nonindustrial source appear to demand a 260 to 270 ppm concentration. There are suggestions that prehistoric climate changes may have been due to natural fluctuations in CO_2 . Proof of this idea would strongly support present-day climate modeling which predicts such changes and opens the door to significant natural variability of atmospheric CO_2 .

Integrated Modeling

Most models of the carbon cycle used for current estimates of future CO_2 concentrations are one-dimensional in character. More realistic models should expand the details of both the ocean and biosphere components. Progress in these areas will depend upon other components of the program, although the present models, and improved

versions, can be used to study sensitivities to various factors and so help guide carbon cycle research. The limitations on modeling are not now in computer hardware but in understanding the system and in data inadequacies.

Progress

Sources and Sinks of Atmospheric CO₂

Industrial and Other Sources of CO₂. Contributions to this area have been made primarily by the Institute for Energy Analysis (IEA) in updating actual fossil fuel, cement production, and natural gas flaring releases of CO₂ and in projecting world energy needs to the year 2025. There have also been new estimates of biospheric sources and sinks by the National Oceanic and Atmospheric Administration (NOAA), Scripps Institution, The Institute of Ecology (TIE), Oak Ridge National Laboratory (ORNL), and the Institute of Tropical Forestry. The historic growth rate of the release of fossil fuel (plus cement manufacture and flaring of natural gas) has been just over 4 percent per year. Preliminary data suggest that in the past 2 or 3 years there has been a strong tendency toward leveling off, but such changes in long-term trends have occurred in a few previous periods. Such annual changes must be watched carefully to note whether they bode a permanent slowdown in world fossil fuel consumption and whether they are reflected in reduced atmospheric CO₂ growth rates.

The 1978 provisional determination of CO₂ release provided by IEA based on UN estimates was $5,191 \times 10^{12}$ grams of carbon (gC) in the form of CO₂. In 1977, the same quantity, more or less a final number was $5,225 \times 10^{12}$ gC. There was a prolonged coal strike in early 1978 in the United States and in 1979, coal production increased again. It is not certain that the reported drop in coal production in 1978 necessarily implies a reduced release of CO₂ to the air; reserve stocks may have been used. However, the significance of the leveling

off in total CO_2 released from fossil fuel combustion lies in the possibility of a reduced future growth rate because of oil shortages, high fuel costs, etc.; there may even be some protracted periods of zero growth. Since a slowing down of the fossil fuel CO_2 production has occurred previously, this possibility must be approached with caution.

The projections made by IEA, however, suggest that annual energy usage over longer time spans will continue to grow, and in one estimate for the year 2025 A.D., the annual release rate of CO_2 from fossil fuel combustion would be almost four times the 1975 values. The bulk of the growth during this coming half century is predicted to take place in the underdeveloped world, which has tremendous needs but questionable ability to pay for coal and oil.

Biospheric Sources and Sinks. The role of the biosphere as a source or sink bears on the interpretation of the source of increased atmospheric CO_2 . Elsewhere in this report, new estimates of CO_2 resulting from deforestation are discussed. Here, some evidence for growth in the north temperate and boreal biosphere is suggested. The seasonal amplitude, it is believed, reflects an increase rather than a decrease in northern hemisphere forests north of about 30°N . This new finding is qualitatively consistent with the TIE estimate of 1×10^{15} gC sequestered by these forests, as noted in the section on terrestrial biomass studies. It should be pointed out that this evidence is not necessarily contradictory to the views of Woodwell, Bolin, and others who have argued for a past net CO_2 source from reduction in biomass since it is in the tropics that important recent deforestation is believed to have occurred. Additional discussion of biospheric sources and sinks appears in the section on terrestrial biomass.

Cryospheric Sources and Sinks. Research conducted so far by the Naval Arctic Research Laboratory suggests that the Arctic is a small net source for atmospheric CO_2 . This arises from the surprising fact that sea ice is a fairly strong source of CO_2 . It is estimated that this

source somewhat exceeds the summertime uptake by the open ocean surfaces. The imbalance of tundra plants and soils is thought to be much smaller than the exchanges across the ice/water surface of the ocean and lakes. Preliminary estimates give the Arctic a source of about 0.18×10^{15} gC.

Oceanic Sources and Sinks. A discussion of the role of the oceans in taking up and releasing CO_2 to the atmosphere appears in the section on oceans.

Atmospheric Storage

CO_2 Gas Standards. During this past year, there have been two new developments in gas standards: (1) there is now virtually unanimous agreement that the standards should be CO_2 in air rather than CO_2 in N_2 ; and (2) steps are being taken for the National Bureau of Standards (NBS) to assume responsibility from Scripps Oceanographic Institution for providing world CO_2 gas standards.

A number of years ago it was recognized that most of the non-dispersive infrared CO_2 analyzers respond differently to gas samples with different composition. The CO_2 in oxygen and argon in ambient air absorbs differently from CO_2 in pure N_2 used as the CO_2 carrier in the Scripps standard gas. The unfortunate result is the inability to compare data quantitatively among different instruments. Conversion of CO_2 standards to CO_2 in air demands pure (pollution-free) air and containers which are stable for oxygen over extended periods. The National Oceanic and Atmospheric Administration has converted its standard for gases, within its CO_2 flask sampling program, to CO_2 in air by tying absolute values to the Scripps provisional 1974 CO_2 in N_2 calibration scale. Scripps has formulated plans to make the conversion. National Bureau of Standards standards will contain exclusively CO_2 in air. The NBS removes all the CO_2 from air and then mixes it with precisely known amounts of CO_2 .

The NBS has prepared 12 CO₂ in air standards in the range of 260 to 380 ppm. Preliminary comparison suggests precision of better than 0.1 percent by volume (about 0.3 ppm). The preparation involves gravimetric techniques. Further work is needed to determine the bias, if any, and the cross comparison with the existing Scripps standard.

CO₂ Measurements. An expanded network of stations to measure the concentration of atmospheric CO₂ serves a number of scientific functions. These include: improved estimates of globally averaged trends in atmospheric CO₂ content, geographical distribution of the range of seasonal variation in CO₂ concentration, and gradients of concentration. To minimize costs and manpower requirements and to determine the location of important stations, flasks rather than in situ continuous CO₂ analyzers were used. Instead of measuring the concentration on station as is done at Mauna Loa and a few other locations, flasks are filled with local, clean air on station and shipped to a NOAA central analysis laboratory in Boulder, Colorado, or Scripps at La Jolla, California. In addition to the expanded flask network, both Scripps and NOAA are continuing to operate a number of stations with in situ analyzers. The Scripps Institution is cooperating with New Zealand, which conducts an analyzer program, and with Canada at Ship Papa in the North Pacific in a flask sampling program. Scripps also maintains flask programs at Fanning and Christmas Islands in the equatorial Pacific and at the South Pole.

The stations in the expanded network appear in Figure 2-2. The figure also shows all other locations at which the United States and other countries already have or are planning to conduct CO₂ measurements. The NOAA flask program involves the exposure of two 0.5-liter duplicate flasks each week. The Scripps technique uses 5-liter flasks. A comparison of the reliability of the two types of flasks is being undertaken. The results and the value of the expanded network will be assessed periodically.

Figure 2.2 Stations monitoring atmospheric CO₂ trends, July 1979.

Interpretation of Atmospheric CO₂ Concentrations. The atmospheric concentrations of CO₂ represent perhaps the best-known information on the carbon cycle. Measurements demonstrate an unequivocal increase of 6-7 percent in atmospheric CO₂ concentration between 1957 and 1979. Other information besides this growth may also be derived. This includes the change in seasonal amplitude noted earlier and other evidence bearing on sources and sinks for atmospheric CO₂.

The CO₂ concentrations measured at Scripps and NOAA stations (in situ and by flasks) continue to increase. None of the trends based on data collected during the past year differ significantly from those of the past. Those stations with records extending backward in time for over 10 years exhibit a larger year-to-year increase in more recent periods than in earlier times. In fact, an analysis of the Mauna Loa record suggests that the growth rate can be explained without a net biospheric source of CO₂.

The Scripps Institution has reported concentrations of CO₂ in air from the ships involved in the First GARP Global Experiment (FGGE). Data taken at about 105°W display a clear north-to-south gradient over the entire latitudinal range of the cruises, 20°N to 19°S. The seasonal variation in the northern hemisphere damps out sharply toward the equator.

Several groups (Scripps, NOAA, ORNL and the Massachusetts Institute of Technology) are studying the fluctuations in the year-to-year growth of CO₂ at various stations in relation to equatorial sea surface temperatures and the Southern Oscillation. The consensus of these analyses indicates that the equatorial region, particularly the Pacific Ocean, is an important source of variability in atmospheric CO₂. While this ocean area is a source for atmospheric CO₂, its emission rate can be variable.

The Naval Arctic Research Laboratory is engaged in research aimed at understanding source and sink mechanisms and transfer between air and tundra and water/ice. For several years, the large range of the seasonal variation of atmospheric CO₂ concentrations at high

latitudes could not be accounted for from conventional estimates of photosynthesis and atmospheric mixing. Further, one of the expected consequences of CO₂ warming, should it occur, is a recession of the ice line and possibly loss of summertime sea ice. These processes, should they occur, could feed back to the carbon cycle with large new exchanges of CO₂ between air and the new underlying surface.

Although the net annual outflow from the arctic surface to the air is relatively small, its winter and summer components may contribute to the seasonality of the observed atmospheric CO₂ record at high latitudes. In winter, 0.9×10^{15} gC enters the atmosphere (a bit more in the winter than in summer) and 0.73×10^{15} leaves the air in summer. Much of this seasonality is associated with a short period of summertime transfer of CO₂ from air to water. Most model calculations of seasonality have heretofore considered only biospheric exchange of CO₂ with the air and not considered the change in ice cover.

Stable Carbon Isotopes in Atmospheric CO₂. The $^{13}\text{C}/^{12}\text{C}$ responds to variations in the input of CO₂ with different ratios than in present-day air. Thus, CO₂ in air has a ratio of $^{13}\text{C}/^{12}\text{C}$ of about -7.3 percent, while CO₂ formed from the combustion of fossil fuels or wood or the oxidation of wood has a ratio of about -26 percent. By measuring the time history of $^{13}\text{C}/^{12}\text{C}$ in air (or as noted later, in tree rings) one can estimate the release of CO₂ from fossil fuel plus deforestation (or soil disturbance). After subtracting the fossil fuel contribution, these measurements, in principle, yield the amount of CO₂ derived from non-fossil fuel sources. There are several problems yet to be resolved in the $^{13}\text{C}/^{12}\text{C}$ method.

Both Scripps and NOAA are embarking upon programs to measure routinely $^{13}\text{C}/^{12}\text{C}$ at established stations. Special measurements made by Scripps have shown that the mean annual ratio has dropped by 0.55 percent between 1956 and 1978. When this decrease in the ratio was interpreted by Scripps, it was found that the result failed to dis-

criminate between CO₂ sources from deforestation and fossil fuel combustion. However, Scripps also concluded that future changes in the ratio could be definitive in terms of identifying deforestation sources of CO₂ and were, therefore, worth pursuing.

Oxygen. The oxygen technique is also intended to estimate CO₂ increases from deforestation. Atmospheric oxygen is depleted whenever carbon is combusted or oxidized. In theory, by subtracting expected depletion due to fossil fuel combustion from the observed decrease in atmospheric oxygen, any remaining amount would be due to oxidation of carbon from other sources, such as the biosphere.

The potential for using the oxygen method for determining the contribution of deforestation has been analyzed provisionally. Ideas for developing instrumentation to measure oxygen with the precision needed have been explored by NOAA, Scripps, and NBS.

Historic CO₂ Concentrations

Estimates of CO₂ concentrations during either geological or historical times can prove valuable in understanding both the carbon cycle and the possible relationship between atmospheric CO₂ and climate. Thus far, the DOE program only supports research to determine CO₂ concentrations during the past 100 years. Another literature review has been initiated by NOAA and, in particular, personal contacts have been made with the family of G.S. Callendar to gain access to his unpublished notes. Callendar, a British scientist, made the most comprehensive survey of early CO₂ measurements to date, but had not published all of his findings before his death.

The Pacific Northwest Laboratory (PNL) has started a study of past spectroscopic records in order to estimate CO₂ contents of a column of air. If successful, another 30-50 years of CO₂ air concentrations would become available.

The late nineteenth century measurements of CO₂ suffer from analytical techniques that are poor by present-day standards. Further, the scientific community failed to appreciate the confusion contributed

by pollution sources and biospheric sinks of CO_2 . One measurement in 1935, however, that has not received attention is a sample collected on a manned balloon at 21.5 km altitude (which avoids contamination or biospheric losses). Shepherd (1936) found it to be 0.029 ± 0.002 percent by volume (290 ± 20 ppm).

Considerable preliminary work has been undertaken both by the Pacific Northwest Laboratory and by San Diego State University preparatory to determining the CO_2 absorption of infrared lines in the Smithsonian spectrographic plates. Strenuous efforts by San Diego State University to preserve the integrity of the plates are in progress. Much of the protocol for selecting the spectroscopic lines to determine CO_2 absorption has been worked out by the Pacific Northwest Laboratory. Even if the techniques fail to provide reliable measurements, the CO_2 spectroscopy may become valuable for other components of the program.

Carbon Cycle Modeling

The Scientific Committee on Problems of the Environment (SCOPE) held a workshop in La Jolla, California March 20-24, 1979 to review the status of carbon cycle modeling and presented some important progress, especially in formulating ocean transport processes relevant to the CO_2 issue. It was recognized, for example, that the single most important uncertainty in modeling the oceans lies in the treatment of ocean water between 100 and 1,000 meters in depth. On the other hand, model parameters for the transfer of CO_2 between air and sea are reasonably well known; this uptake occurs on a time scale of years rather than tens or hundreds of years. The models of the ocean now incorporate bulk transport in addition to vertical diffusive mixing. The diffusive mixing, in turn, is more sophisticated than that of the earlier box models (first-order kinetics).

Oceans

North Pacific Experiment (NORPAX)

The warm surface ocean waters of the equatorial belts in the Atlantic, Pacific, and Indian oceans are supersaturated with respect to atmospheric CO_2 , and thus act as a CO_2 source for the air. On the other hand, the cold ocean waters located in the high latitudes (in particular, the northern North Atlantic) are undersaturated and thus act as a CO_2 sink. The CO_2 concentration in the earth's atmosphere is regulated by a dynamic balance of CO_2 fluxes from active sources such as outgassing from the equatorial oceans, biological decay of organic debris, volcanic exhalations, and fossil fuel combustion and absorption into active sinks such as the uptake by the polar oceans, plant photosynthesis, and organic debris accumulation.

The degree of supersaturation of CO_2 relative to air can be expressed as the difference between the CO_2 partial pressure or $p\text{CO}_2$ (the vapor pressure of CO_2 gas) exerted at the water surface and that in the overlying air. The difference in partial pressures multiplied by an exchange coefficient yields the air-sea CO_2 flux. In the Pacific equatorial belt between 15°N and 15°S latitudes, the ocean water is supersaturated by about 60 ppm. In the equatorial belts of the Atlantic Ocean, it is about 40 ppm. Each year the oceans are estimated to exchange 90 to 100×10^{15} gC as CO_2 , with a net uptake in high latitudes by cold waters and a net release in the warm tropics. The net release from the equatorial tropical ocean may be a significant fraction of the amount released from the combustion of fossil fuels, $5-6 \times 10^{15}$ gC. Thus, one may understand why relatively minor variations from year to year in surface water conditions of the Pacific Ocean (such as El Nino or the Southern Oscillation) appear to be observable in the record of atmospheric CO_2 . The major CO_2 objective of the shuttle component of the North Pacific experiment (NORPAX) is to observe the seasonal and secular variabilities in the degree of supersaturation of CO_2 in the equatorial Pacific Ocean.

Research Program. The program is being carried out by Scripps Institution of Oceanography, Lamont-Doherty Geological Observatory and the University of Washington. It takes advantage of the planned observational program in FGGE, a program supported in the United States by the National Science Foundation and NOAA. A research vessel shuttles between Hawaii (20°N) and Tahiti (19°S) once a month across the equatorial Pacific. Besides measuring $p\text{CO}_2$ in air and water, measurements of ^{14}C and nutrients are made. The program is still in progress and the few results indicated below are tentative.

Initial measurements of $p\text{CO}_2$ (Leg 3, April 1979) were made with conventional equipment. More recent measurements of carbon dioxide are being carried out by a newly developed automated gas chromatographic system which provides exceptionally precise (± 0.04 percent) analyses of carbon dioxide in very small samples. Further development of this instrumentation as a tool in the study of the global carbon dioxide problem is another objective of research. This instrument also measures concentrations of nitrous oxide and methane in the same samples. In addition to their own environmental importance to the atmosphere, the concentrations of these gases in the sea have been shown to be valuable analogs of carbon dioxide in the study of air-sea exchange dynamics.

Because biological activity can affect CO_2 concentration in water and this, in turn, is affected by nutrient supply, sea water has been analyzed for its nutrients. In addition, measurements have been made of alkalinity, temperature, salinity, and oxygen to identify water masses.

Another aspect of this research uses the temporal and spatial distribution of bomb-produced radiocarbon (^{14}C) in the equatorial Pacific Ocean to determine mixing rates in the upper 1,000 m of the ocean. To do this, approximately 300 ^{14}C samples were collected during one leg of the NORPAX shuttle and additional surface water samples and some deep water samples were collected during the November 1979 leg of NORPAX. It will take approximately 2 years to measure the ^{14}C activities of all the sea water samples with the two counters that are presently in use for this program.

Preliminary Results. 1. The results obtained for the FGGE Leg 3, April 1979, from Tahiti to Hawaii, confirm that the equatorial Pacific water between 10°N and 8°S is a strong source of CO₂.

2. The results from the same leg also show that the atmospheric CO₂ concentration appears to increase abruptly at 8°S by about 2 ppm, from 340.6 ppm in the south to 342.6 ppm in the north of this latitude. This abrupt change appears to be associated with the intertropical convergence zone of the atmosphere, which represents a boundary zone between the northern and southern hemispheric air masses. This finding aids our understanding of the way in which the industrial CO₂ discharged into the atmosphere is dispersed.

3. The North-South profile of the surface water indicates lower ¹⁴C in equatorial than in adjacent surface waters. This feature of the surface water ¹⁴C distribution, coupled with the depth distribution of ¹⁴C and the physical oceanographic data collected during the NORPAX program, will allow scientists to estimate the rate of upwelling in the equatorial Pacific. This information will be of critical importance in understanding the role of the equatorial ocean as a source of atmospheric CO₂.

Transient Tracer Program

Planning for a large, multiuniversity, multiyear study of the distribution of transient tracers in the ocean water was completed. The program, Transient Tracers in the Ocean (TTO), is being developed to learn more about the mixing and transport properties of the ocean. The measurement phase will attempt to map the three-dimensional distribution of such man-produced substances as ¹⁴C, ³H and its daughter product ³He, ³⁹Ar, and stable tracers such as the chlorofluoromethanes. The first measurement phase will take place in the North Atlantic Ocean. By examining the penetration of the airborne tracers into and through the ocean, it is hoped to learn how the oceans would absorb and dis-

tribute CO_2 taken from the air. Ultimately, the intent is to be able to estimate future rates of removal of atmospheric CO_2 .

Funds were provided to several universities to upgrade their equipment in anticipation that the TTO program would be undertaken.

Deliberate Tracer Injection

It will be difficult to determine the relative roles of cross-isopycnal¹ and along-isopycnal mixing and transport in the ocean from the TTO program. The TTO tracers enter the sea from the air, where several isopycnal surfaces intersect the ocean surface. To distinguish the two kinds of mixing and transport process, Lamont-Doherty Geological Observatory (LDGO) is evaluating the deliberate injection of a known quantity of a unique tracer to assess the benefits to understanding oceanic mixing and transport. Helium-3 and tritium appear to be suitable tracers, but others, such as perfluorocarbons, might prove feasible. Thought has been given to the mode of injection as well as the analysis of the data in terms useful to the total CO_2 effort.

Carbon Isotopes in Seawater

Along with the collection of new data on the distribution of carbon isotopes in the ocean, some analysis of previously collected samples is being carried out. The samples were collected between 1964 and 1974 over various parts of the oceans to depths of 4,000 m. The original samples were analyzed for inorganic carbon and were preserved for isotope work. They are now being analyzed by the University of Washington. The final results will be a tabulation of sample depth, temperature, salinity, total CO_2 , ^{14}C concentration, $\delta^{13}\text{C}$, $\delta^{14}\text{C}$ and $\Delta^{14}\text{C}$.²

Oceanic corals contain annual growth rings analogous to tree rings. Thus, coral rings preserve the chemical history of the water in which they have grown. Samples collected from Pacific, Atlantic, and Indian

¹ An isopycnal is a line or surface of equal density.

² The quantity of these isotopes is usually expressed as deviations (δ) from established standards. The $\Delta^{14}\text{C}$ term reflects corrections needed to account for fractionation effects in sample preparation.

ocean corals suggest the corals to be accurate recorders of the ^{90}Sr concentrations in sea water. Thus, ^{14}C and ^{90}Sr contained in these corals should provide information on the exchange of deep and surface waters through mixing or upwelling.

Support was provided to the Lamont-Doherty Observatory to measure pCO_2 in the air and ocean on the final segment of the Geosecs program in the Indian Ocean. The data permit the mapping of the pCO_2 difference between air and oceans for all the Geosecs cruises in the world's oceans. As expected, the Indian Ocean is similar to the equatorial Atlantic and Pacific oceans in that the pCO_2 in the water is larger than in the air, implying outgassing in the tropical waters.

Biosphere

Until recently, most models of the carbon cycle assumed the carbon pool of the biosphere to be in steady state or increasing slightly due to elevated CO_2 from the combustion of fossil fuels. But very small changes in the biosphere, analogous to fluctuations in ocean-air exchanges, can produce significant alterations of the atmospheric CO_2 content. The biosphere is believed to contain about 560 to 700×10^{15} gC. The loss of even 1 percent per year of this carbon more than equals current emissions of CO_2 from fossil fuel consumption, about $5\text{--}6 \times 10^{15}$ gC/yr. The difficulty in detecting such small changes in the biomass has led scientists to seek other, indirect methods of estimating the contribution of biospheric CO_2 .

The main indirect technique examined so far uses records of carbon isotope changes, to be discussed below. Other indirect measures will be pursued as well. The Marine Biological Laboratory in collaboration with SCOPE, held a workshop to assess the feasibility of measuring directly the interannual changes in the carbon content of the world's forests and soils.

Carbon Isotope Studies

Fossil fuel carbon contains a lower $^{13}\text{C}/^{12}\text{C}$ ratio than does air but does not contain any ^{14}C . Terrestrial biomass carbon is also

depleted in ^{13}C relative to air, but it has ^{14}C . Tree rings should provide records of changes in $^{13}\text{C}/^{12}\text{C}$ and $^{14}\text{C}/^{12}\text{C}$ ratios with time. In principle, the temporal changes of atmospheric CO_2 due to fossil fuel combustion plus net additions to or subtractions from the atmosphere as a result of biomass changes could be estimated from tree rings.

Several problems with this idea must be solved before the technique can be applied, however. The ^{14}C content of the air and tree rings has been increased as a result of nuclear weapons tests after the 1950s. The ^{14}C content has also varied over time since cosmic rays, the source of natural ^{14}C , fluctuate with time. The $^{13}\text{C}/^{12}\text{C}$ ratio in tree rings is affected by local growing and climate conditions in ways now imperfectly understood. Various specimens of trees from different parts of the world have yielded different histories of the $^{13}\text{C}/^{12}\text{C}$ ratios. Finally, the uncertainties of isotope fractionation of carbon in CO_2 at the sea surface and during biospheric uptake add to the difficulties of interpretation. The isotope measurements by themselves may not provide a unique solution to the history of atmospheric carbon sources, but they can provide a useful constraint on modeling efforts. These factors were discussed at a meeting on tree rings held in May 1979 by the Lamont-Doherty Observatory.

The University of Arizona is extending the tree-ring chronology backward in time for special trees and will supply dated wood samples for ^{14}C analysis. They will provide independently dated samples so that the temporal variations in atmospheric ^{14}C can be measured and thus provide assistance in interpreting the isotopes stored in tree rings.

The University of Washington is collecting samples for isotope analysis from islands along the Pacific Coast. Attempts are made to sample trees as uninfluenced, as far as possible, by local sources of pollution and by CO_2 uptake release of other trees. The sites are on Kodiak Island and Sitka in Alaska and Graham and Vancouver islands in British Columbia.

Terrestrial Biomass Studies

The amount of carbon in tropical forests is being evaluated by a joint effort at the Institute of Tropical Forestry in Puerto Rico and Cornell University. They have prepared summaries of several worldwide forest inventories showing that about one-third to one-half of the tropical countries are covered by forests, one-half of which are "closed," that is, having a continuous canopy cover. The areas are being mapped into life zones. An analysis of the tropical hardwood trade suggests that a significant amount of carbon has not been stored in structures and furniture. Their studies of ecosystem biomass and organic production data indicate that soil organic matter accounts for a significant portion of the total biomass and that stored biomass in tropical forests may be larger than reported earlier. Their modeling efforts have indicated the importance of acquiring data on the properties of virgin vs. second growth cutting; the rates at which land enters and leaves shifting agriculture; changes in following periods and rates of change in land usage. They find few data on these aspects for tropical forests.

Their work also suggests that slash-and-burn agriculture may result in a net transfer of carbon from living vegetation to the soil or large boles (dead tree trunks or large branches). They tentatively believe that man's activities may make tropical forests a net sink for atmospheric carbon rather than a source, as is usually thought.

The Institute of Ecology conducted several workshops on problems of carbon storage in the temperate and polar biosphere. Based on existing data and their deliberations, analysts there have constructed estimates of the changes in stored carbon in extratropical ecosystems. They find the data somewhat variable throughout the world, but reach the conclusion that extratropical forests may be storing carbon at a rate nearly 20 percent of the current fossil fuel emission. They also feel that organic soils that are being drained are releasing a small amount of carbon while a

smaller amount is being stored in undrained soils. Freshwater lakes and streams may be storing an additional quantity equal to about 5 percent of the fossil fuel emission. These figures are, of course, subject to great uncertainty, but they are in qualitative agreement with the analyses of the Mauna Loa record carried out at GMCC/NOAA where the data suggest the seasonal forests may be increasing in carbon content (see the section on atmospheric interpretation of CO_2 concentrations).

Another study has begun at the University of Michigan using an area in Michigan with the best long-term set of plant succession study plots in North America. The purpose is to study the rates of photosynthesis, respiration, and water use by forest trees in an area that was logged over in the early part of the century and has been regrowing since then. The rates of carbon exchange in such a forest will be useful in estimating carbon storage in these regrowing areas of the midlatitudes.

At Oak Ridge National Laboratory, models emphasizing the detailed function of terrestrial ecosystems are being developed. Anthropogenic fluxes of CO_2 resulting from forest clearing are explicitly treated. These models for the terrestrial circulation of carbon are continually tested, in conjunction with several ocean models, for consistency with data sets that reflect the global dynamics of carbon. Particular emphasis is being given to measurements of isotopic ratios such as ^{13}C in tree rings. As carbon cycle models are refined, the implications for potential increases in atmospheric CO_2 concentration are reassessed.

None of the studies reported here claims to be definitive, but the suggestion that both tropical and midlatitude forests could be storing carbon, at least over the past few decades, is likely to provoke controversy. These preliminary results suggest that acceptance of the hypothesis that the terrestrial biosphere is a large, net source of atmospheric carbon would be premature.

Reference

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3 Climate Research

Michael C. MacCracken

Introduction

Climate research, especially during the past 20 years, has demonstrated that man's activities may soon be able to perturb the climate on a global scale. Injection of CO₂ is believed to be foremost among potential modifiers of the natural system. The climate research element of the Department of Energy's (DOE) program is designed to develop estimates of the climatic impacts resulting from increased CO₂, focusing particularly on the magnitude and temporal and spatial patterns of the anticipated changes.

The effort that DOE will be devoting to climate during this 10-year research program will be substantial. Yet, this effort is only a relatively small (although highly focused) part of the extensive national and international scientific effort now underway to improve understanding of climate, its variations, and the potential impacts of various perturbing factors. The coverage of specific research activities in this progress report is heavily weighted to DOE-supported activities. The general analysis and discussion, however, recognize the breadth of the total research effort and DOE's need to interface with it. Thus, we want to acknowledge the important contributions made to CO₂-related research by the programs of other agencies, particularly the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA) in the United States and under the auspices of the Global Atmospheric Research Program (GARP) at the international level. Without these strong basic and applied research efforts, the DOE effort would not be productive, even with a substantially greater level of support.

The following sections outline, first, the research approach that

DOE believes is essential to generating the necessary capability for determining and assessing CO₂-related climate impacts and, second, the progress made as part of the DOE program during the past 2 years. Activities supported jointly by DOE and other agencies, particularly NSF, are also reviewed.

Research Approach

Society's sensitivity to the natural climate has led to major initiatives to improve scientific understanding of climate in recent years. Extensive modeling efforts, although still perhaps oversimplified, are providing new insights into the processes controlling the climate. The climate studies element of the CO₂ program plans to utilize results of modeling calculations with increasing CO₂ concentrations to help construct a most plausible scenario (or scenarios) for evaluation of ecological, social, and economic costs. Particular attention will be paid to estimating changes in the critical climate parameters (e.g., seasonal temperatures, precipitation and moisture patterns, etc.) in key agricultural, watershed, ocean and polar shelf-ice areas and to evaluating how rapidly the present climate will change when consideration is given to the stabilizing effects of the oceanic heat capacity. The program will provide major support for numerical modeling of the air-surface-ocean-ice system.

Evidence of past climate conditions makes it clear that the climate has always been changing. It must be remembered that CO₂-induced changes will be in addition to any natural changes, which in themselves would be expected to have social and economic effects. Although the factors governing past changes are not yet understood, it seems certain that the future climate, even without increased CO₂, will be different and will exhibit some fluctuations. The sign and relative magnitudes of the natural and CO₂-induced climate changes will determine whether the effects tend to cancel and thereby reduce impacts, or, alternatively, tend to be additive and thereby exaggerate impacts. If the costs of impacts are such that they increase markedly if certain climatic changes

are exceeded, then we must estimate ranges of possible changes that may be induced by both natural and perturbed causes before a satisfactory assessment of potential CO₂ impacts can be made.

A second approach to developing estimates of future CO₂-induced climate changes is to study the past climatic record. Past changes have involved different time and space scales, with changes in both the means of various properties (e.g., annual temperature, frequencies of anomalies, etc.) and in their variability (e.g., maximum and minimum temperature). These changes have had important economic and social effects in historic times (the "Little Ice Age," the "Dust Bowl," the Sahelian droughts, etc.) and, even with (and perhaps because of) our present technological capabilities, climate changes and fluctuations may affect our society, particularly agriculture, even more greatly in the future. The DOE program will seek to identify those periods in the past that have had climatic anomalies generally similar (e.g., warmer, moister) to those predicted by models for increased CO₂. Of particular interest are the hypsithermal period (approximately 4,000-8,000 years ago), the Viking or medieval period (about 1,000 years ago), and the early parts of this century. In addition, changes that have occurred in going from colder to moderate conditions will be extrapolated as another means of obtaining estimates of the consequences of climatic warming. If periods can be identified when increased CO₂ concentrations actually occurred, they will receive extensive attention.¹

In order to develop a climatic scenario, future CO₂ concentrations must be projected - a task being undertaken as part of the carbon cycle research. As that work proceeds, with all of its own difficulties and uncertainties, the climate element of the CO₂ program will develop a consensus climate scenario (or scenarios) by reconciling the results from the modeling efforts and analyses of past climates being conducted under DOE support and by others. Because of different approaches to modeling various processes, inherent limitations in dating proxy climate

¹Investigations of possible past variations of the atmospheric CO₂ concentration are described in the carbon cycle sections of this report.

data, and so on, we must expect that the results of different approaches will be somewhat different. Development of a plausible scenario requires careful evaluation of such factors as the importance of particular assumptions, the consistency of results, identification of areas of agreement and disagreement, and evaluation of ranges of likely natural climate fluctuations. Not only must we be concerned with climatic effects when new climate conditions have been established, but we must also be able to project the temporal pattern of such changes, recognizing that they may not occur as rapidly as CO_2 concentrations change because of time delays induced by oceanic characteristics. Close coordination with the planning of impact studies and their results will be required in order to focus on the most relevant parameters and regions.

Because of the inherent uncertainties in estimating future climatic changes, the climate studies will also include a subcategory to investigate the possibility of identifying the climatic response induced by increasing CO_2 concentrations in the background noise of natural fluctuations. Because it may be 20 years or more before CO_2 -induced changes in global average temperature are identifiable amidst the natural variability, consideration will be given to identifying those climatic parameters (or sets of parameters) that may be most sensitive or may respond earliest to increasing CO_2 . Recent analyses have indicated that the large heat capacity of the ocean's relatively well mixed upper layers may delay detection of global changes although we may be able to see evidence of the changed land-ocean temperature contrast that might be expected during the interim adjustment period. Particular attention will be paid to identifying parameters that change in a coupled fashion during the development of a climate change. The goal will be to determine a means of confirming theoretical expectations as soon as is feasible.

Research Progress

During the past year there has been a substantial increase in appreciation of the role of the ocean in controlling not only atmospheric CO_2 concentrations, but also the resulting climatic response of the atmosphere. Model simulations of the effect of doubled CO_2 concentrations

carried out with fixed ocean temperatures, a situation to be expected during perhaps the next 20 years, showed relatively small summer heating over land areas only (e.g., Gates et al., 1980). On the other hand, simulations in which the ocean temperatures could come into instantaneous equilibrium with atmospheric conditions continued to predict global warming of $3 \pm 1.5^{\circ}\text{C}$, accentuated at high latitudes (e.g., Manabe and Wetherald, 1980; Hansen, 1980). Clearly, estimating the transition from the relatively steady present climate to the evolving one that will prevail during the next century will require substantial improvements in the model's representation of the ocean's heat capacity, vertical structure, circulation, and response time. Plans for such improvements indicate that models with interactive oceans should begin to be available in 1980. The section on modeling climate effects reports on DOE-sponsored activities in this area.

During the past year also, efforts to reconstruct regional climatic patterns prevailing during past warm periods were accelerated; these periods may serve as analogs to an increased CO_2 climate. Particular attention centered on the climates of the United States and other countries bordering the North Atlantic Ocean during the warm period 5,000 to 7,000 years ago. Work during 1980 will both expand these efforts and augment on-going work in Great Britain to look at warm years during this century, as described in the section on reconstructing and analyzing past climates.

We are only beginning to appreciate the efforts that will be required to develop plausible climate scenarios that integrate our knowledge of past climates with that obtained from current models, and which are both consistent with observed fluctuations in weather patterns and sufficiently detailed to be of use in carrying out environmental assessments. As described in the section on developing climate scenarios, this will be a subject for future research.

Finally, to confirm our expectations, we need to develop statistically valid evidence that the predicted changes are occurring and are not just

a result of compounded uncertainties in our observations. Even more clearly than before, recent studies (e.g., the report of the NAS committee chaired by Prof. J. Charney) have pointed to problems in early identification of the expected surface temperature changes because the large heat capacity of the oceans delays these temperature changes. Present estimates are that oceanic heat absorption will simply cause a delay of 20 years in the expected change, but that the ultimate equilibrium warming estimated for a doubling of CO_2 concentrations will still come about. If the CO_2 concentrations continue to increase beyond a doubling, this delay will continue to cause great difficulty in properly confirming our predictions. This makes better modeling of the oceans a necessity. There is also the possibility, probably remote, that the different time constants of the oceans and the land-atmosphere systems (and also the cryosphere) will cause the climate to reach a slightly different equilibrium than the present calculations indicate by, for example, inducing temporary climate changes (e.g., increased land-ocean summer temperature contrasts that lead to altered precipitation patterns) that induce biospheric responses (e.g., changes in vegetation type), which in turn affect the climate (e.g., by albedo change). The very limited efforts in this area are described in the section on signals of climate change.

Modeling Climate Effects

Because CO_2 appears to be such an important factor in determining the present climate, numerical modeling research concerning climate and the effects of increasing CO_2 concentrations has been and continues to be extensive. Rather than duplicate the major efforts by NOAA, NASA, and NSF, DOE is working with these agencies to provide the additional support that may be needed for existing groups to concentrate even more on the climate questions raised by increasing CO_2 concentrations. Where additional efforts are needed, particularly in the area of developing simplified and statistical approaches to climate prediction, DOE is funding, and considering funding, projects directly.

There are two basic approaches to climate modeling: (1) detailed simulation of atmospheric motions using general circulation models (GCM) and then averaging the resulting state to derive the model climatology; and (2) averaging or simplifying the simulation of the atmospheric motions (e.g., using statistical dynamic models--SDM) and then calculating the model climatology directly. The most simplified form of this second approach involves eliminating transport effects entirely and just calculating radiative effects (i.e., global energy balance models). In fiscal year 1979, DOE support for GCM and SDM efforts was \$460,000 and \$225,000, respectively.

Both approaches have their advantages and disadvantages. The use of GCMs allows calculation of regional effects, includes an essentially complete representation of the complex role of eddy motions, and provides as realistic a simulation of the atmosphere's instantaneous evolution as is possible. Such calculations are, however, extremely expensive, thereby limiting the range of sensitivity studies and the length of the simulation (10 years appears to be the practical upper limit at present). GCMs, like all models, also contain many parameterizations and simplifications that are not wholly satisfactory so that, even with unlimited computer resources, there are other causes of potential error (see the section on historical warm climate analysis).

The major attractions of the statistical dynamic model approach (here taken to include use of energy balance models) are the more reasonable requirements for computer time and the ability to conduct more extensive sensitivity studies as a means of focusing on the role of particular processes. One major shortcoming of such models is the inadequacy of their treatment of transport processes, the available approaches to this problem all being theoretically somewhat unsatisfactory. A second major drawback has been dimensionality, in that most models of this type are either one or two dimensional. The effect of this approximation is to eliminate the chance of identifying regional effects. A three-dimensional SDM could be developed if it were not for the remaining problem of statistically averaging the dynamic equations in time.

As with the GCM approach, there are also many other simplifications and parameterizations that reflect the inadequate theoretical understanding of atmospheric processes (see the section on statistical-dynamic models).

There are also a number of shortcomings common to both approaches. Major among these are the limitations caused by inadequate understanding of the very complex processes taking place in the atmosphere, as for example: the height, type, and distribution of clouds; the interaction of the cryosphere (sea ice, glacial ice, and snow cover) and the atmosphere; and treatment of the ocean's great capacity to absorb, store, transport, and release heat.

DOE is planning a research effort that combines both modeling approaches. SDMs will be used to look closely at the roles played by particular processes and to investigate the long-term changes that may occur in slowly evolving boundary conditions (i.e., the oceans, biosphere, and cryosphere). GCMs will be used in addition to investigate regional effects and climatic variability.

General Circulation Models. The Department of Energy presently contributes to the support of two of the six U.S. groups developing and using general circulation models in climate studies (see Table 3-1). Of the others, three are largely excluded by governmental policy from accepting DOE funds and the fourth is pursuing more fundamental research. Nonetheless, at least two of the first three groups are undertaking CO₂ sensitivity studies under their own auspices. In the case of both the National Center for Atmospheric Research (NCAR) and Oregon State University (OSU), the National Science Foundation (NSF) is also providing major support and the joint NSF-DOE efforts are administered by NSF.

As indicated earlier, major advances have been made during the past year in recognizing the important role of the parameterization of the oceans in delaying the model response. This is not to say

Table 3-1. Major U.S. General Circulation Modeling Groups

Institution	Sponsoring agencies	Scientists having GCM papers on CO ₂
Geophysical Fluid Dynamics Laboratory (GFDL), Princeton, N.J.	NOAA	Manabe, Wetherald, Stouffer
Goddard Institute for Space Studies (GISS), New York, N.Y.	NASA	Hansen
Goddard Laboratory for Atmospheric Sciences (GLAS), Greenbelt, Md.	NASA	
National Center for Atmospheric Research (NCAR), Boulder, Col.	NSF, DOE ^a	Washington
Oregon State University (OSU) Corvallis, Ore.	NSF, DOE	Gates
University of California (UCLA) Los Angeles, Calif.	NSF	

^aSupport level presently relatively minor.

that the many types of models that have assumed that the effects of heat capacity could be ignored (all except Gates in Figure 3-1) and that have indicated that doubling the CO₂ concentration will increase average northern hemisphere temperatures by 1.5 to 4.0°C are not correct; only that the time at which such changes occur may be somewhat further away (perhaps 20 years after the doubling has occurred).

One indication of the importance of the role that ocean parameterizations play in model results came out of a limited study of the climate change that would be induced if ocean feedback were not permitted (Gates et al., 1980). This study was done using OSU two-level atmospheric GCM. The model's boundary conditions consisted of seasonally varying insolation at the top of the model atmosphere (the tropopause), surface topography and albedo, and prescribed present-day sea-surface temperatures. This representation of the oceans is, of course, one of

Figure 3-1. Estimates of the change in surface temperature due to various changes in CO₂ concentration. Investigator: o Manabe and Wetherald (1967); Δ Manabe and Wetherald (1975); □ Manabe (1971); ▽ Ramanathan (1975); — Augustsson and Ramanathan (1977); x Manabe and Stouffer (1979); + Manabe and Wetherald (1980); • Wetherald and Manabe (1980); ▲ Hansen (1980); ▼ GISS (1978); ■ Gates (1980); ★ Potter (1978), NH value; ◆ Hunt and Wells (1979); ◇ Ramanathan et al. (1979). Manabe and Wetherald (1980) also refer to an eight times CO₂ increase that led to even further heating. Shading shows present range of natural fluctuations (Mitchell, 1979).

the simplest possible in that it assumes infinite oceanic heat capacity and allows no feedback. The only change made for the CO₂ experiments was to increase the optical depth of the model atmosphere to correspond to a doubling or quadrupling of the CO₂ concentration. The monthly varying distribution of global sea-surface temperature and sea ice was the same observed data set as used in control integrations of the atmospheric GCM. The model's response is thus confined to the direct radiative effects of increased CO₂. There is no significant enhancement of the model's feedback processes associated with ice albedo and humidity changes.

The initial conditions for the integrations for both doubled and quadrupled CO₂ were taken as the data for November 1 of the second year of a three-year control integration of the atmospheric GCM and the experiments have so far each been carried out for nine simulated months. The behavior of the monthly-averaged tropospheric temperature during the course of the experiments carried out so far is shown in Figure 3-2, along with the mean of the three corresponding monthly-averaged temperatures in the three-year control run. The CO₂-induced warming has reached a statistically steady value of about 0.3°C (0.5°C) with respect to the control mean for doubled (quadrupled) CO₂. This warming is due to the increase in the radiative heating of the earth-atmosphere system. In the present model most of the increase in the net downward surface radiative flux may be considered to pass into the ocean, and has no further effect in the model since the sea-surface temperature is not permitted to respond. The oceans are serving as a sink for much of the anomalous radiative flux caused by increased CO₂, in contrast to land surfaces, the temperature of which is determined on the assumption of a surface heat balance.

In contrast to earlier studies in which the sea surface temperature could vary instantaneously (i.e., assuming zero oceanic heat capacity), no significant change in the intensity of the hydrologic cycle was found, so the model temperature response is not dominated

Figure 3-2. The variation of the monthly averaged mean tropospheric temperature during the experiments with doubled and quadrupled CO₂, along with that of the monthly mean in the 3-year control integration.

by enhanced latent heating or by enhanced positive feedbacks between the temperature and water vapor. With fixed ocean temperatures, the temperature-sea ice albedo feedback is also not operative here. Given all of these limitations, then, it is not surprising that the model's response is substantially less than the earlier studies.

The geographic distribution of the anomaly of the surface air temperature simulated in January with doubled CO_2 with respect to the mean of the three January months in the control is shown in Figure 3-3. Figure 3-4 gives the corresponding information for July and a summary of the data is given in Table 3-2. It is clear from these figures (in which the shading denotes a warming and the isolines are drawn at 2.5°C intervals) that the larger changes of surface air temperature are almost exclusively confined to the land area, as was expected. In view of the high levels of natural (and essentially unpredictable) variability to be expected in association with wintertime synoptic activity in middle and high latitudes, we do not regard the simulated changes of surface air temperature during winters in the northern or southern hemispheres as significant.

During summer, especially in the northern hemisphere (Figure 3-4), there are predominately positive changes of surface air temperature greater than 2.5°C over large portions of the interiors of North America and Asia. These same general features are also seen, and are more pronounced, for quadrupled CO_2 . Although these localized summertime temperature anomalies have not yet been tested for statistical significance against the local natural variability simulated by the model, their pattern strongly suggests that they are a systematic effect of the increase in CO_2 .

To help further address the issues raised by these studies, DOE support to the National Center for Atmospheric Research through the National Science Foundation began in May 1979. To prepare for the planned CO_2 perturbation studies, they have constructed a three-dimensional general circulation model (GCM) coupling the global atmosphere, oceans,

Figure 3-3. The geographical distribution of the change (with respect to the control mean) of surface air temperature simulated for January in the experiment with doubled CO₂. Here the isolines are drawn every 2.5° C, with the regions of warming greater than 2.5° C shaded.

Figure 3-4. The geographical distribution of the change (with respect to the control mean) of surface air temperature simulated for July in the experiment with doubled CO₂. Here the isolines are drawn every 2.5° C, with the regions of warming greater than 2.5° C shaded.

Table 3-2. Simulated Climatic Anomalies (Defined as Experiment Mean - Control Mean) for January and July over Ocean and Land Areas with Doubled and Quadrupled Atmospheric CO₂ Concentrations.

Quantity	Month	Doubled CO ₂ anomaly			Quadrupled CO ₂ anomaly		
		Ocean	Land	Total	Ocean	Land	Total
Net surface heating (W m ⁻²)	Jan.	2.7	0.3	1.8	9.4	0.7	6.4
	July	5.5	0.9	3.8	8.9	0.9	6.1
Change in tropospheric temperature (°C)	Jan.	0.22	0.38	0.27	0.42	0.43	0.42
	July	0.12	0.66	0.30	0.35	1.00	0.56
Change in surface air temperature (°C)	Jan.	0.10	0.34	0.18	0.19	0.75	0.38
	July	0.03	0.48	0.18	0.14	1.14	0.49

and sea ice (Washington et al., 1980). This climate model provides for improvements in several of the areas of uncertainty in model parameterization by including a version of the NCAR third-generation atmospheric GCM; an up-to-date representation of radiation and variable cloudiness; an ocean model with slightly simplified dynamics; and a simplified thermodynamic model of sea ice. Preliminary results from the ocean model show the correct seasonally changing patterns of ocean surface temperature and heat flux into and out of the oceans. The major ocean gyres and mass volume transports are correctly simulated in the coupled system. This model, then, will be a major step in improving our modeling of ocean-atmosphere interactions.

However, before attempting an augmented experiment to determine the regional effects of increasing atmospheric CO₂ concentration on

the regional effects of increasing atmospheric CO₂ concentration on the ocean-atmosphere system, results from this newly constructed coupled climate model must be closely compared with observed atmospheric and oceanic climatological data.

In summary, the steps have been laid for major progress in this area by both NCAR, OSU (which is pursuing similar approaches), and other institutions over the next several years. With such models, there should be substantial improvements in the confidence with which we can predict the global, regional, and seasonal climatic effects of increasing CO₂ concentrations.

Statistical - Dynamic Models. In addition to the general circulation model approach to improving the understanding of climate, a wide variety of simplified models are being developed and applied to climate problems at universities and institutions throughout the country. Of critical importance to the CO₂ issue is the use of such models to investigate the role of particular processes (e.g., clouds) and the feedbacks involving such domains as the oceans and the cryosphere. We expect that the results of such models will provide a better basis for planning application of GCMs.

During the past year, a suite of simplified climatic and mechanistic models, including a statistical-dynamic climate model (SDM), a radiative-kinetics model (RKM), and a coupled carbon cycle-climate model, have been used by the Lawrence Livermore Laboratory (LLL) to address a variety of questions. These have included: estimating the climatic effects of increased CO₂, investigating the role of cloud feedback on the CO₂-modified climate, assessing the effects of increased CO₂ on stratospheric chemistry,² and determining the importance of the interaction of the climate on the carbon cycle.

Using a two-dimensional (i.e., latitude and altitude) SDM that includes cloud and radiative prescriptions very much like GCMs,

² Changes in CO₂ concentration affect atmospheric chemistry by changing the temperature, which in turn affects rates of reaction. Subsequent changes in the concentration profiles of radiatively active species can alter the radiation balance and thereby further affect climate.

climate perturbation studies were carried out assuming half, double, and quadruple the present atmospheric CO_2 concentrations. The SDM was run assuming annual-average solar radiation at each latitude (seasonal calculations are planned during the coming year). As shown by the results of Potter (1978) in Figure 3-1, estimates of the northern hemisphere average surface temperature change for a doubling of CO_2 are in good agreement with results from other types of models, even though the range of processes treated and the sophistication of the mathematical representations are quite varied. As with the other models, the Lawrence Livermore Laboratory model shows amplification of the changes at the poles, an aspect of the problem deserving further study in seasonal simulations.

One area of special interest in studying the climatic effects is the role of clouds. Results from the CO_2 perturbation studies indicate that the effects of changes in cloud amount and distribution on the infrared radiation balance are consistent with analyses of satellite data by Cess (1976) if appropriate global averaging techniques are used. However, when the latitudinal dependence of the effect was investigated, a range of sensitivities was found because of the latitudinal redistribution of cloud amount and height. This redistribution led to situations at some latitudes where the effects of clouds on solar and long wave fluxes tended to amplify rather than cancel. Such studies need to be continued and compared with GCM results in coming years.

Substantial effort is being devoted to improving model simulations in future studies in order to expand the capability to evaluate the role of various feedback processes. Particular attention is being devoted to improving the radiation balance (e.g., by inclusion of the effect of ozone on infrared radiative fluxes) and the eddy transport of momentum (by incorporation of a parameterization developed by Green (1970)). To account for the important effects of seasonal variations in the depth of the oceanic mixed layer, efforts are

underway to improve modeling of the oceanic mixed layer for planned seasonal simulations during the coming year.

Two special studies were undertaken by the Lawrence Livermore Laboratory using other types of models to evaluate the potential effects of the predicted climate changes on processes not treated interactively by present climate models. As shown in Table 3-3, results from a radiative-kinetics model indicate that stratospheric cooling resulting from increased CO_2 could lead to an increase in stratospheric ozone concentrations. A doubling of CO_2 increased O_3 concentrations by 4 to 5 percent, depending on model assumptions. These results are in agreement with work by British scientists. Such changes in O_3 concentration would then affect both solar and long wave radiative fluxes. An increase in O_3 reduces the amount of solar radiation reaching the troposphere slightly, but increases the amount of downwelling long wave radiation from the stratosphere. Assuming hydrostatic equilibrium allows the air density to change as temperature and pressure change. Changes in density in turn affect ozone by changing reaction rates due to their dependence on species concentrations. Changing the ozone concentration and its vertical profile in turn affects the radiation balance and thus again changes stratospheric chemistry. The net effect on surface temperature of all of these

Table 3-3. Change in Total Ozone due to Doubling of CO_2 Concentrations^a

Assuming hydrostatic equilibrium	Change in surface temperature (K)	Change in total ozone due to CO_2 doubling (%)
Yes	0	5.06
No	0	4.74
No	2.0	4.17

^aThe possible change in surface temperature is specified, not internally computed, based on other model results.

processes is comparatively small, so these interactions need not be introduced as an additional complexity in climate modeling studies focusing on changes at the surface. The change in O_3 may cause stratospheric temperatures to decrease several degrees; however, this change is not expected to have any substantial climatic or environmental consequences.

The second study concerned the interaction of climate and the carbon cycle. Because the solubility of CO_2 in ocean water goes down as temperature goes up, the effect of warmer climate conditions induced by CO_2 may lead to increased atmospheric CO_2 concentrations--a positive feedback. Coupling a simplified parameterization of radiation effects to a carbon cycle model indicated that, on an annual average basis, this feedback leads to only about a 2 percent additional increase in CO_2 concentrations. The coupled model also indicated that seasonal ocean temperature variations cause an out-of-phase variation in atmospheric CO_2 concentrations that is only 10-15 percent of the observed seasonal variations measured at Mauna Loa. Both results indicate that there is little need at this time to couple carbon-cycle and climate models interactively in studies of first-order effects.

Future Directions. The major focus during the next several years will be in three areas:

- o Representation of the effects of the ocean,
- o Investigation of seasonal effects, and
- o Estimation of regional effects.

To pursue these efforts, parameterizations of cryospheric, oceanic, and surface processes in the various models will have to be improved and the results of such models compared with the observed climate. This work will continue to involve many groups throughout the world, with DOE funding emphasizing those areas of model development, verification, and application that are particularly significant to the CO_2 problem.

Reconstructing and Analyzing Past Climates

Unraveling the puzzle of past climates has been of great interest during this century. Analysis of tree rings, ocean cores, pollen counts, isotope ratios, and many other surrogate indicators have all played major roles in establishing a record of past climate variations. There is also substantial evidence indicating how climate changes have influenced food production, cropping patterns, and human migration. Figure 3-5, taken from the National Academy of Sciences 1975 report, Understanding Climatic Change, illustrates some of the many variations that have been identified.

Much of the current research, funded largely by NSF, NOAA, and the U.S. Geological Survey, focuses on periods that were colder than at present. This emphasis is understandable in that over the past 500,000 years, almost 90 percent of the period was colder than the present. In particular, during the past 500 years the Atlantic basin countries, and perhaps the world, experienced a "Little Ice Age" that had severe effects on food supplies, leading in some cases to human migrations and the demise of colonies previously established.

To help provide insight into the potential effects of CO₂-induced perturbations, DOE is seeking to augment efforts to describe the conditions existing during periods as warm or warmer than the present. This interest stems in part from model studies indicating that CO₂-induced warming appears similar in many respects to warming induced by other factors--a similarity that suggests data from past warmings, whatever the cause, may be useful for forecasting the regional definitions of the future CO₂-perturbed climate.

The important advantage of estimates based on past data over estimates made by models is that such conditions actually occurred. Understanding past conditions in terms of warm climate analogs can thus provide needed information on regional changes and on the responses of precipitation, soil moisture, the cryosphere, the biosphere, ground water, lake levels and ocean temperatures and

currents. We may not yet know the causes of the change--although many people are trying to determine the causes--but we do have a demonstration of an actual climatic state, representative of a period of temperature anomaly.

When we look back at the past, there are three major warm periods: earlier this century, earlier this millenium, and about 4,000 to 8,000 years ago (the hypsithermal). The first two are "historic warm climate analogs," and the last a "paleoclimatic warm climate analog." There were warm periods even earlier, but so little is known about them that it is doubtful that much additional insight into regional patterns can be gained. During fiscal year 1979, DOE contributed about \$125,000 to research in reconstruction of historic and paleoclimates. These rather modest amounts recognize the major efforts to reconstruct past climates being funded by the National Science Foundation and the U.S. Geological Survey. The Department of Energy is planning to support additional research on this subject during the next few years, concentrating on better defining regional effects.

Historic Warm Climate Analogs. The historic period, taken to be roughly the past 1,000 years, contains two major warm periods: earlier this century, and the period about 800-1,100 years ago. One can also look at warm years of the recent past that may be assembled into a warm climate composite. Although these periods are not as warm as the CO₂-induced warming is expected to be, indications of the types of changes that might occur may be found. In addition, there was an extremely cold period lasting about 200 years, perhaps the coldest period in the past 2,500 years, that immediately preceded the warm period earlier this century. The transition from that period to the present may provide further evidence of trends that might be expected as CO₂ continues to increase.

Although there is agreement on many of the general results for the high-CO₂ world that have been estimated using GCMs (and other, simpler models), the only spatial detail that has been estimated to

date is the latitudinal variation of changes in temperature. Greatest temperature changes are expected to occur at high northern latitudes (particularly above 60°N). Greatest changes are also expected to occur in winter. In these respects, CO_2 -induced temperature changes show a dependence on latitude and season similar to the "natural" fluctuations that have occurred earlier this century.

The initial area of emphasis in looking at the recent past has been on using selected years for which instrumental records are available as a guide to establishing possible future patterns of climatic change (e.g., Williams, 1980). The mean annual surface temperature of the northern hemisphere (and quite probably of the whole globe) varies considerably from year to year. Because of this variability, one can select individual warm years or use a composite of warm years as analogs for a future warmer world (resulting from increased CO_2 or other causes). Clearly, recent year-to-year fluctuations in climate were not caused by changes in atmospheric CO_2 content. However, numerical model results appear to indicate that, whatever the cause of the warming, there are broad similarities in the patterns of climatic change, so there may be good reason to believe that a scenario based on recent fluctuations will be useful as a CO_2 analog.

DOE is supporting acceleration of on-going research at the University of East Anglia to derive a warm-world scenario from such yearly data (Wigley et al., 1980). They have used the variations in mean annual surface temperature as a basis for comparing a composite of the five warmest years in the period 1925 to 1974 with a composite of the five coldest years in this period. The terms "warmest" and "coldest" are defined in terms of the latitudinal zone 65°N to 80°N . For this zone the five warmest years are 1937, 1938, 1943, 1944 and 1953, and the five coldest years are 1964, 1965, 1966, 1968, and 1972. The average temperature difference between the warm and cold year groups is 1.62°C in the high latitude zone and 0.6°C for the hemisphere as a whole.

Spatial patterns of temperature and precipitation differences between anomalously cold and anomalously warm years have also been derived from these groups of years. Maximum warming occurs in high latitudes and in continental interiors; up to more than five times the hemispheric mean in a region extending from Finland across the northernmost parts of Russia and Siberia to about 90°E. A large part of North America has positive temperature changes of two or more times the hemispheric mean. These results are in quite good agreement with results from model simulations. Some regions, however, show significant negative differences, including Japan, much of India, the southwest coast of the United States and a region in central Asia.

For precipitation, decreases are found for much of the United States, most of Europe and Russia (especially France, Spain, and the Central Russian Plain) and Japan, and increases in precipitation occur in India and the Middle East, again in reasonable agreement with schematic modeling studies. The potential impact of any such reductions in rainfall depends on their timing. Reductions occur mainly in winter and autumn; but most regions (especially eastern Europe) also show reductions in summer precipitation. For the central and western parts of the United States, where there is a reduction in annual precipitation, most places show an increase in the winter and spring and a decrease in the summer and autumn. Further north, in Canada, summer precipitation increases.

These results are being put together as a possible scenario, and in no way constitute a prediction. Their aim is to provide a guide to the type of climatic conditions that are possible in the high-CO₂ world. Because of possible changes in ocean and cryosphere boundary conditions as the climate changes, this scenario is representative only of conditions that might prevail up to the early decades of the twenty-first century.

Another somewhat different approach to analysis of recent data is being carried out by the Oak Ridge National Laboratory. These

studies have sought to identify large-scale spatial patterns of climatic anomaly from multivariate analysis of climatic data. One characteristic pattern of summer climatic anomaly over the North Pacific sector and western North America prevailed during the period of relatively high hemispheric mean temperatures, from the mid-1920s to the mid-1950s, but was conspicuous by its absence during the period prior to about 1920, which was relatively cool according to published temperature data. This pattern also shows warm and dry (droughty) conditions over much of the central United States (Figure 3-6). This climatic pattern is qualitatively similar to the climatic change simulated by general circulation models of the atmosphere for a doubling of atmospheric CO₂.

Paleoclimatic Warm Climate Analogs. There is substantial evidence that the global climate was quite warm for most periods more than a few million years ago. There have also been several periods of about 10,000 years duration during the past million years that have been quite warm. However, only the hypsithermal period of 4,000-8,000 years ago offers the potential for intensive investigation during the next several years. This period is of special interest because it was apparently 2 to perhaps 4°C warmer than the present, at least in some regions. This is almost as large a change as model simulations indicate might be induced by increasing CO₂ concentrations during the next 50 years. Understanding summer precipitation and moisture patterns during these periods could offer, for example, significant insight into evaluating agricultural impacts as the world warms.

In coordination with on-going studies sponsored by NSF, research is being accelerated to improve understanding of this period. The goal of the major DOE research effort on this subject at Brown University is to document the climatic patterns of 5,000 to 7,000 years ago (the warmest part of the hypsithermal) over as wide an area of the earth as possible. Multivariate statistical methods

Figure 3-6. Summer pressure anomaly type 1 (top) and associated temperature and precipitation anomaly patterns that were more frequent during warm years of the past century than during cooler years. Pressure anomalies are in millibars. Temperature and precipitation anomalies are in units of standard deviation at each station analyzed.

permit using the modern distribution of pollen and marine-plankton data to transform the distribution of their fossil remains into estimates of the temperature patterns of past times. In addition to mapping the temperatures, the moisture conditions and the airmass patterns occurring 5,000 to 7,000 years ago can also be reconstructed. These maps will update those published by Kellogg (1978). The goal is to produce global maps; first efforts will concentrate on mapping the northern hemisphere, however.

To produce the paleoclimatic reconstruction developed to date, an already-assembled data base for central eastern North America, northwestern Europe, and the western Soviet Union is being augmented by data from eastern Canada (in cooperation with the University of Minnesota); the North Atlantic, North Pacific, and Indian Oceans (Columbia University); southern and eastern Europe (University of Cambridge); and eastern Africa. In cooperation with F.A. Street at the University of Oxford, maps of lake-level data from the western United States and from northern and central Africa have also been made available. Because of a lack of pollen data sites in central and eastern Asia and in the central North Pacific Ocean, coverage is uneven across the northern hemisphere, but this broad-scale mapping will still be both more quantitative and more detailed than previous efforts. A summary of the available data points is shown in Table 3-4.

In cooperation with ten major groups of palynologists working in eastern Canada and New England, raw pollen data from these regions will soon be incorporated into the data base. The project focus will also be expanded to include construction of temperature and moisture maps (1) from pollen data from eastern North America, Europe, the Soviet Union, and eastern Africa; (2) from marine plankton data from the North Atlantic, North Pacific, and Indian Oceans; and (3) from lake-level data in the western United States and northern and central Africa. Examination of the data, dates, and reconstructions should

Table 3-4. Data Available for Development of Paleoclimatic Maps
for 5000 to 7000 B.P. in the Northern Hemisphere

	Pollen data	
	Sites with modern data	Dated fossil sites
Central Eastern North America	800	100
Northwestern Europe	350	150
Western Soviet Union	200	30
Eastern Canada ^a	400	50
Southern and Eastern Europe ^a	200	50
East Africa ^a	70	6
Marine-plankton data		
North Atlantic ^a	150	40
North Pacific ^a	100	10
Indian Ocean	200	12
Lake-level data		
North Africa	—	30
Western United States	—	30

^aData assembled in part with Department of Energy funding.

help in further assessing the nature of the global circulation from 5,000 to 7,000 years ago, in evaluating how it has changed between then and present, and in identifying key areas for future research.

Developing Climate Scenarios

Over the past several years, a large number of model calculations of the global climatic effects of perturbed CO₂ concentrations and an

increasing amount of information on past warm climates has become available. Schneider (1975, p. 2060) carried out an extensive review of modeling efforts and concluded that "a state-of-the-art order-of-magnitude estimate for the global surface temperature increase from a doubling of atmospheric CO₂ content is between 1.5 and 3 K, with an amplification of the global average increase in polar zones." Two reviews during the past years, one for the Office of Science and Technology Policy (NAS, 1979) and one as part of a World Meteorological Organization (WMO) working group meeting (WMO, 1979) generally agreed with the lower limit as an ultimate value for the warming but would raise the upper estimate somewhat. On the other hand, both groups felt that the actual response would likely be delayed perhaps several decades through the moderating influence of the large heat capacity of the oceans.

Although development of a plausible comprehensive scenario through evaluation of model results and comparisons with the climatic record has been one aspect of several recent workshops (McDonald and Roberts, 1978; AAAS-DOE, 1979), there are not yet any projects funded by DOE that attempt to draw together and reconcile available information. Such efforts in this area are expected to begin, however, within the next few years so that a comprehensive review of the various results will be available for the pentadel report of the CO₂ program in 1984. This work will need to extend the available reviews to include the data being learned about past climates and to develop estimates of regional as well as global changes. Input from environmental researchers is also needed in order to identify other parameters of interest, including precipitation, length of growing season, seasonality, and so on.

Signals of Climate Change

Because the present CO₂ concentration is 10-15 percent higher than the levels believed to have occurred 100 years ago, it might

seem that all we need do is measure the climatic changes that have occurred during this period and extrapolate into the future. Indeed, several researchers have claimed that they can demonstrate an effect using simple statistical climate models that include changes supposedly due to sunspots, volcanoes, CO₂, and anthropogenic dust. Unfortunately, many scientists believe that the climatic record is too variable, the possibility of other factors (including natural variability) exerting an influence too great, and the expected change too small for there to be any confidence in results derived by such an approach. Madden and Ramanathan (1980), however, looking at a 72-year data record from stations near 60°N indicate that the largest model-predicted changes should now be discernible in summer records. Since evidence of change is not now apparent, they believe that either the largest predicted changes are overpredictions or that other compensating factors are active. Deciding which factor is primary will require even longer data records for analysis.

Thus, most researchers believe it will take until the year 2000 or beyond (particularly in the case of regional changes) before anticipated CO₂-induced changes can be identified as exceeding natural fluctuations of climate with high statistical confidence.³ Figure 3-7 illustrates the difficulty inherent in the present limits to our understanding, even assuming that the climate responds rapidly to the CO₂ stimulus. As indicated earlier in this section, the large heat capacity of the oceans is expected to delay the response, although probably not change its magnitude.

Because it seems unlikely that policy decisions related to fossil fuel energy could be made without addressing forthrightly the issue of identifying signals of a changing climate, DOE expects to initiate a modest program during the next several years to determine when we can expect to identify the projected climatic effects and

^aThere are those who believe that major climatic fluctuations of the past have been in turn induced by other natural features (e.g., volcanoes).

Figure 3-7. Range of global mean temperature from 1850 to 2100 with and without the projected instantaneous climatic response to increasing CO₂ concentrations (Mitchell, 1979).

which particular effects we can expect to see the soonest. The research will include consideration of what parameters should be taken into account (e.g., polar ice, cloud cover), what regions should be analyzed, whether changes between correlated parameters should be investigated (e.g., stratospheric vs. tropospheric temperatures), and whether better measurements now will assist in earlier identification of the climatic response in years to come.

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4 Environmental and Societal Effects Related to CO₂

Roger C. Dahlman

A CO₂-induced change in the climate system and an increase in atmospheric carbon dioxide concentrations would be expected to result in a cascade of effects on the remainder of the environment. These environmental effects, some damaging and others perhaps beneficial, would be expected to cause changes and dislocations in the global social, political, and economic order. A program has been initiated to define the nature and extent of both the environmental and societal consequences of a change in the climate system.

Definition of Issues

About 85 distinguished and internationally recognized scientists were assembled by the American Association for the Advancement of Science (AAAS) to examine environmental and societal implications of the CO₂ issue (Workshop on Environmental and Societal Consequences of a Possible CO₂-Induced Climate Change, Annapolis, April 1979). This workshop identified many possible effects related to changes in CO₂ or to CO₂-induced climate change. The workshop panels focused on environmental effects on oceans, cryosphere, and ocean biota (Panel I); environmental effects on the less-managed biosphere (Panel II); environmental effects on the managed biosphere (Panel III); social and institutional response (Panel IV); and economic and geopolitical consequences (Panel V). Among the most interesting results of panel deliberations were: (1) the realization that consequences of CO₂ changes may not all be deleterious, but rather benefits may also occur; (2) the identification of important physical and biological effects (for example, changes in sea level or agricultural productivity); (3) a recognition that a better understanding of social and institutional systems is needed before one can predict responses to a CO₂-induced climate change (for example, major forces such as wars, famines, politics, and fundamental social evolution may substantially outweigh perturbations from CO₂); and (4) the existence of

flexible, adaptable societal/institutional systems may be the best response to a global environmental problem. The most important outcome of the Annapolis workshop was the initiation of interdisciplinary dialogue on how to deal with an issue as complex as CO₂. This first systematic attempt to define physical and biological effects, social-institutional responses, and geopolitical consequences laid an interdisciplinary foundation for dealing with broad-based CO₂ impacts of future decades or centuries.

The AAAS is continuing its efforts to define specific environmental and societal research issues through more narrowly focused meetings and individually authored position papers. Research issues being investigated are listed in the Preface Table. Nineteen issues related to environmental effects on oceans, cryosphere, agriculture, and the less-managed biosphere are being reviewed in category III of the program. Six issues related to social and institutional responses and four issues related to economic and geopolitical consequences make up program category IV. Detailed analyses of these issues by individuals or groups of experts will provide the basis for the environmental and societal segment of the comprehensive plan for CO₂ research and assessment (Part II).

Research on Environmental/Societal Effects

While initial attention has been devoted to defining important environmental and societal issues, several conceptual investigations have been started on evaluating ecological change and societal consequences. The objectives of the ecosystem impact study, under the direction of C. F. Cooper, San Diego State University, are to review and assess existing and potential models for predicting ecological responses to climate change, to determine which methods of prediction are likely to prove most effective, and to recommend research needed to improve predictive capability. Ecological predictions will likely be indirect, based on biogeographic and ecological features in different climates, extrapolations from small-scale laboratory or field

experiments, statistical analyses of observed ecological responses to climatic variables, or computer simulations based on presumed cause-and-effect relationships. Modeling strategies are given serious consideration because classical experimental methods would be difficult, if not impossible, to apply to problems of ecosystem response to climate change.

Another study under the direction of W. O. Roberts, Aspen Institute for Humanistic Studies, is attempting to define the economic, social, and political issues related to CO₂-induced climate change and to suggest in detail how the necessary research may be most effectively accomplished. The work is coordinated with the National Climate Program Office in order to obtain mutual benefit from studies of the societal impacts of present climate variations and fluctuations.

5 Environmental Control Technology for CO₂

Roger C. Dahlman

The application of conventional engineering methods to control industrial emissions is sometimes suggested as a way to minimize the atmospheric increase of CO₂. Proposals for collecting CO₂ from fossil power station flue gas and injection into oceans (Marchetti, 1977; Hoffert et al., 1979) suggest at least transient control of CO₂; e.g., the model projections of Hoffert and coworkers range from no effect over the next few centuries for 100 percent injection of fossil fuel CO₂, to a ninefold atmospheric increase for 0 percent injection. Over the longer term of several thousand years, their studies suggest a new steady-state equilibrium of about 1,150 ppm CO₂ in the atmosphere if the entire fossil fuel reserve is depleted and injected into oceans. These studies indicate that collection and ocean disposal has some merit over the course of several centuries, provided economic and political factors are favorable.

An engineering study carried out by Brookhaven National Laboratory (Albanese and Steinberg, 1980) determined the energy requirements for capturing CO₂ from flue gas, for transferring concentrated CO₂ to ocean disposal sites, and for injecting CO₂ into the deep ocean. Two control scenarios were evaluated, one based on the absorption of CO₂ contained in power plant flue gas by seawater; the other, based on absorption of CO₂ by monoethanolamine (MEA). Captured CO₂ is injected into the deep ocean in both cases. The study indicated that capture and disposal by seawater is not feasible, whereas capture and disposal using MEA may hold some promise.

The energy requirement for CO₂ removal from flue gas and disposal in oceans is high (Table 5-1). Typically, the production of 1 pound of CO₂ from fossil fuel results in 0.55 kwh(e); however, removal by direct absorption by seawater is obviously too inefficient to warrant further consideration. The MEA option, which requires an expenditure of 0.19

Table 5-1. Energy Requirements for CO₂ Removal by Seawater or Monoethanolamine (MEA) Absorption and Seawater Disposal^a

	Energy Requirement (kWh(e) per lb ⁻¹ CO ₂)					
	50 or 60% Efficiency ^b			90% Efficiency		
	Gas	Liquid ^c	Solid ^c	Gas	Liquid	Solid
Seawater absorption	0.60			0.81		
MEA absorption	0.19	0.20	0.32	0.31	0.32	0.44

^aAlbanese and Steinberg (1980).

^b50 percent removal efficiency applies to the MEA option; 60 percent to seawater absorption option.

^cDisposal options following CO₂ removal from flue gas.

to 0.44 kwh(e) per pound of CO₂ controlled, may have some merit, but it, too, carries significant economic penalties. For example, at a CO₂ removal efficiency of 50 percent, it is estimated that the power generation efficiency of a conventional coal-fired power plant would be reduced from 34 to about 25 percent. The cost of power generation would be expected to double. For 90 percent CO₂ removal, power generation efficiency is reduced to between 15 and 6 percent, and the cost of power generation increased by factors of four to seven. This initial study makes a rather convincing argument against serious consideration of conventional engineering control technology approaches for mitigating the CO₂ problem. Furthermore, engineering controls would stand the greatest chance of success when applied to concentrated sources of CO₂ such as power plant emissions. But less than 50 percent of fossil fuel CO₂ in the United States comes from stationary power plant sources. Engineered control of CO₂ at diffuse sources would likely be more difficult, less practical, and more costly.

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6 Research Projects

<u>Institution</u>	<u>Project Title</u>	<u>Principal Investigator</u>
^a University of Alaska	Gases in Sea Ice	Kelley, J. J.
American Association for the Advancement of Science	AAAS-DOE Workshop on Environmental and Societal Impacts of a Possible CO ₂ -Induced Climate Change	Burns, David H.
Aspen Institute for Humanistic Studies	The Consequences of a Hypothetical World Climate Change Produced by Increased Atmospheric Carbon Dioxide	Roberts, Walter Orr
^b University of Arizona	Dendrochronology of the Bristlecone Pine	Ferguson, Charles W.
Brown University	Global Temperature Patterns 6,000 Years Ago	Webb, Thompson
University of East Anglia	On the Geographical Patterns of Climatic Change over Recent Millennia, Particularly Since About 800 AD	Wigley, T.M.L.
^c Environmental Research Laboratories/NOAA	Expansion of Global Atmospheric Monitoring of Carbon Dioxide	Hanson, Kirby J.
University of Florida/ Cornell University	Models of Carbon Flow in Tropical Ecosystems with Emphasis on Their Role in the Global Carbon Cycle	Lugo, Ariel E. Hall, Charles A.S.
The Institute of Ecology	Problem Definition and Feasibility Workshops Terrestrial Biosphere Subcomponents on the Global CO ₂ Balance	Loucks, Orie L.
Lamont-Doherty Geological Observatory	Coral Growth Rings and the Temporal History of Nuclear ¹⁴ C and ⁹⁰ Sr	Broecker, Wallace S.
Lamont-Doherty Geological Observatory	International Meeting on Dendro-isotopic Research	Broecker, Wallace S.
Lamont-Doherty Geological Observatory	Interpretation of Equatorial Hydrographic, Nutrient Element, and Radioisotope Data	Broecker, Wallace S.
Lamont-Doherty Geological Observatory	Investigation of the Surface Water pCO ₂ in the Equatorial Pacific Ocean	Takahashi, Taro

<u>Institution</u>	<u>Project Title</u>	<u>Principal Investigator</u>
Lamont-Doherty Geological Observatory	Large-Scale Deliberate Trace Releases in the Ocean Thermocline	Broecker, Wallace S.
Lamont-Doherty Geological Observatory	Natural Catalysis of the $\text{CO}_2\text{-HCO}_3$ Reaction in Surface Sea Water	Broecker, Wallace S.
Lawrence Livermore Laboratory	Miniaturized Rapid Response Sensor for Atmospheric Concentrations of Carbon Dioxide	Bingham, Gail
Lawrence Livermore Laboratory	Modeling Climatic Effects of Carbon Dioxide Increases	Knox, Joseph B.
University of Miami	Coordination and Technical Planning for the DOE Carbon Dioxide Effects Research Oceanographic Subprogram	Ostlund, H. Gote
University of Michigan	Successional Forest Stands as Sinks for Atmospheric Carbon Dioxide	Gates, David M.
National Bureau of Standards	Development of Standards for Measurement of Atmospheric Carbon Dioxide	Hughes, Ernest E.
^b National Center for Atmospheric Research	Enhanced Research Program on the Long-Range Climatic Effects of Increasing Atmospheric CO_2	Washington, Warren M.
Oak Ridge Associated Universities	Global Effects of Increasing Levels of Carbon Dioxide	Rotty, Ralph M.
Oak Ridge National Laboratory	Global Carbon Cycles and Climatic Risks	Olson, J.S.
^b Oregon State University	Research on the Dynamics of Climate	Gates, Lawrence W.
San Diego State University	Modeling Ecosystem Impacts of Climate Change from Energy Development	Cooper, Charles F.
Scientific Committee on Problems of the Environment	Support of International Research Activities on the Global Carbon Cycle	White, Gilbert F.
^b Scripps Institution of Oceanography	A Study of the Abundance of Carbon Dioxide in the Atmosphere and Its Exchange with the Oceans	Keeling, Charles D.
Scripps Institution of Oceanography	Carbon Dioxide Measurement in the Equatorial Pacific	Weiss, Ray F.

<u>Institution</u>	<u>Project Title</u>	<u>Principal Investigator</u>
Scripps Institution of Oceanography	Nutrient Measurements for NORPAX	Williams, Robert
Scripps Institution of Oceanography	Technical Support for Collection of C-14 Samples During FGGE	Williams, Robert
University of Washington	Bomb Radiocarbon Sections Along the Hawaii-Tahiti Shuttle Track	Stuiver, Minze
University of Washington	Geochemical Determination of Biospheric CO ₂ Fluxes to the Atmosphere	Stuiver, Minze
University of Washington	Historical C-14 Measurements from the Atlantic, Pacific and Indian Oceans	Fairhall, Arthur W.

- a Joint funding with the Office of Naval Research
- b Joint funding with the National Science Foundation
- c Joint funding with the National Oceanic and Atmospheric Administration

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Carbon Dioxide and Climate Research Program

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