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Carbon Dioxide and Climate: Summaries of Research in FY 1989

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FOREWORD

Scientific and public interest in greenhouse gases, climate warming, and global change has virtually exploded in 1989. The Department's focused research on CO_2 contributed sound and timely scientific information to the myriad of questions produced by the groundswell of interest and concern. Research projects summarized in this document provided the data base that made timely responses possible, and the contributions from participating scientists are genuinely appreciated. The nation's interest has been well served.

In the past year, the core CO_2 research has continued to improve the scientific knowledge needed to project future atmospheric CO_2 concentrations, to estimate climate sensitivity, and to assess the responses of vegetation to rising concentrations of CO_2 and climate change. The Carbon Dioxide Research Program's goal is to develop sound scientific information for policy formation and governmental action in response to changes of atmospheric CO_2.

During this year, the Program was moved into the Office of Health and Environmental Research and was combined with other atmospheric research activities. The work is now administered by the Atmosphere and Climate Research Division (ACRD). In addition to supporting core CO_2 research and developing a program around the new initiatives, ACRD is responsible for atmospheric science and climate. Its scope includes atmospheric chemistry, numerical modeling, laboratory studies, and field experiments.

This Program Summary describes projects funded by the Carbon Dioxide Research Program during FY 1989 and gives a brief overview of the objectives, organization, and accomplishments of that research.

Ari Patrinos, Acting Director
Atmospheric and Climate Research Division
Office of Health and Environmental Research

PREFACE

This document describes the activities and products of the Carbon Dioxide Research (CDR) Program in Fiscal Year (FY) 1989. The report is organized into four main sections.

SECTION		DESCRIPTION
Introduction	o	Describes overall CO_2 issues
	o	Ties CO_2 issues to the research approach, program goals, and objectives
	o	Relates each specific research area to the overall goals of the program
Research Areas and Project Descriptions	o	Describe scientific questions in each research area
	o	Provide descriptions of individual research projects
	o	Show the level of effort
	o	List the expected products for each project
	o	Show the research approach or method used in each project
	o	Provide results to date when applicable
Appendixes	o	Provide more in-depth information on the total research approach
Indexes	o	Provide locator information on subjects, principal investigators, and research institutions for the whole report

Questions about the Carbon Dioxide Research Program or specific projects may be addressed to the Atmospheric and Climate Research Division, U.S. Department of Energy, ER-76, Washington, DC 20545. The Carbon Dioxide Research Program's telephone number is (301) 353-3281.

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INTRODUCTION

Research Program. The goal of the Carbon Dioxide Research Program is to develop the scientific knowledge base for policy formation and governmental action in response to changes of atmospheric CO_2 and primary effects dealing with the earth's climate and biological systems. Achievement of this goal requires increased understanding of CO_2 interactions involving the global atmosphere, biosphere, oceans, and cryosphere.

Policy considerations fall into two distinct areas: those directed at slowing the rate of CO_2 (and other radiatively active gas) emissions, and those dealing with potential "regions in jeopardy" created by changing climatic conditions.

Future atmospheric CO_2 levels are estimated from models of the energy system and the carbon cycle, including fundamental information about natural carbon exchanges between atmosphere, ocean, and the terrestrial biosphere. This information is used to quantitatively predict future changes of atmospheric CO_2 concentration from human activities, such as CO_2 emissions from fossil-fuel burning and land clearing. Subjects of study are fossil-fuel CO_2 emissions; observations of atmospheric CO_2; fluxes among atmosphere, ocean, and biosphere; and global carbon cycle modeling.

Knowledge of atmospheric retention of CO_2 is a key determinant in estimating the atmospheric CO_2 concentration. Research has reduced estimates of atmospheric CO_2 retention from a scientifically-plausible range of 30 to 80% of human-related carbon releases to the atmosphere to a "most likely" range of 50 to 60%. An apparent relationship between global climate and atmospheric retention of CO_2 suggests that the 50 to 60% atmospheric retention may change as global warming continues. An understanding of the global carbon system and its sensitivity to human and climate perturbations is crucial for reliably estimating future increases in the atmospheric CO_2 concentration.

Climate research is directed toward reducing scientific uncertainties and predicting CO_2-induced regional and seasonal patterns of climate change. Subjects of study are climate and geophysical data, climate models and validation, first detection of climate change caused by increasing CO_2, and estimates of CO_2-induced climate change.

Climate research in the 1980s has advanced the scientific knowledge for detecting and predicting possible CO_2-induced climate change. The observational temperature data base has been expanded from only the Northern Hemisphere land area to a global data set. The time series has been expanded to about 130 years. Analyses of the global data suggests that the earth has warmed about 0.5°C during the past 100 to 130 years. However, the warming is not a simple monotonic increase; decades of cooling are also reflected in the data. Details of warming, cooling, and stasis cannot yet be fully explained by existing models, and definitive causes of the warming trend cannot yet be assigned.

Climate models have improved and expanded in number. Model improvements include atmosphere-ocean coupling, which provides for transport and storage of heat, and the source of moisture for GCM prediction of precipitation. Coupled ocean-atmosphere models are now essential for estimating the time rate of climate change.

Models agree well with each other and with data for global average temperature, and all of these models predict a warming for increased CO_2, which is consistent with theoretical expectations. However, models do not agree with each other nor with observed data for small regions; for areas the size of several western states, differences as large as 5°C in predicted average temperature are possible.

Vegetation research determines responses of crops and wild-type vegetation to increased concentration of atmospheric CO_2 and to climate change. Specific objectives are (1) to determine fundamental effects on plant physiology and growth of long-term exposure to elevated CO_2 and (2) to evaluate ecosystem responses to CO_2 in terms of productivity and altered plant and animal composition of ecosystems. Subjects of study include crop and ecological systems with special attention to the

effects of CO_2 on vegetation and the possible effect of CO_2 on the carbon balance of the terrestrial biosphere.

Laboratory and field studies have demonstrated that increased concentration of CO_2 fertilizes plants and improves water-use efficiency. This latter finding is important because lack of water is often regarded as the single most limiting factor for plant growth. These direct effects are obviously important to the Earth's vegetation and cannot be ignored in analyzing CO_2 and climate influences on productivity, structure, function, and plant-animal-microbial relationships of ecological and agricultural systems.

Needed Research. The Department of Energy's goal for the next decade is to improve capabilities to estimate the future composition of the atmosphere so that climate, vegetation, and other resource changes can be predicted on a regional basis.

The understanding of the global carbon system needs to be improved.

- Future increases in fossil-fuel carbon emissions may equal or surpass the natural rates of carbon exchange among the atmosphere, the oceans, and the terrestrial biosphere. The sensitivity of the global carbon system, and hence the sensitivity of atmospheric CO_2 retention, to perturbations of such magnitude is not now known.

- Gradual warming of the global climate in the order of several degrees centigrade may affect the ability of the atmosphere to retain CO_2, thus casting some doubt that the present 50 to 60% range for atmospheric CO_2 retention will apply over the foreseeable future. The global carbon system-climate system relationship must be further elucidated.

- Oceans are primary carbon reservoirs; however, models do not systematically treat transfer and storage of CO_2 in oceans nor the possible return of CO_2 to the atmosphere if oceans warm.

The knowledge of the global climate system needs to be improved.

- Causes of the differences among the models and between the data and the models' predictions need to be understood. This reconciliation is essential to expedite model advancement for regional applications.

- Ocean heat storage capacity may to be delaying the observation of greenhouse-induced climate change. Current coupled atmosphere/ocean models are not adequate to estimate this delay. Continued ocean measurements (e.g. the World Ocean Circulation Experiment, WOCE) and ocean model development are required. DOE will concentrate on coupled model development and diagnosis.

- Clouds can counteract or enhance the greenhouse effect but are only included in the climate models in a rudimentary manner. Improved cloud data and improved cloud modeling capabilities are required for accurate representation of hydrology in climate as well as of cloud/radiation relationships.

Research is needed to understand greenhouse effects on vegetation.

- Experiments are needed to evaluate simultaneous effects (including interactions) of CO_2 and climate variables on vegetation (e.g., what net changes in productivity they produce).

- Biophysical models for representative plants and vegetation need to be developed and tested.

- New field experimental data should be collected to confirm laboratory results and model simulations.

The ultimate goal of the Carbon Dioxide Research Program is to provide adequate scientific knowledge to government and others for identifying responses to the greenhouse effect (i.e., climate change, CO_2 fertilization,

and their simultaneously induced influences on natural and human resources). For obvious practical reasons, the research payoff must consider regional properties and processes.

Climate, vegetation, and other resources exhibit regional characteristics. For example, the southwest is generally hot and semi-arid with limited surface water resources, whereas the northwest is cool and moist and possesses plentiful surface water. Climate change may be apparent globally, but is expected to influence regional climates non-uniformly (e.g., to produce larger changes at higher latitudes). As a result, the aggregate influence of the greenhouse effect on the nation's resources will be the sum total of differential effects on resources in a wide range of regions.

Developing a successful national response to the greenhouse effect must account for regional differences in climate, the associated resources and their uses, and the differential influences of the greenhouse effect on climate and resources in different regions. Moreover, some responses are likely to evolve at regional scales and could influence the development, selection, and implementation of *national policies* for coping with the global greenhouse effect. For example, renewable energy may be a preferred alternative to fossil fuels in the southwest if climate change permits the practice of large-scale agriculture and passive solar utilization. However, renewable-energy alternatives may not be viable if climate change promotes industrialization as a replacement for agriculture.

Carbon Dioxide Research Approach. Major emphasis of efforts to date has been placed on three topics: global carbon, climate research, and vegetation research.

Accompanying the entire CO_2 research program is a continual effort to communicate the resulting information to interested members of the research and policy-making communities.

Distribution of Research. Because of the diverse types of research needed to meet the objectives of the research program, a wide range of research institutions and agencies is participating. DOE is supporting leading scientists in universities, the national laboratories, private industry, and other government agencies. The distribution of research funds to types of research institutions by fiscal year and for the overall program is presented in Fig. 1.

Level of Effort. Research sponsored by the CDR Program has increased steadily since its beginning in FY 1978 when $1,479,000 was made available for program development and research. By FY 1989, the budget reached $17,369,000. The distribution of research funds to research areas by fiscal year and for the overall program is presented in Fig. 2.

Organization of the Program Summary. Descriptions are provided for all projects funded by DOE under annual contracts in FY 1989. Each description contains the project's title; three-year funding history (in thousands of dollars); the contract period over which the funding applies; the name(s) of the principal investigator(s); the institution(s) conducting the projects; and the project's objectives, products, approach, and results to date.

Project descriptions are categorized within this report according to program areas: global carbon, climate research, vegetation research, resource analysis, scientific interface, and integration and evaluation. Within these categories, the descriptions are presented alphabetically by principal investigator. Each program area is preceded by a brief text that defines the program area, states its goals and objectives, lists principal research questions, and identifies program managers and/or principal scientists.

Indexes and Keywords. This document has been indexed to aid the reader in locating research topics, participants, and research institutions in the text and the project descriptions. Comprehensive subject, principal investigator, and institution indexes are provided at the end of the text for this purpose. The comprehensive subject index includes keywords from the Introduction and chapter texts in addition to those from the project descriptions.

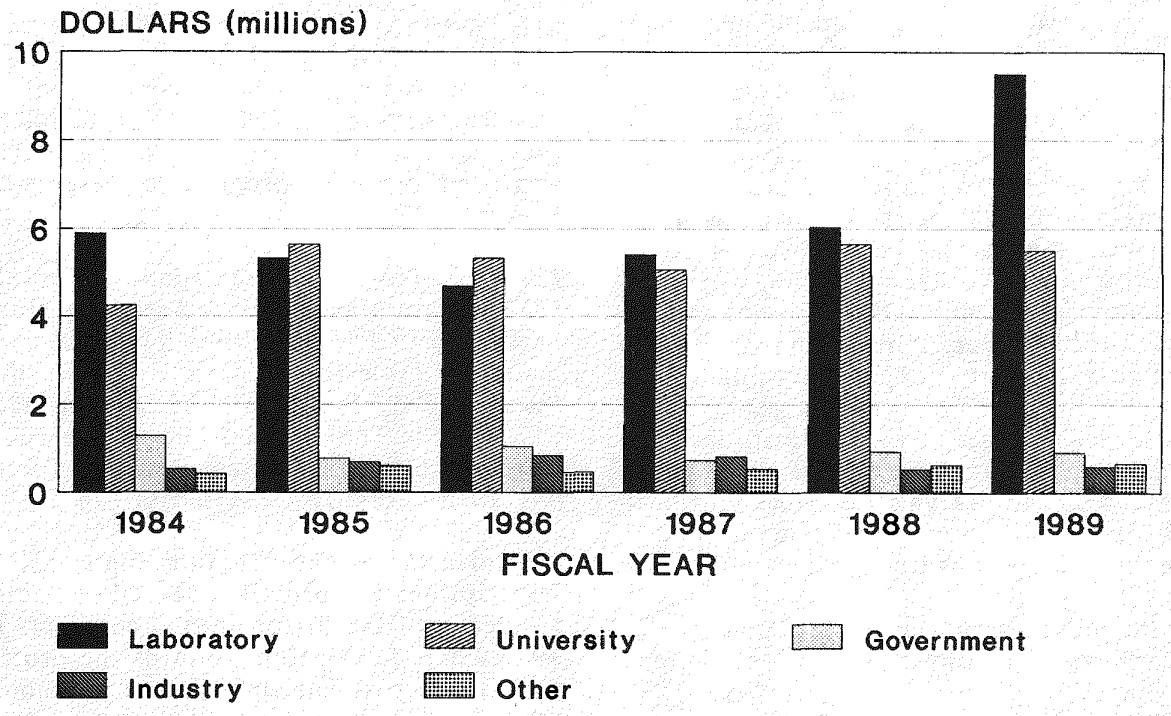

Figure 1. Carbon Dioxide Budget History by Type of Institution.

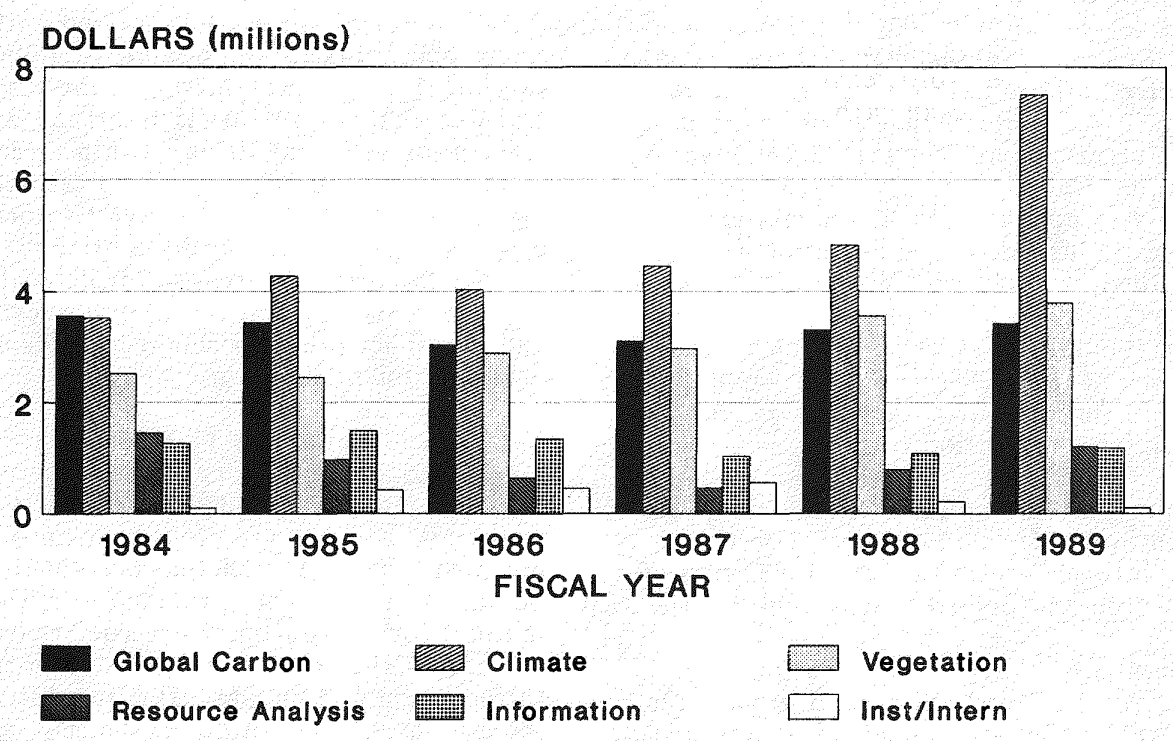

Figure 2. Carbon Dioxide Budget History by Research Category.

GLOBAL CARBON RESEARCH

The global carbon area covers research conducted in three domains: carbon cycle, energy emissions, and energy technology. The goal of the Energy Systems area is to make and bound forecasts of future concentrations of CO_2 in the atmosphere. The pursuit of this objective requires research to understand the natural systems that govern the presence of CO_2 in the atmosphere including the oceans, the terrestrial ecosystem, and the mechanisms that determine the exchange rates of carbon with the atmosphere; the technologies for recovering and sequestering CO_2 emissions; the relationships among technology, economics, geology, and other factors in determining fossil-fuel use and emissions of CO_2 and other greenhouse gases; and the technologies for producing, transforming, and using energy.

During the past decade, significant progress has been made in all three areas. Major studies have measured the current and historical release of CO_2 from fossil-fuel use, examined the effects of existing and possible future technologies on global CO_2 emissions, estimated the uncertainty surrounding future global fossil-fuel CO_2 emissions, estimated the sizes of carbon reservoirs, examined the components of the ocean carbon cycle, estimated fluxes between the terrestrial biosphere and the atmosphere, and integrated components of the carbon cycle into global models.

Despite a decade of substantial progress, major uncertainties remain in all three components of the carbon cycle and energy research.

Research Objectives The current program is designed to take the next step beyond the State-of-the-Art inventory of our current knowledge about the carbon cycle. It is aimed at implementing recommendations to increase our knowledge and understanding of the carbon cycle, as perturbed by energy emissions, and the impact of energy technology advances on it so that we can project atmospheric concentrations of CO_2 with greater confidence. The overall goal is the best possible projection of future atmospheric CO_2 concentrations. More-specific objectives are (1) to reduce the uncertainties in the various parts of the carbon cycle, (2) to develop the capability to project energy emissions of CO_2, (3) to identify technological developments that could reduce CO_2 emissions, and (4) to develop suitable models for projecting atmospheric concentrations of CO_2.

Research Questions In the carbon-cycle area:

- Will the assumption that carbon-cycle processes will remain unaltered by future atmospheric CO_2 levels cause significant errors in atmospheric CO_2 projections? What additional knowledge of carbon-cycle processes is needed to accurately estimate the contribution of fossil-fuel burning to the level of CO_2 in the atmosphere? Although fossil-fuel emissions appear to dominate the carbon-cycle processes that regulate atmospheric CO_2 concentrations, are there any other significant sources or sinks for carbon that must be considered, and if so, what are they and their ramifications?

In the energy-emissions area:

- What are the scientific, technological, and socio-economic data needed to make assessments and projections of energy emissions? What will be the contributions of individual countries to atmospheric CO_2 emissions in the future? What are future global emissions of CO_2 and other radiatively important gases (RIGs) expected to be? What is energy's contribution to CO_2 and other RIGs relative to other human activities, such as land-use change, agriculture, and manufacture?

In the energy-technology area:

- What is the potential for improvement in useful energy output from fossil-fuel technologies compared to their levels of CO_2 emission? What effects on CO_2 emissions might improvements in energy and environmental control technologies have? What energy- efficiency profiles are expected for fossil-fuel, renewable, and other energy technology mixes for major fossil-energy-using nations? What effects are such improvements in energy and environmental-control technologies and changing energy systems expected to have on CO_2 emission levels?

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DEVELOPMENT OF A 3-D MODEL OF THE NATURAL CARBON CYCLE IN THE OCEAN AND ITS PERTURBATION BY ANTHROPOGENIC CARBON DIOXIDE

BACASTOW, ROBERT B.

SCRIPPS INSTITUTION OF OCEANOGRAPHY

FY 1989	100
FY 1988	86
FY 1987	157

11/01/89-02/28/90

Objective: To develop and verify a three-dimensional (3-D) transport model of the natural carbon cycle in the world's oceans. The model will be used to estimate the uptake of anthropogenic CO_2 by the oceans and to better understand the relationships among the oceanic biota, oceanic circulation, and atmospheric CO_2 level.

Product: The principal products will be a 3-D model of the carbon cycle in the oceans and a better understanding of the capability of 3-D models to predict future atmospheric CO_2 levels.

Approach: A 3-D oceanic transport model is being developed by modifying a model of the natural carbon cycle in the oceans already developed in collaboration with E. Maier-Reimer and Klaus Hasselmann of the Max Planck Institute for Meteorology in Hamburg, Germany. The model is based on ocean currents from a dynamic general circulation model of the world's ocean waters. These ocean currents advect nutrient (phosphate or nitrate), total dissolved inorganic carbon, alkalinity, and oxygen, all of which are important to the oceans' carbon cycle, and also ^{13}C and ^{14}C, which are important for diagnostic purposes. Mixing takes place through numerical diffusivity, which arises from the discretization required by numerical models, convective overturning, and a very small horizontal diffusivity. Photosynthesis mainly drives the chemical distributions in the model. Detrital material from photosynthesis sinks to deeper water, where it remineralizes and is returned to the surface layer by circulation of the water. At the ocean surface, CO_2 exchanges across a resistive film with an atmosphere represented by a well-mixed box. Validity of the model is judged by comparing predicted chemical distributions to observed chemical distributions.

Results to Date: The horizontal structure of the large-scale circulation is qualitatively realistic. The vertical circulation field, which essentially comes from differentiating the horizontal field, is less realistic. Chemical tracer distributions indicate too much vertical convective mixing in the southern oceans relative to the North Atlantic. The ^{14}C

depletion is a little too large in the Atlantic and a little too small in the Pacific. Uptake of fossil fuel CO_2 since the advent of the industrial revolution is close to the uptake of the box-diffusion model calibrated by natural ^{14}C. Deconvolution of the ice-core plus Mauna Loa records gives a land biota source to the atmosphere from forest clearing etc. that, when compared with direct estimates, supports CO_2 fertilization of the land biota. Predicted oceanic distributions of phosphate and dissolved oxygen are more realistic if some of the new production flux is advected as dissolved organic carbon than if it all falls vertically.

EXCHANGES OF CARBON BETWEEN THE ATMOSPHERE AND TERRESTRIAL ECOSYSTEMS AS A RESULT OF LAND-USE CHANGE

BROWN, SANDRA, and LUGO, ARIEL

UNIVERSITY OF ILLINOIS and
UNIVERSITY OF PUERTO RICO

FY 1989	83
FY 1988	80
FY 1987	0

08/31/89-05/14/90

Objective: (1) To determine geographically referenced biomass estimates of different tropical forest types (wet to dry, undisturbed, logged, and secondary). Emphasis will be on forests of south and southeast Asia.

(2) To summarize and integrate data on net primary productivity (NPP) of tropical forests and to incorporate that data into a geographically referenced data base.

(3) To explore whether the information contained in the spatial and temporal variations in the NDVI (normalized-difference vegetation index) data base can be used to describe variations in biomass within tropical forested landscapes.

(4) To evaluate and synthesize the current year's research.

Objectives (1) and (2) represent the major part of our effort in this research program, accounting for 90%. Objective (3) will be done in cooperation with Inez Fung who has major responsibility. Objective (4) will be done in cooperation with several other researchers (Houghton, Fung, Hall, Richards, Skole, and Moore).

Product: (1) A method for converting different types of structural data for forests (inventory of trees by species, diameter, and height from plots of known size; stand and stock tables from large-scale forest inventories; stand tables only; and total commercial volumes of forests) into biomass estimates for all the tropical region; more-accurate and -precise biomass estimates for tropical forests in South and Southeast Asia, geographically referenced; preliminary models for predicting forest biomass for areas where no information is available using the Geographic Information System (GIS); and a revised estimate of the biomass of tropical forests for all tropical countries based on the commercial volumes reported in FAO publications and new expansion factors.

(2) A method for converting different types of forest data into estimates of net primary productivity (NPP) and a geographically referenced data base of NPPs of tropical forests in south and southeast Asia.

(3) Details for this objective are given under the research summary of Inez Fung.

(4) Details for this objective are given under the research summary for R. Houghton.

Approach: (1) Components of the method for estimating biomass of forests have already been established under prior support and include the development of biomass regression equations and application to detailed forest-plot data for calculating expansion factors (total biomass to commercial biomass). This method has been applied to stand tables produced during forest inventories, and the resulting biomass estimates have been compared to the commercial biomass obtained from corresponding stock tables. A comparison of the resulting expansion factors with those determined from previous work established that this method is valid. All possible data sources useful for estimating biomass will be gathered from the literature and subjected to the methods described above. We will also develop a method to use forest-inventory data that only includes trees down to a minimum

diameter of greater than 30 cm and we will apply it to a more extensive inventory data set. All resulting biomass values will be geographically referenced and entered into the GIS. Although the data base described above is vast, there will still be areas for which no data are available. To fill these gaps, we will develop relationships between biomass and climate type, soils, slope, elevation, etc.

Results to Date: (1) A paper "Biomass Estimation Methods for Tropical Forests with Applications to Forest Inventory Data" by Brown, Gillespie, and Lugo has been accepted for publication in *Forest Science*. This paper deals with biomass estimation from information commonly available from forest inventories. A discussion of the development and application of biomass regression equations and ratio estimators is given. Point and interval biomass estimates are made using data from four tropical countries (Malaysia, Sri Lanka, Cameroun, and French Guiana). New expansion factors (ratio of total above ground biomass to commercial biomass) were developed from these data and were found to be negatively exponentially related to the mean diameter of the stand. These expansion factors were used to calculate a new weighted estimate of the biomass of all tropical closed forests based on the commercial volume data reported by the FAO (a new estimate for undisturbed closed forests = 192 t/ha versus the old estimate of 150 t/ha).

(2) A paper "Estimation of Stem Frequencies from Truncated Stand Tables in Tropical Moist Forests" by Gillespie, Brown, and Lugo has been submitted to the *Canadian Journal of Forest Research*. Methods are presented in this paper for estimating numbers of stems, volumes, and biomass in small diameter classes (10 to 30 cm) when such diameter classes are not recorded in inventories. We show that such trees can account for 20 to 40% of the total aboveground biomass in tropical moist forests.

(3) A geographically referenced data base of biomass estimates (mean and 99% confidence interval) for forests in south and southeast Asia has been compiled based on our methods. These estimates are based on large-scale commercial forest inventories and were carried out under a statistically sound sampling design. The inventories cover parts of Bangladesh, Burma, Cambodia, India, Malaysia (Peninsula and Sarawak), the Philippines, Thailand, and Vietnam. The data for each country include a table of biomasses (t/ha) for the different forest types, area (ha) of forests inventoried, source of data, geographic reference (coordinates and/or maps), and information about the environment and inventory. This data base provided approximately 150 point and interval estimates of biomass for tropical moist forests and about 10 for tropical dry forests. Most of the moist-forest biomass estimates were between 100 and 250 t/ha, and most of the dry-forest estimates were between 50 and 100 t/ha. A paper on these results is in preparation for submission to the *Canadian Journal of Forest Research.*

(4) A geographically referenced data base on NPP (aboveground; sum of fine litter production and wood production) of tropical forests of south and southeast Asia was compiled. This data base is small (14 estimates) because few studies on the NPP of tropical forests have been made. More than half of the NPP estimates are based on actual results of the studies, and the rest are based on estimates of litterfall and ratios of wood production to litterfall. The NPP values range from 9.0 to 17.1 t/ha-yr for humid forests and from 6.0 to 7.2 t/ha-yr for dry forests.

ENERGY END-USE PATTERNS AND ENERGY TECHNOLOGIES IN MAJOR CO_2-EMISSION COUNTRIES

CHENG, HSING C., and
STEINBERG, MEYER

BROOKHAVEN NATIONAL LABORATORY

FY 1989	200
FY 1988	200
FY 1987	200

10/01/88-09/30/89

Objective: To obtain a better understanding of energy end-use patterns and energy technologies in major CO_2-producing countries, to shed light on energy efficiencies in these countries, and thus to estimate the potential fossil fuel savings and associated global CO_2 emission reductions through the use of improved energy technologies.

Product: A report will document the characterization and related data of energy use and technologies by end-use sector and fuel type for a group of important CO_2 emitting countries, and will summarize the comparisons of energy efficiency among these countries.

Approach: One task is to develop a data base on energy uses and technologies in major CO_2 producing countries. The main emphasis will be on the identification and characterization of the present energy technologies used in these countries. Three benchmark years to be studied are 1975, 1980, and 1885. Requisite energy information on these countries will be collected through detailed research and study of a wide variety of information sources. These sources include, but are not limited to, the United Nations, the World Bank, the International Energy Agency, and the Energy Information Administration of DOE. The energy uses and technologies will be presented for three end-use sectors: residential and commercial, transportation and industrial, and electricity generation. With this information, the potential fossil-fuel savings and associated global CO_2 emission reductions resulting from improved energy technologies can be made. This task will be performed in close cooperation with the energy emission study of Battelle Pacific Northwest Laboratories.

The other task is to devise a systematic approach of coal refining to use coal without producing CO_2 emissions.

Results to Date: U.S. CO_2-emissions reduction potential from energy conservation and the substitution of natural gas for coal in the period to 2010 has been analyzed.

Energy end-use data has been developed for 1975, 1980, and 1985 for the major CO_2 producing countries including U.S., U.S.S.R., China, Japan, Federal Republic of Germany, United Kingdom, Canada, France, Italy, and Australia. These data include electricity generation and energy use in (1) the residential and commercial and (2) the transportation and industrial sectors.

A systematic design that includes energy and material balances has been developed for converting coal to carbon black and hydrogen. Such a process could result in zero CO_2 emissions from the use of coal.

An option has been developed for the coal industry in dealing with the CO_2 global greenhouse effect, including estimates for reduced-CO_2-emission technologies.

ENERGY AND FUTURE CARBON DIOXIDE EMISSIONS

EDMONDS, JAMES A.

PACIFIC NORTHWEST LABORATORY

FY 1989	300
FY 1988	300
FY 1987	335

10/01/88-09/30/89

Objective: To develop the scientific basis to make and bound projections of future energy-related emissions to the atmosphere of carbon dioxide and other radiatively important gases.

Product: 1. The DOE will receive support in its participation in the Intergovernmental Panel on Climate Change, Response Strategies Working Group, Energy and Industry Subgroup (IPCC/RSWG/EIS).

2. The theoretical structure will be developed for a revised energy-economic model of CO_2 and other radiative precursor emissions, and the initial development of a model code will be completed.

3. A global, disaggregated, energy production and use data base will be completed for the years 1975, 1980, and 1983. It will be consistent with the revised long-term, global energy-economic model. This work is to be coordinated with the Brookhaven National Laboratory (BNL) and the Oak Ridge National Laboratory and will complete work begun on the development of this data base in FY 1987.

4. The observed differences in aggregate energy intensity between the U.S. and Japan will be analyzed.

5. The relationship between energy production and use and the release of methane to the atmosphere will be examined. This project will complete work begun in FY 1988.

Approach: 1. Quantitative support will be provided for DOE participation in the IPCC, and IPCC/RSWG/EIS meetings will be attended.

2. The Edmonds-Reilly model will be revised to improve the representation of energy supply and the interaction of energy and GNP.

3. The global, disaggregated, energy production and use data base for the years 1975, 1980, and 1983 that is consistent with the revised long-term, global energy-economic model will be completed. Two data bases will be developed: Primary and Internally Consistent. The Primary energy data base refers to a data base that is traceable to primary source material. Because no international group collects data for all countries that includes end-use energy detail, primary data sources are in general not consistent with one another. The Internally Consistent data base resolves inconsistencies between alternative primary data sources, but is not necessarily traceable to specific primary data sources. An internally consistent data base is necessary to benchmark the second-generation model.

4. Comparable data will be developed for the U.S. and Japan and a common set of measurements used to compare energy use and efficiency in the residential and commercial and the industrial and transportation sectors. This study will consider cultural, geographic, and other differences between these two countries that help to explain differences in energy intensity.

5. Methane emissions from four energy-related activities will be analyzed: (1) natural gas production and transport; (2) deep-mined coal; (3) energy combustion, including traditional biomass fuel use; and (4) landfill sources. Methane emission rates will be developed for each of these activities, and emission coefficients will be combined with rates of energy production to develop estimates of annual energy-related methane emissions.

Results to Date: 1. Support was provided for the DOE in preparing for and during the IPCC/RSWG/EIS Experts meetings of Bildhoven, the Netherlands, and Tokyo and in meetings in Paris and Geneva. Served as rapporteur to the Tokyo meeting. Made presentations to the Paris, Geneva, and Tokyo meetings. Headed ad hoc committees in Paris and Geneva.

2. The original version of the Edmonds-Reilly model has been modified to improve the representation of the energy-GNP feedback relationship, the description of nuclear power supply, and the representation of tax policies. Work on the Second Generation Model was begun in coordination with the Office of the Director of Environmental Analysis (EH) with the development of the capital module.

3. The global, disaggregated, energy production and use data base for the years 1975, 1980, and 1983 was completed and submitted to the Carbon Dioxide Research Program.

4. The report *A Comparison of Energy Intensity in the U.S. and Japan* was completed and submitted to the Carbon Dioxide Research Program. This report concludes that, while the energy intensity to gross national product ratio is smaller by half in the U.S. than it is in Japan, this ratio reflects a number of important factors unrelated to energy efficiency. Much of the difference in energy consumption per capita in the residential sector between these two countries, for example, can be explained by differences in the amount of residential space per capita and the number of heating degree days. Differences in the mix of transportation modes used in Japan and the U.S., rather than significant differences in the efficiency of those modes, explain most of the differences in energy consumption per passenger- (or tonne-) kilometer. Energy intensity in the industrial sector is higher in the U.S. than in Japan, but these differences are less than a factor of two. Unambiguous measures are difficult to obtain in light of exchange rate fluctuations without resorting to a highly detailed energy analysis based on physical measures of output.

5. The report *An Evaluation of the Relationship Between the Production and Use of Energy and Atmospheric Methane Emissions* was completed and submitted to the Carbon Dioxide Research Program. This report finds that emissions from natural gas production and distribution are likely to be approximately 40 Tg/year (near the mid-point of other estimates), from coal mines to be approximately 25 Tg/year (near the bottom of the range of other estimates), from direct combustion of fossil fuels to be negligible, from fuelwood and bagasse combustion yields to be significant (12 Tg/year), and from landfills to be 51 Tg/year (the largest single energy-related source of methane release to the atmosphere). Landfills are energy related both in the sense that the organic material is a potential source of fuel

for solid waste combustion and in the sense that the methane released from the landfill is a potential direct source of natural gas.

CARBON CYCLE PROGRAM MANAGEMENT

FARRELL, MICHAEL P.

OAK RIDGE NATIONAL LABORATORY

FY 1989	1529
FY 1988	205
FY 1987	250

10/01/88-09/30/89

TASK I: GLOBAL PATTERNS OF NET ECOSYSTEM PRODUCTION (W. M. Post)

Objective: To determine global patterns of terrestrial production, turnover, and dynamics of organic matter in relation to climate and geography.

Product: Data on aboveground and belowground litter, standing crop, and production will be collected from published literature and analyzed. The data base will be documented and made available to the Carbon Dioxide Information Analysis Center.

Approach: In forest ecosystems, more than 90% of NPP becomes litter and decomposes on the soil surface or in the soil. Thus, litter production is a good indicator of NPP. The ratio of litter production to litter mass indicates the turnover or decomposition rate of ecosystem production. The litter production, mass, and turnover in relation to the amount of soil organic matter gives an indication of the long-term dynamics of soil organic matter. An additional benefit of this approach is that these ecosystem properties are easier to measure than NPP, and as a result many more measurements of them have been taken than for NPP.

This study will assemble and analyze data on litter production (aboveground and belowground) and litter mass from locations worldwide. Most of these data will be from the biogeochemically important forest ecosystems. Compilation and analysis of the data will be compatible with available soil organic matter data thereby linking the production of living biota with decomposition and storage dynamics in soils. Climate factors that modify and contribute to organic-matter cycling and accumulation on a worldwide basis will be emphasized.

Results to Date: A library search has yielded more than 400 papers that contain litter production and/or mass data for more than 5000 locations worldwide. Computation of the data into standard units and compilation of ancillary data (latitude, longitude, altitude, soil order, climate, ecosystem designation, nitrogen, phosphorus, cations, etc.) has been completed for about 10% of the data. A computerized relational database is being used to record the information. Not enough data has been entered into the computer yet to allow preliminary analyses of the data.

TASK II: ESTIMATES OF CO_2 EMISSIONS FOR FOSSIL-FUEL BURNING AND CEMENT MANUFACTURING (G. Marland)

Objective: To determine and evaluate global, regional, and national estimates of CO_2 emitted to the atmosphere from fossil-fuel consumption, natural gas flaring, and cement manufacture for the years 1950 to 1987.

Product: A data base of carbon dioxide emissions by country, year, and fuel type, which is carefully documented and available on magnetic tape will be compiled. Also, open-literature publications that analyze the regional and temporal trends and their significance with respect to energy systems and global climate change will be identified.

Approach: The basic data set has been maintained and updated since the late 1970s. It is important to provide annual updates and a continual assessment of data quality and opportunities for improvement. The data set has relied on energy statistics from the U.N. Statistical Office plus cement statistics from the U.S. Bureau of Mines. This year we have, for the first time, included by country estimates of CO_2 emissions from gas flaring. This additional data relied primarily on the U.N. data set. That data set was subjected to a detailed evaluation of its completeness and comparisons with other sources of data. These efforts suggested the inclusion of some data from other sources plus in-house estimates of some important and obviously missing entries. It is also becoming increasingly apparent that other sources of energy data exist and that we must understand where and why our CO_2 emis-

sions estimates differ from what would have been derived from other sources of energy data. As part of a formal agreement reached with the U.N., CDIAC continues to perform quality-assurance reviews of the U.N. energy data set and to advise the U.N. on components needing reexamination. The data set also now incorporates U.N. population data so that per capita emissions data can be generated routinely.

Results to Date: The data set, including gas-flaring estimates, is now complete through 1987 and has been released to numerous scientists and policy makers around the world. It has been released in whole and in subsets, in hard copy and machine readable versions.

Analysis of the data by country has to date excluded the gas-flaring data because, like bunkers data, those data often have no relevance to internal energy consumption. Gas flaring by Saudi Arabia, for example, is more related to global oil trade than to Saudi energy consumption.

The data show that global emissions of carbon dioxide from fossil-fuel burning totaled 5.60 billion metric tons of carbon in 1987, up 1.59% from 5.51 billion metric tons in 1986. This value is slightly over 1.1 metric tons of carbon for every person on earth. The U.S. contribution to this total is 1.22 billion metric tons of carbon (approximately 22% of the world total), which amounts to just over 5 metric tons of carbon per capita. U.S. emissions increased 1.87% from 1986 to 1987 in contrast to a 0.42% increase in Western Europe and a 6.35% increase in south and southeast Asia.

Global emissions of carbon dioxide from fossil-fuel burning climbed steadily until the energy crisis of 1973 and the oil price jumps of 1978 and 1979 stalled world growth in energy use and carbon dioxide emissions. The rate of emissions stalled in 1974 and 1975 and dropped from 1980 to 1983. Now 1987 represents the fourth consecutive year of growth. The largest rate of growth during the past four years has been in emissions from burning natural gas, the fuel that actually discharges the least carbon dioxide per unit of useful energy. Emissions from natural gas have risen 47% since 1973, while emissions from solid fuels have grown by 43% and emissions from liquid fuels have been virtually constant (2% total growth) during the 15 years. Although emissions from the U.S. have nearly doubled (1.8 times) since 1950, the U.S. share of total global emissions has declined from 42% in 1950 to 22% in 1987 because other areas of the earth have been experiencing higher growth rates. It is still true, however, that collectively three countries (the U.S., the U.S.S.R., and China) accounted for more than 50% of global carbon dioxide emissions in 1987.

Task III: MODELING THE OCEAN VENTILATION AND PREDICTION OF ATMOSPHERIC CONCENTRATION IN THE OCEAN-ATMOSPHERE SYSTEM (T. H. Peng)

Objective: To understand and to establish the relationship between the level of atmospheric CO_2 concentration and the patterns and rates of ocean ventilation in the ocean-atmosphere system. The role of changing ocean circulation in controlling the distribution of carbon in the ocean-atmosphere system will be studied so that the recent increase in atmospheric CO_2 level will be better understood in terms of both the increase caused by the natural processes and the oceanic feedback processes caused by the CO_2 increase.

Product: The principal products will be a ten-box geochemical model of the global oceans for the natural carbon cycle and a better understanding of the role of ocean in controlling the level of atmospheric CO_2 concentration, both in a natural carbon system before human disturbances and in a perturbed carbon system of recent centuries produced by anthropogenic activity.

Approach: Measurements of polar ice cores revealed that the atmospheric CO_2 concentration increased substantially (from about 200 to 280 ppmv) between glacial and Holocene time. Research indicates that the causes of the CO_2 change must lie in the sea and the most critical waters of the ocean are those at the surface in polar regions. Hence, an ocean model needs to be developed based on the principles that the CO_2 partial pressure of surface waters in the polar ocean dominates that of the warm surface ocean and that of the atmosphere. Most existing scenarios call on decreases in the concentrations of the nutrients in polar surface waters. However, the cadmium content of planktonic foraminifera from polar regions, which represents the nutrient concentration in the past, did not

decrease from glacial to Holocene time. A new hypothesis is needed that requires the rise of alkalinity in polar surface waters. This requirement can be met by changes in ocean circulation and ventilation rates responding to climate changes.

A ten-box geochemical model of the global ocean will be developed with various patterns of ocean circulation. Emphasis will be placed on the formation and the demise of North Atlantic Deep Water (NADW), which is considered to be a major force in ocean circulation. A natural carbon cycle will be incorporated to study the natural rise and fall in atmospheric CO_2 level responding to changes in circulation and ventilation rates.

Results to Date: The ten-box geochemical model of the global oceans, named PANDORA, has been developed and verified with the distribution of ^{14}C and nutrients. It consists of four boxes for the Atlantic Ocean, with one box representing the northern source region of NADW, one warm surface box, one thermocline box, and one cold deep box. The Antarctic Ocean is represented by two boxes, surface and deep. Four boxes represent the combination of the Pacific and Indian oceans, with one northern box, one warm surface box, one thermocline box, and one cold deep box. Ten circulation patterns are devised with strong interaction taking place in the Antarctic surface waters. Test runs for the temperature distribution show that these patterns are quite reasonable for simulating temperatures of the deep waters. Carbon chemistry and carbon isotope distribution responding to circulation changes are yet to be implemented and tested.

Task IV: INTEGRATING TRANSPORTATION MODELS AND ECOLOGICAL THEORY TO ESTIMATE DEFORESTATION IN BRAZIL (V. H. Dale)

Objective: To combine transportation models and ecological understanding of the areas of forested land and its associated carbon into a prediction of land-use changes and the estimation of the magnitude of changes that can be expected under certain road-establishment patterns. The long-term goal of this study is to explore the reliability with which transportation theory can be used to estimate land-use changes in Brazil and to test the predictions with remote imagery and past land-use information.

Product: This project will

* demonstrate a linking of socioeconomic models and ecological models critical to understanding the impact of humans on the environment,
* provide the ability to predict patterns and rates of tropical deforestation in the aftermath of road establishment, and
* establish critical connections with Brazilian and remote-sensing scientists that are essential for addressing global environmental issues.

Approach: Brazil contains the largest area and biomass of tropical forest, but those forests are being cleared at an increasing rate. Much of the deforestation results from road development and the associated clearing for agriculture. Road development is an outgrowth of government policies to open new regions for development and redistribute population and economic activity. Roads are financed by the Brazilian state and federal government as well as by international loans.

The approach involves two major tasks: data collection and integration and model development and testing. Studying the effects of road development on deforestation requires data on population growth and economic activity by sector, road development, environmental conditions, land-use changes, and deforestation. The data will be assimilated into geographic information systems so that spatial relations can be analyzed with software and hardware already available in the Environmental Sciences Division. However, some software procedures will need to be developed to allow the integrated use of the available SAS, ARC/INFO, and ERDAS software. Expanding these capabilities will put ORNL into a unique position in being able to handle and analyze spatial data.

The model will relate geography, transportation, and ecology. The first phase of model development and testing involves quantification of the relationships among deforestation, different kinds of road networks, and land uses. The initial effort will be to develop these relationships for Rondonia, Brazil, where road access has opened the area for settlement and deforestation. Subsequent efforts will consider other types of land uses, such as mining, lumbering, or cattle ranching. The second phase is to test the model predictions of deforestation against measures of deforestation

based on remote sensing. The third phase will be to project the extent of deforestation that would result if a new road development were undertaken for similar purposes. This phase will include development of a road-design/forest-management model and comparison of its projections with those for unmanaged road development.

Results to Date: A report has been drafted that surveys the causes of deforestation in Brazil, concentrating on Rondonia. Contacts have been established with Brazilian scientists and remote-sensing scientists who have obtained the most recent measures of deforestation in Brazil.

Task V: AN INTERMODEL COMPARISON OF GLOBAL CARBON CYCLE MODEL RESPONSE TO THE HISTORICAL RELEASE OF CO_2 ASSOCIATED WITH CHANGES IN LAND USE (A. W. King and W. R. Emanuel)

Objective: To evaluate the contribution of uncertainty in historic CO_2 emissions that accompanied past land-use changes to uncertainty in model projections of future atmospheric CO_2.

Product: (1) A documented comparison among several global carbon cycle models of how alternative histories of CO_2 emissions from changes in land use influence the correspondence between model simulation and observations of historic atmospheric CO_2 from ice-core records and extant monitoring. (2) An assessment of how current revisions in land-use emissions influence model simulation of past and future atmospheric CO_2.

Approach: This research is part of a larger project comparing projections of atmospheric CO_2 among several global carbon cycle models and the uncertainties that contribute to uncertainty in those projections. Each model in the collection (which samples the history and variety of existing compartment-style global carbon cycle models) will be used to simulate historic concentrations of atmospheric CO_2 using the models' original initial conditions, parameters, and inputs from industrial and biospheric land-use-change sources. The simulations will be compared with proxy observations from the Siple ice-core and the monitoring record from Mauna Loa Observatory. The year and magnitude of the assumed preindustrial equilibrium atmospheric CO_2 concentration and the history of industrial emissions will then be standardized across models (the original land-use emissions will be retained), and the simulations and comparisons with observations will be repeated. A series of simulations with standard alternative land-use emission histories will then be compared among models and with the historic observations. Analysis of this sequence of simulations will be used to assess how alternative estimates of historic land-use emissions influence model simulation of historic atmospheric CO_2 and model projection of future concentrations. At the same time, the combined models' abilities to incorporate a specified land-use emission history will be used to evaluate and compare land-use emission histories.

Results to Date: Model simulations that have been run reinforce earlier assessments that, given the current understanding of atmosphere-ocean CO_2 exchange represented in existing compartment-style global carbon cycle models, there exists a significant incompatibility between the historic records of atmospheric CO_2 and existing estimates of biospheric CO_2 emissions derived by reconstruction of historic carbon storage and land-use change in terrestrial ecosystems. The most recent published reconstructions do not adequately resolve this incompatibility. A published land-use emissions history derived by deconvolution of the ice-core data using the Oescher box-diffusion model provides reasonable correspondence between simulation and observation for many of the models, but model dependency is an obvious concern, and the deconvolution and reconstruction estimates differ significantly. The results suggest the need for continued research in the reconstruction of historic land-use emissions and the need for deconvolutions from a larger sample of models in an effort to resolve this basic incompatibility.

Task VI: TESTING AND COMPARISON OF MODELS FOR ATMOSPHERIC CO_2 FORECASTS (M. J. Sale; H. I. Jager)

Objective: To acquire a number of different carbon-cycle models for use in making future predictions of atmospheric CO_2 concentrations and to subject these models to a standardized testing protocol, including deterministic CO_2 forecasts under alternative emission scenarios, and sensitivity and uncertainty analysis.

Product: Atmospheric forecasting models will be acquired, implemented, tested, and documented within CDIAC with standardized proce-

dures. Individual models will be subjected to quality-assurance testing, to a series of deterministic simulations with uniform fossil-fuel and land-use emissions of CO_2 and to a uniform process of sensitivity and uncertainty analysis. Model performance in response to alternative emission scenarios will be quantified and compared. Models will be archived and maintained for use in future projections and carbon-cycle research.

Approach: The CO_2 forecasting models acquired under this project will be transferred to CDIAC/ORNL computers, where they will be subjected to testing protocols. Whenever possible, models will be converted to a machine-independent format, such as FORTRAN 77, and to the VMS/VAX operating environment. If feasible, microcomputer versions of the models will also be developed. Numerical analysis subroutines will be replaced with equivalent, public-domain subroutines from ORNL's CORLIB or the LINPACK library to facilitate intermodel comparisons. Verification testing of the acquired models will be conducted to assure that the original version is consistent with existing documentation and that the CDIAC standardized version of the model passes minimum performance criteria. The enhanced and verified version of models acquired under the project will be archived at CDIAC and returned to their original developers. The results of the model-acquisition phase of the project will be documented in Model Implementation Reports. Where appropriate, additional documentation in the form of Computer Model Packages will be published.

Following the successful acquisition of each forecasting model, sensitivity and uncertainty analysis will be conducted on the model. Model sensitivity analysis will show the local response of model outputs to changes in model inputs (i.e., dy/dx, where y is an output and x is an input). Model uncertainty will show error/confidence bounds around model outputs caused by uncertainty in model inputs or parameters. Model response to alternative CO_2-emission scenarios will be tested by examining the effects that different emission levels have on forecasting uncertainties. Important information derived from this sensitivity-uncertainty analysis will be a prioritization of model components (inputs and parameters) by their influence on CO_2 forecasts. The sensitivity analysis will also show whether model response (e.g., the importance of individual parameters or inputs to CO_2 forecasts) is consistent with current theoretical understanding of carbon cycles or research priorities. For example, model performance may indicate certain rates of CO_2 exchange have little or no effect on future CO_2 levels; this means that either research on estimating that particular exchange rate should be a low priority or the model structure is flawed.

As additional models are acquired and tested by the project, intermodel comparisons will be conducted. The objective of these comparisons is to quantify the uncertainty in future concentrations of CO_2 that is attributable to differences among forecasting models. Some of the questions that can be answered with this research are: Are some model structures more robust than others? Does the role of inputs or parameters (i.e., contribution to forecast uncertainties) differ among model types? Are the responses of some model types more consistent with theoretical concepts than others are? The products of this research will help establish future research needs for the Carbon Cycle Program and reduce forecasting uncertainties.

Results to Date: The quality assurance, sensitivity-uncertainty analysis procedures, and associated computer protocols for this project were defined in the fourth quarter of FY 1988. Eleven carbon-cycle simulation models were acquired in the past year and are in various stages of testing. All eleven models can be used to make deterministic simulations of future conditions. The first model acquired under the project was the Gardner and Trabalka implementation of the Emanuel et al. model. This model was used as an example to design and demonstrate standardized outputs from the model-acquisition and -testing process. The other models that are being evaluated range in complexity from simple airborne-fraction models to multiple-ocean, advection/diffusion models including primary production.

The modified version of R. H. Gardner's PRISM program for sensitivity and uncertainty analysis was implemented as a principle analytical tool. The GRESS program (Gradient Enhanced Software System developed at ORNL) was also implemented on CDIAC computers as an alternative tool for sensitivity analysis.

The major conclusion from this past year's research is that a significant discrepancy

exists among (1) the historic record of atmospheric CO_2 concentrations, (2) the best-available estimates of CO_2 estimates of CO_2 emissions from land-use changes, and (3) the simulation capabilities of the suite of models we are currently testing. Further model development is needed to produce a forecasting tool that can satisfy the constraints of the historic record and our current understanding of emissions.

TASK VII: CARBON CYCLE PROGAM MANAGEMENT (M. P. Farrell)

Objective: To coordinate the research funded by the DOE's Carbon Dioxide Research Program (CDRP) by developing and managing the carbon cycle research plan within CDRP's carbon cycle program area.

Product: Integrated carbon cycle research developed from the Global Carbon Cycle Research Plan of CDRP's Energy Systems.

Approach: The main objective of the Global Carbon Cycle Research Program is to develop a scientific basis for predicting changes in atmospheric CO_2 concentrations in response to continued releases of CO_2 by fossil-fuel combustion. Research will be concentrated on assembling, integrating, and implementing multidimensional models of the global carbon cycle, which will yield various estimates of atmospheric carbon dioxide when given different levels of fossil-fuel use and other variables relating to biogeochemical dynamics. Specific research initiatives will be focused on 3-D ocean carbon cycle modeling (including biological and ecosystem components), reduction of uncertainties associated with net biotic fluxes produced by land-use changes since 1800, atmospheric and oceanic measurements of seasonal variations in CO_2 concentrations, understanding climate feedback effects on carbon dynamics from northern boreal ecosystems, and analysis and understanding of carbon-cycle models' sensitivities and uncertainties.

SIMULATIONS OF THE CARBON CYCLE IN THE OCEANS

FASHAM, MICHAEL J. R.

INSTITUTE OF OCEANOGRAPHIC SCIENCES

FY 1989	49
FY 1988	43
FY 1987	0

09/30/89-09/30/90

Objective: To develop geographically robust ecosystems models of the nitrogen and carbon flow in the oceanic euphotic zone that can be embedded in global 3-D models for predicting the fate of anthropogenic carbon dioxide releases.

Product: A fully documented description of an euphotic-zone ecosystem model describing the nitrogen and carbon cycles, including estimates of parameter values.

Approach: The existing model of the nitrogen cycle will be tested against other data from various oceanic areas. The model will be developed to investigate the role of size structure in the autotropic and heterotrophic organisms, and the problems of constructing a model linking the carbon and nitrogen cycles will be investigated.

Results to Date: The first version of the ecosystem of nitrogen flows has been formulated and validated against data from Bermuda Station S. A parameter sensitivity analysis of the model has been carried out. The equations of this model have been included in the Princeton 3-D seasonal model of the North Atlantic, and the resulting seasonal simulations of phytoplankton biomass have been compared with CZCS satellite data.

EXCHANGES OF CARBON BETWEEN THE ATMOSPHERE AND TERRESTRIAL ECOSYSTEMS AS A RESULT OF LAND-USE CHANGE

FUNG, INEZ Y.-S.

NASA GODDARD INSTITUTE FOR SPACE STUDIES

FY 1989	75
FY 1988	72
FY 1987	0

08/01/89-08/31/90

Objective: To reduce the uncertainty related to estimates of the net flux of carbon between terrestrial ecosystems and the atmosphere caused by deforestation and other changes in land use.

Product: A justified reanalysis of the net flux of carbon to the atmosphere as a result of land-use changes, especially in the tropics. The reanalysis will involve the use of satellite data and will be consistent with observed concentrations and gradients of atmospheric CO_2.

Approach: Biomass will be estimated from the normalized difference vegetation index (NDVI). Information contained in NDVI variations (spatial and temporal) will be examined to describe the variations of biomass within an ecosystem. This investigation, if successful for south and southeast Asia, will provide a starting point for the inventorying and monitoring of ecosystem biomass on a global basis.

The GISS 3-D model atmospheric transport model will be used to simulate atmospheric CO_2 response to refined estimates of CO_2 fluxes from land-use modification. The modeled concentrations and gradients will be compared with those observed.

The data for south and southeast Asia acquired by Duke University will be evaluated. The evaluation will be based on three analyses: (1) checking the data for internal consistency and attempting to calculate the annual net flux of carbon with them, (2) comparing the carbon flux calculated with this data with the flux calculated previously by different methods, and (3) defining the sample size appropriate for detailed analyses using a Monte Carol approach.

Results to Date: NDVI data have been acquired and mapped at about 15-km resolution for south and southeast Asia. The annual NDVI integral for 1984 has been computed from the weekly composite data. Visual comparison of the NDVI data and a map of forest types of Peninsular Malaysia shows that broad spatial patterns of landscape variations from ground surveys are discernible in the satellite data. The satellite data distinguish between "old" forest regions, poor hill forests, disturbed/logged forests in the lowlands, as well as agricultural areas. This comparison demonstrates that satellite data, even at coarse resolution, remain a useful tool for monitoring large-scale landscape modification.

Reliable biomass estimates for the 11 forest types in Peninsular Malaysia have been obtained by Brown et al. Regression analysis of the NDVI against biomass estimates was carried out for two 1° x 1° cells, one in which "old" forest predominates and one mixed forest and nonforest. The analysis failed to show any statistically significant correlation. The causes of the failure are many, the most important of which is that very little undisturbed forest remains in Peninsular Malaysia. The use of 15-km resolution NDVI data makes it difficult to establish direct spatial correspondence between satellite and ground information. Also, the undisturbed area is too small to test the link among the NDVI, net primary productivity (NPP), and biomass, a link hypothesized to exist for old-growth forests.

For the NDVI to be useful for quantifying biomass variations on the ground, the study must be repeated with fine-resolution (e.g., 4-km or 1-km resolution) NDVI data that have been calibrated and from which atmospheric effects (especially cloud contamination) have been removed. The test region can be Africa or Brazil, where in large extents of primary forest remain for which the assumed relationship between NPP and biomass may hold.

EXCHANGES OF CARBON BETWEEN THE ATMOSPHERE AND TERRESTRIAL ECOSYSTEMS AS A RESULT OF LAND-USE CHANGES

HALL, CHARLES A. S.

STATE UNIVERSITY OF NEW YORK

FY 1989	37
FY 1988	34
FY 1987	0

10/01/89-05/14/90

Objective: To further update the assessment of net carbon exchange between tropical vegetation and the atmosphere resulting from human activities for the entire tropics and other selected regions. Data from a variety of sources (e.g., FAO and other DOE-funded researchers, including J. F. Richards, S. Brown, A. E. Lugo, G. Woodwell, and D. Skole) will be integrated with an existing tropical-land-use and carbon model developed by C. A. S. Hall and colleagues. This year's objectives are to: (1) update the carbon release for 76 countries based on new, updated FAO land-use analyses and new biomass estimates of A. Gillespie and S. Brown, which were derived using new regression relations; (2) try to assess the importance of, and if possible reconcile differences between, the widely divergent estimates of shifting cultivation; and (3) produce disaggregated analyses of carbon release for southeast Asia, including Thailand, Malaysia, and Burma, with region-specific cutting and biomass estimates.

Product: The product will be an analysis of refined estimates of carbon released from tropical land-use change. A sensitivity analysis will be conducted against the benchmark of our 1988 estimates that ranged from 0.42 to 1.55 Gt released per year.

Approach: The existing computer model (GLOBC8) will be used with new estimates of land-use change, (e.g., FAO/UNEP 1981 and FAO/UNEP 1988, John Richards's data, and country-specific data), biomass, and soil-carbon estimates.

Results to Date: To date, our new statistical approaches for estimating biomass have produced an approximately 30% increase in our earlier low estimates of carbon release but not changes in our high values. New FAO estimates of land-use change increased our earlier estimates by about 5%. Uncertainties in estimates of shifting cultivation result in changes in our release estimates that vary from 16% (global, including nontropics) to 27% (Asia and Latin America) to 300% (selected countries in southeast Asia). Our research program is attempting to choose from among the different available estimates.

EXCHANGES OF CARBON BETWEEN THE ATMOSPHERE AND TERRESTRIAL ECOSYSTEMS AS A RESULT OF LAND-USE CHANGE

HOUGHTON, R. A.

MARINE BIOLGICAL LABORATORY

FY 1989	135
FY 1988	130
FY 1987	0

08/01/89-07/31/90

Objective: To improve the accuracy of the estimated flux of carbon to the atmosphere from land-use change in the tropics.

Product: Current estimates of the net flux of carbon to the atmosphere from tropical deforestation and reforestation range between 0.4 and 2.5 x 10^{15} g for 1980. The product of this research will be a reduced range of estimates for 1980 and new estimates of the rates of flux between 1850 and 1980.

Approach: Estimates of the net flux of carbon between terrestrial ecosystems and the atmosphere are calculated with models based on rates of land-use change and on the carbon stocks of the ecosystems involved. New, improved data on both rates of land-use change and carbon stocks are being obtained by other scientists involved in this group research. The data are georeferenced so that the appropriate carbon stocks are assigned to regions of change. The emphasis of the research is on south and southeast Asia, a region that contributes significantly to current and past fluxes of terrestrial carbon.

Results to Date: Preliminary results show that the long-term (1950-1980) flux of carbon to the atmosphere from worldwide changes in land use are about 100 x 10^{15} g. The annual rate of

release has been accelerating; about half of the net flux for this 150-year period occurred in the last 40 years. Earlier studies reported a total release of about 180 X 10^{15} g. The new estimate is lower because of revisions in the data on the amount of carbon lost from newly cultivated soils, the mass of carbon held in tropical forests, and the amount of vegetation damaged during logging.

MONITORING OF ATMOSPHERIC CO_2 AT MAUNA LOA OBSERVATORY

KEELING, CHARLES D.

SCRIPPS INSTITUTION OF OCEANOGRAPHY

FY 1989	150
FY 1988	0
FY 1987	122

08/01/89-07/31/90

Objective: 1. To continue to monitor atmospheric CO_2 concentrations at Mauna Loa Observatory for a one-year period.

2. To complete updates to the existing Mauna Loa CO_2 record (1958 to the present) with newly available advances in computer technologies. The seasonal and interannual variability of atmospheric CO_2 will be reinterpreted as a means of detecting the effects of climatic change, rising CO_2, and human activities on the worldwide carbon cycle.

Product: 1. Hourly atmospheric CO_2 concentrations in preliminary form that have received basic quality-assurance evaluations and reports documenting any anomalies or deviations from standard procedures.

2. The calibration of existing instrumentation with CO_2-in-nitrogen gases and CO_2-in-air gases and inclusion of calibration curves into the quality-assurance and editing computer program.

3. The semifinal edited and calibrated hourly atmospheric CO_2 concentration data for an additional year, including all detected corrections established in Products 1 and 2 above. Editing will be final except for any need to adjust further the data to a revised manometric primary scale conforming to a possible agreement with the World Meteorological Organization and the U.S. National Institute of Standards and Technology, which agreement has not yet been established.

Approach: With the series of measurements developed and refined earlier, the seasonal and interannual variability of atmospheric CO_2 will be reinterpreted as a means of detecting the effects of climatic change, rising CO_2, and human activities on the worldwide carbon cycle. The results of these new interpretations will be applied to recent data to assess the feasibility of using the Mauna Loa record to sense short-term future changes in the carbon cycle. The Mauna Loa record has shown a recent trend in the carbon cycle of an increasing biospheric CO_2 release since 1975, and the possible continuation of this trend will be studied with precise measurements of both CO_2 concentrations and the $^{13}C/^{12}C$ ratio.

Results to Date: The Mauna Loa Record reveals a surprising 15% increase in amplitude on the seasonal cycle because of land-plant activity in 29 years. Interannual variations in the seasonally adjusted record have been found to correlate with the large-scale weather patterns associated with El Nino events and the Southern Oscillation. According to companion measurements of the $^{13}C/^{12}C$ isotopic ration of CO_2, these correlations are caused in part by climatic perturbations of land-plant activity rather than exclusively to air-sea interaction as initially supposed.

Three-dimensional atmospheric transport models have helped to explain the mechanism by which the carbon cycle influences atmospheric CO_2 patterns. The seasonal variation, observed to repeat with nearly the same phase and harmonic composition from year to year, is well represented by a model of the land biosphere prescribed from satellite data of the greenness of the land and by temperature-dependent emissions of CO_2 from plants and soil. Day-to-day variations of CO_2 at Mauna Loa reflect large-scale patterns in the wind related to major weather disturbances that alternately transport marine and continental air and high- and low-latitude air to the station. Steady progress is thus being made in linking atmospheric CO_2 data with parameters of the carbon cycle to produce more-reliable predictions of possible future perturbations of the carbon cycle by mankind.

EXCHANGES OF CARBON BETWEEN THE ATMOSPHERE AND TERRESTRIAL ECOSYSTEMS AS A RESULT OF LAND-USE CHANGE

MOORE, B., III, and SKOLE, D. L.

UNIVERSITY OF NEW HAMPSHIRE

FY 1989	138
FY 1988	132
FY 1987	0

09/01/89-08/31/90

Objective: To improve the accuracy of the estimates of the net flux of carbon between terrestrial ecosystems and the atmosphere produced by deforestation and other land-use changes. Both the current net flux (1975 to 1985) and the long-term net flux (1800 to 1985) will be addressed with the specific objective of developing a means for predicting future releases of carbon to the atmosphere from terrestrial systems.

Product: (1) Computer code for a hierarchial version of a terrestrial carbon model and associated sets of data. (2) A data set on land-use patterns in south and southeast Asis.

Approach: While some aspects of the research will be carried out globally, other aspects, such as documentation of long-term trends in land use, will be done regionally. First-year research is focused on the tropics, in particular south and southeast Asia. In these areas, the current biotic flux is high, and a wealth of experience and current and long-term data exist on land use, vegetation type, and biomass of these regional ecosystems. The approach in these regional studies uses tabular statistics, remotely sensed data, ecological literature, etc. The results of this evaluation will provide an estimate on the scale of resolution and intensity of effort required to obtain data on land-use change and biomass in other regions of the globe.

Results to Date: This research has resulted in an initial compilation of a historical land-use data set for a large portion of south and southeast Asia. In addition, a compilation of a suite of geographically referenced global data sets on such factors as soil type and vegetation type have been completed. The first stage, the development of a geographic information system (GIS) for managing these data and remotely sensed data, has also been completed. Geographically detailed land-use and environmental data sets are being integrated in the GIS-based data management system to form the framework for a geographically referenced terrestrial carbon model. A further application of the GIS framework is the land-use- and land-cover-change models. Preliminary results indicate that the distribution and time-variant dispersion of land-cover conversion can be predicted from data on physical features of the environment, soil type, vegetation characteristics, and other geographically varying biophysical parameters. Maps of agricultural areas in India produced from such a model and actual land-use maps have an 80% overlay.

THE INFLUENCE OF ECONOMIC, SOCIAL, AND BIOPHYSICAL FACTORS ON LAND-USE CHANGE IN BIHAR, INDIA

PARKS, PETER J.

DUKE UNIVERSITY

FY 1989	16
FY 1988	0
FY 1987	0

05/01/89-11/31/90

Objective: To improve the ability and accuracy of predicting global biotic flux. While some aspects of this research can be carried out globally, other aspects, such as documentation of long-term trends in land use, are best done regionally. As proposed, the research will focus on an evaluation of the data recently obtained by John G. Richards in the regions of south and southeast Asia. These data include geographically detailed records of land use, vegetation types, and biomass for the period 1880 to 1980. These data will be tested and evaluated with a combination of modeling and literature studies. The ability of biophysical and socioeconomic parameters in this Asian data set will be explored to explain the rates and locations of land-use change.

Product: (1) A modeling strategy for applying this approach to other countries in the global carbon modeling effort. (2) Regression equations for predicting areas in different ecosys-

tem types from socioeconomic data. (3) A computer data set describing agricultural economic activities in Bihar, India.

Approach: The approach closely follows modeling strategies that have been successfully used to model land-use changes in the U.S. In general, these strategies employ economic reasoning and models to suggest social and economic drivers for land-use decisions and trends.

The districts in Bihar serve as individual observations for regression estimation and hypothesis testing. Each of the 17 districts in the province of Bihar yields eleven vectors of land allocations for the period from 1880 to 1980. The vectors describe the allocation of land among eight major cover types (arable, settled/built-up, forest, interrupted woods, grass/shrub complexes, desert/tundra, major wetlands, and surface water). The major types are also divided into several subcategories.

Land area in each category is estimated as a separate regression rather than as a system of interrelated equations. This means that the maximum sample size available for each regression is 17 times the number of decades included.

Results to Date: The population data provided by Richards and Flint and commodity prices derived from the series *Agricultural Statistics of India* from 1918 to 1947 were used in district-level log-linear models of hectares in temporary and in permanent crop ecosystems. From these models, average populations and average prices for four decades (1920, 1930, 1940, and 1950) for twelve commodities (winter rice, autumn rice, wheat, barley, maize, gram, raw sugar, cotton, linseed, rape, jute, and mustard) were calculated. When available, all ten years surrounding each decade contributed to each average. The log of land area was found to give a slightly better fit for simulation purposes. Analogous approaches can be used when provinces or even countries are the units of observation rather than the districts used here.

PARTIAL SUPPORT FOR THE CONSTRUCTION OF A MANOMETRIC CALIBRATION SYSTEM FOR CO2 STANDARDS

PETERSON, J., TANS, P., and THONING, K.

GMCC/NOAA

FY 1989	125
FY 1988	0
FY 1987	0

02/01/89-01/31/90

Objective: To construct a manometric analysis system for the determination by first principles of the concentration of CO_2 in air, which system will be used for the calibration of primary standards. This capability will help maintain the calibration precision of CO_2 measurement by laboratories participating in the WMO BAPMoN network.

Product: A partially automated manometric system for the volumetric analysis of CO_2 in air.

Approach: The pressure and temperature of an aliquot of dry air will be measured in a calibrated volume after thermal equilibrium has been reached. Then the CO_2 will be extracted at liquid nitrogen temperature, and the pressure and temperature of the CO_2 will be measured in the calibrated internal volume of a quartz spiral manometer. The quartz manometer will be calibrated at regular intervals against other pressure standards. A microprocessor will record instrument reading and control the timing of valve openings. To provide continuity for the WMO CO_2 standards, intercomparison will be performed with the primary standards at the National Institute for Standards and Technology and at Scripps Institution of Oceanography.

METHANE IN ARCTIC PERMAFROST

RASMUSSEN, R. A.

OREGON GRADUATE CENTER

FY 1989	62
FY 1988	0
FY 1987	0

08/01/89-07/31/90

Objective: To determine the amount of CH_4 and CO_2 in the upper layers of permafrost. The experiment will also provide an analysis of vertical gradients, if any, and spatial inhomogeneities. These measurements have the most direct bearing on the potential increase of CH_4 and CO_2 fluxes from the high arctic tundra if some permafrost melts in response to a global warming resulting from increased CO_2, CH_4, and other trace gases.

Product: An estimate of the importance of the release of methane from permafrost for the global concentration of methane, if the global temperatures increase from increasing levels of carbon dioxide and other trace gases. This will be compared with increases of methane from other causes, such as sources controlled by human activities and the potential depletion of tropospheric OH.

Approach: The main experiment consists of obtaining a number of samples from at least a dozen sites in Alaska. The locations of the cores are to be spread out over as large an area as allowed during the field work. Small cross-sections, marked with their depth and place, will be sealed and kept frozen until analysis.

Once brought to the laboratory, small 100- to 200-g pieces will be taken from each sample (representing a given core from a given depth) and placed in a sealed container with distilled water. The sample will be thoroughly mixed with the water. After it has reached equilibrium, the air in the headspace will be analyzed. Several such extractions will be done for each run of the experiment. The resulting data will then be used to estimate the total amount of methane in the original samples that were put into the container.

Results to Date: Permafrost cores were collected between August 14 and 17, 1989, at 13 sites along two transects from Prudhoe Bay west to Kooparik and south toward the Brooks Range. These cores represent a variety of permafrost soils as well as peat bogs available from the Alyeska pipeline road. The cores were returned to the Oregon Graduate Center frozen and are presently being processed for analysis of CH_4 and CO_2.

EXCHANGES OF CARBON BETWEEN THE ATMOSPHERE AND TERRESTRIAL ECOSYSTEMS AS A RESULT OF LAND-USE CHANGE

RICHARDS, JOHN F.

DUKE UNIVERSITY

FY 1989	94
FY 1988	90
FY 1987	0

07/15/89-05/31/90

Objective: To narrow the range of estimates and to improve the accuracy of current estimates of carbon dioxide release from land use. Our research is aimed at documenting long-term trends in land use in south and southeast Asia. From these data, we are trying to estimate long-term reductions in standing stock of biomass to calculate carbon release for the region.

Product: The results will be incorporated in the global model of carbon flux developed by R. Houghton (Woods Hole Research Center). The results from this regional study will also be used to estimate the scale of resolution and intensity of effort required to obtain comparable data for the remaining regions of the world.

Approach: Comprehensive land-use data will be compiled for the period 1880 to 1980, and changes in biomass converted to carbon will be estimated. Our reconstruction will cover a contiguous area of 1.7×10^6 km^2 in northern India, Bangladesh, and Burma. The data will be compiled first by subcountries and then by the entire study region. The data will be estimated for four dates: 1880, 1920, 1950, 1980. The total land-use area will be divided into eight categories of use: net cultivated area, settled and built-up, forest/woodland, interrupted woods (less than 30% canopy), grass/shrub complexes, barren/sparsely vegetated, wetlands, and surface water. Net cultivated area will be

further subdivided into temporary and permanent crops. At each date, estimates for area in each category rely upon numerous statistical and narrative sources.

We will convert area figures for land use at each level into estimates of carbon in standing stock of vegetation. These estimates will be based upon a large regional ecological and botanical literature measuring biomass for various types of vegetation. We will also account for degradation of vegetation within classes of land use by systematic adjustments based upon increasing human and livestock populations in the region.

Results to Date: For the entire study region, our estimates of total carbon release are as follows: 1880 to 1920: 911 million tons; 1920 to 1950: 750 million tons; and 1950 to 1980: 964.4 million tons. The total release for the century is estimated at 2.63 billion metric tons. Forest woodlands accounted for 84.8% of the total release; interrupted woods for an additional 11.0%. We therefore conclude that our greatest concern in the future must be to obtain accuracy in the estimates of changes in forest/woodland area and biomass density.

SIMULATIONS OF THE CARBON CYCLE IN THE OCEANS

SARMIENTO, JORGE L.

PRINCETON UNIVERSITY

FY 1989	200
FY 1988	200
FY 1987	0

10/01/89-09/30/90

Objective: To develop models of the oceanic carbon cycle based on 3-D primitive equation models of ocean circulation for use in predicting the uptake of anthropogenic CO_2 by the oceans. This project is a collaborative effort with M. Fasham (Institute of Ocean Sciences) and U. Siegenthaler (University of Bern). These models will be used to study the response of the ocean carbon cycle to climate changes and the possible feedback of such carbon cycle changes on atmospheric CO_2.

Product: Three-dimensional ocean-model simulations of the uptake of anthropogenic CO_2, including possible feedback effects from changes in the ocean carbon cycle.

Approach: Our strategy involves two parallel approaches. The first assumes that the pre-anthropogenic ocean carbon cycle continues to operate without being affected directly by anthropogenic perturbations. This "steady state" approach enables us to treat the anthropogenic CO_2 as a passive tracer. The only information we need regarding the carbon cycle, other than the appropriate thermodynamic constants, is the pre-anthropogenic surface total carbon and alkalinity concentrations. U. Siegenthaler is helping us in dealing with the chemistry and boundary conditions for these experiments as well as collaborating in the analysis of the results. The second approach that the oceanic carbon cycle will quite likely respond dynamically to is the effect of the anthropogenic greenhouse gas perturbations on climate. M. Fasham has primary responsibility for developing the ecosystem models that we require to implement this approach and to carry out seasonal simulations of the CO_2 uptake; we have primary responsibility for placing these ecosystem models into our ocean circulation models.

Results to Date: (1) Two nonseasonal perturbation 3-D simulations of CO_2 uptake by the oceans have been carried out, one using the combined Siple ice core/Mauna Loa atmospheric CO_2 history as a boundary condition and the other using the estimated fossil CO_2 production to calculate the atmospheric CO_2. These two experiments give airborne fractions of 0.638 and 0.671 for the period 1958 to 1980, respectively, compared with the observed airborne fraction of 0.568. (2) The sensitivity to gas exchange rate has been found to be small: the CO_2 uptake in the Siple ice core/Mauna Loa simulation increases by only 2.7% and 9.7% for gas exchange rate increases of 20% and 100%, respectively, over the same time span of 1958 to 1980. (3) Three major simulations of the behavior of ocean biology in the upper ocean have been carried out for the North Atlantic. They differ in the efficiency with which they recycle nutrients; and, therefore, in their ability to retain nutrients in the upper ocean and sustain continued production through the year. A measure of this efficiency is the ratio of production based on recycled

nutrients to the total production, which is 0.82, 0.60, and 0.22 for the three experiments. (4) A comparison of the implied chlorophyll content of these simulations with satellite color observations suggests that the middle one of the three experiments gives the best results. Major areas of disagreement occur, such as in the basic pattern in the Equatorial region, where the model circulation appears to be at fault. A number of simulations have been carried out to try and improve the circulation in the Equatorial region, thus far without success.

PEAT CARBON ACCUMULATION RATES OF ARCTIC ALASKAN TUNDRA

SCHELL, D. M.

UNIVERSITY OF ALASKA

FY 1989	62
FY 1988	0
FY 1987	0

09/07/89-07/31/90

Objective: To estimate the accumulation rates of peat carbon in arctic Alaskan tundra during the recent Holocene.

Product: Carbon accumulation (or loss) rates from coastal plain and foothills arctic tundra. Such data will used to estimate carbon sources/sinks for the Alaskan arctic.

Approach: Carbon accumulation rates in arctic tundra during the recent Holocene will be determined from the ^{14}C profiles in soil cores. A coast-to-foothills transect and additional cores taken parallel to the coastline will be collected and processed for radiocarbon content, total carbon content, and moisture.

Results to Date: The initial field work was undertaken from Aug. 14 to 20, 1989. Cores of peat from the active layer and underlying permafrost were acquired from adjacent to the road system of the Kuparuk oil field and from along the Pipeline Haul Road between Prudhoe Bay and Toolik Camp in the foothills of the Brooks Range. Although processing of the cores has not been completed, initial assessments of peat depths and carbon content indicate that peat carbon standing stocks may be less than previously estimated. Massive ground-ice was evident in many locations and often constituted the bulk of the core in the upper 0.5 m of permafrost.

SIMULATIONS OF THE CARBON CYCLE IN THE OCEANS

SIEGENTHALER, ULRICH

UNIVERSITY OF BERN

FY 1989	33
FY 1988	35
FY 1987	0

10/01/89-09/30/90

Objective: To help develop a 3-D model of the oceanic carbon cycle suitable for simulating the oceanic uptake of anthropogenic CO_2. This project is being carried out in collaboration with J. L. Sarmiento of Princeton University.

Product: Three-dimensional-model simulations of the uptake of anthropogenic CO_2 by the ocean for different emission scenarios. In addition, 1.5-D models will be developed that will be calibrated with the 3-D model to permit fast, economical simulations for arbitrary CO_2-emission scenarios.

Approach: The 3-D-model runs will be carried out at Princeton, where 3-D general circulation models have been developed and much expertise exists. The University of Bern will help in planning the fossil-fuel CO_2 experiments, based on our experience with simple ocean-atmosphere models, and will collaborate in the interpretation of the results to identify the processes and oceanic regions that are of special importance for the transport of CO_2. We will also study simplified models (box and diffusion models that have been calibrated with tracers like ^{14}C and temperature) with the aim of constructing a simple model with the same response characteristics as the 3-D model. This simplified model will allow simulations of future atmospheric CO_2 levels with shorter computer run times and, subsequently, cost-effective evaluations of the 3-D simulations.

Results to Date: The uptake of anthropogenic CO_2 has been evaluated with a four-box high-latitude exchange/interior diffusion-advection model (HILDA) constructed by Shaffer and

Sarmiento and intended to simulate the distributions of both natural tracers and anthropogenic CO_2.

The model was first calibrated from the observed distributions of temperature and ^{14}C. With this calibration, the airborne fraction for a purely fossil-CO_2 input is 71% for the period 1958 to 1980. That is to say, the ocean takes up relatively little excess CO_2. A second calibration with the distribution of bomb-produced ^{14}C (as an approximate analogue for man-made CO_2) yields a considerably larger eddy diffusivity (i.e., a stronger vertical mixing in the interior box). Consequently, the oceanic uptake is larger than for the first calibration, and the value for the airborne fraction for 1958 to 1980 is only 60% (i.e., comparable to the observed ratio of atmospheric increase to fossil CO_2 input of 58%; no biospheric input is, however, considered).

The oceanic uptake is slightly larger for HILDA than for the box-diffusion model of Oeschger and Siegenthaler when the latter is also calibrated using bomb-produced ^{14}C. This result can be attributed to the rapid uptake in the high-latitude surface water of the model. Like other carbon-cycle models, HILDA does not seem able to sequester the CO_2 amount necessary for balancing the difference between estimated total emissions (from fossil fuel burning and from deforestation) and atmospheric increase, which points to the possible role of terrestrial ecosystems as carbon sinks.

CLIMATE RESEARCH

Climate defines the physical environment to which man and the biosphere respond. The principal components of the climate system are the atmosphere, the oceans, the cryosphere, and the land surface. As CO_2 increases in the atmosphere, the climate system will respond (e.g., atmospheric energy balance is modified, with temperature expected to increase; and ocean physical and chemical characteristics are expected to respond). The many complex interactions within the system will further modify the response. For example, changes in cloudiness may either enhance or reduce a greenhouse warming. This is called cloud feedback. Another example is that the oceans can store large quantities of heat, possibly delaying evidence of the greenhouse effect. The general circulation models (called GCMs) are presently incapable of realistically treating the clouds or oceans. Model improvement and data analysis will be required before the ocean-delay and cloud-feedback uncertainties can be resolved.

Specific information is required to analyze changes that may impact man and the biosphere as the climate system responds to increased concentrations of greenhouse gases. The primary information needs are:

- Rate of the regional climate change
- The distribution and magnitude of the regional climate change on a monthly basis

Current climate models cannot adequately provide the rate, distribution, and magnitude of regional climate change. To provide the needed information, it is necessary to understand why the models respond as they do and to develop further the models to provide the regional rate and magnitude of climate change.

Research Objectives A major objective is to develop and improve the capabilities to estimate the range of global and regional climate change resulting from increasing CO_2. This estimation includes but is not limited to the rate and magnitude of changes in such climate parameters as temperature, precipitation, frequency of extreme events, and changes in the variability of these quantities.

The second objective is to detect evidence of the climate system response to the past and continuing increase in atmospheric CO_2. This objective addresses the question: Does the observed climate record reflect the changes that would be expected (as estimated from the climate-model projections) given the past increases in atmospheric CO_2?

The third objective is to provide the information needed for resource analysis. This information includes direction, rate, and magnitude of regional changes in temperature, precipitation, soil moisture, and extreme events. It would be used in the analysis of food, fiber, and other resources.

Research Questions During the next five years of climate research, answers to the following questions will be developed:

- What are the physical and methodological (model formulation) causes for the differences among models and between models and the observed climate?
- Can GCMs, independently or in combination with other techniques, estimate regional, CO_2-induced climate change? This effort will specify what information can be delivered (as requested by the other program areas) and when such estimates can be provided.
- How rapidly can the climate change? To what extent will the ocean delay the change?
- Can a climate response to the greenhouse gases, particularly CO_2, be observed? If not, can it be estimated when the signal might rise above the natural climate variability?
- What are the information requirements for resource analysis?

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EFFECTS OF BREAKING WAVES AND WHITECAPS ON CO2 EXCHANGE

ASCHER, W. E., and
CRECELIUS, E. A.

BATTELLE MARINE SCIENCES LABORATORY

FY 1989	150
FY 1988	0
FY 1987	0

02/16/89-09/30/89

Objective: To determine the importance of bubble plumes formed by breaking waves in air-sea gas exchange relative to other processes. If found to be significant, the feasibility of sensing whitecaps remotely will also be investigated.

Product: A calibrated apparatus for laboratory simulations of whitecap-governed air-sea gas exchange and an empirically based parameterization of the influence of fractional whitecap coverage on gas transfer coefficients.

Approach: This research will investigate the conditions under which breaking waves contribute to CO_2 transport. A model relating the overall transport coefficient k_L to ocean whitecap coverage will be tested. The model equates k_L to the sum of the transport coefficient caused by nonwhitecap-related exchange, $k_m(1 - W)$, and the transport coefficient caused by whitecaps, k_tW, where W is the fraction of the sea surface covered by whitecaps at a given time. As defined here, k_m represents the portion of the gas transport caused by turbulence not generated by breaking waves. Therefore, it is understood that in the present model k_m will be a function of wind speed because some turbulence-generation mechanisms do not involve wave-breaking. Because k_t is assumed to be constant in the model, the wind-speed dependence of the process is contained in W and k_m. Determination of k_m is straightforward in laboratory measurements. If $W = 0$, k_L is equal to k_m, and k_m can be measured under known turbulence conditions. Then, by measurement of k_L with a known amount of bubble generation, k_t may be found; if necessary, the model can be extended to include variation in k_t. The bubble contribution to k_L may then be determined for a range of environmentally important variables. Once this calculation is accomplished, W values and other data from the open ocean may be used to estimate oceanic CO_2 fluxes.

Experiments will be performed in a laboratory wave tank under conditions of controlled aqueous-phase turbulence, interfacial cleanliness, and frequency of wave breaking to constrain the conditions where wave breaking is rate-limiting for air/sea exchange of CO_2. The laboratory experiments will be done in cooperation with Prof. E. C. Monahan of the University of Connecticut. Also, it now appears feasible to estimate oceanic whitecap coverage from satellite microwave images. Information gained from the laboratory studies will be used to design field experiments for the estimation of CO_2 exchange rates from surface pCO_2, exchange coefficients, and passive microwave emissions.

paper on this topic was published in the *Journal of Geophysical Research*. The relationship between precipitation and temperature variations in important grain-growing regions of the world is currently being examined. The structure of polar inversions and their variability through time has been studied for selected stations in relation to high-latitude temperature changes. Extremely large interannual variability is a characteristic feature, but low-frequency changes in inversion intensity and thickness are also apparent.

RESEARCH PROJECT ON CO_2-INDUCED CLIMATE CHANGE

CESS, R. D., and HAMEED, S.

STATE UNIVERSITY OF NEW YORK AT STONY BROOK

FY 1989	513
FY 1988	331
FY 1987	300

03/01/89-02/28/90

Objective: To compare GCMs, documenting the physical processes responsible for agreement and disagreement, and to statistically analyze the U.S. and Chinese regional temperature data set for relationships between large-scale and regional climate.

Product: Understanding of the GCM's abilities to represent large scale climate and the relationships between large-scale climate and regional climate.

Approach: The approach is a model-to-model and model-to-data comparison for GCMs. The current research program concerns the comparison and understanding of CO_2-induced climatic warming as indicated by contemporary general circulation models. An experimental protocol has been developed and is being applied to the model-to-model comparison with a $\pm$2°C sea-surface temperature change as the forcing mechanism. The approach will assist in diagnosing cloud feedback and cloud forcing as probable causes for GCM disagreements. About 10 to 12 GCMs from throughout the world are involved.

Another aspect of the research is devoted to understanding the natural variability in climatic parameters. Subseasonal, annual and interannual variations in air temperature, precipitation, and sunshine durations in station observations are analyzed and compared with their simulations in GCMs. The purpose is dual: to quantitatively ascertain the deficiencies of the models so they may be modified by the modelers and to demonstrate their regime of success so useful applications may be made of the presently available models. Climatic data developed by the National Climatic Data Center in the U.S. and the Institute of Geography of the Chinese Academy of Sciences have been used in this project.

The two tasks will be brought together to guide the estimation of regional climate change.

Results to Date: A comparison of 14 atmospheric general circulation models, for which sea-surface-temperature perturbations were used as a surrogate climate change, showed a roughly threefold variation in global climate sensitivity. Most of this variation is attributable to differences in the models' depictions of cloud-climate feedback, a finding that emphasizes the need for improvements in the treatment of clouds in these models if they are ultimately to be used as climate predictors.

We have carried out diagnostic studies of long-term climate simulations by OSU-LLNL coupled-ocean-atmosphere GCMs. Earlier, we showed that the Southern Oscillation is simulated by the OSU-LLNL GCM that incorporates an oceanic thermocline and a mixed layer. During the past year, we have found that the slab-ocean version of this model generates the see-saw of atmospheric pressure that is characteristic of the southern oscillation in the northern spring season. This finding leads to the conclusion that the oscillation originates within the atmosphere during that season. In another study, we have shown that the OSU-LLNL model with six layers in the ocean simulates a 14.5 month oscillation that can be characterized as the Chandler wobble and that it contributes significantly to interannual climatic variability, especially at higher latitudes.

CLIMATE SYSTEM RESEARCH: STUDIES OF GLOBAL AND REGIONAL INSTRUMENT DATA

BRADLEY, RAYMOND S.

UNIVERSITY OF MASSACHUSETTS

FY 1989	170
FY 1988	0
FY 1987	0

12/01/88-11/30/89

Objective: (1) To extend the DOE long-term surface-climate data set for regional analysis. (2) To analyze data for critical regions with special climate characteristic likely to change under CO_2-induced climate change. (3) To assess spacial and temporal coherence of hydrologic variability. (4) To compare the regional data to climate-modeling results.

Product: An updated global set of station and 5 x 10 gridded temperature data will be produced to provide more reliable data coverage through 1990. Precipitation coverage will be similarly improved and updated. The data set will be analyzed for patterns of regional and hemispheric climatic change for comparison with GCM projections of greenhouse-gas-induced climatic change.

Approach: A primary scientific need is to detect regional climate change and relate the changes documented in the observations to those expected for a CO_2-induced climate change. The proposed research will address this need in four research tasks.

(1) The basic climate data set (prepared under past and continuing grants at the University of East Anglia) will be improved by assessing the quality of additional temperature and precipitation data from the U.S.S.R.. These data have been obtained under the U.S./U.S.S.R. bilateral agreement and now require examination and incorporation into the data set. The Soviet data set is important because the U.S.S.R. is large and thus the data may significantly influence Northern Hemispheric averages (e.g., surface air temperatures). The significance of the additional data will be evaluated. The U.S.S.R. data will also be used to test for regional urban warming. This is not a duplication of the East Anglia effort because they are concentrating on the European urban warming. Because the marine air temperature is important to establishing a true global data set, techniques to correct the data for known problems will continue to be developed. This effort again requires close coordination with the East Anglia group, which is examining the differences between the two existing raw data sets (the NOAA data and the U.K. Meterological Office data) so that one of the two marine data sets can be used to form an improved global temperature data set.

(2) Models and paleoclimate analyses suggest that high latitude and high altitude environments and arid and semiarid marginal zones will be sensitive to climate change. To establish the climate in these regions as a basis for assessing change and for test climate models, special regional data bases will be developed. These data will include sea ice, surface and low-level atmospheric temperatures, and precipitation. The research will attempt to evaluate the evidence for climate change in these regions relative to global changes.

(3) Climate models predict changes in precipitation (a global increase with regional increases and decreases) and increased temperatures. Any changes in the amount and type of precipitation (rain or snow) combined with temperature changes can result in changes in stream flow and other hydrologic variables. The existing data sets will be evaluated, and additional ones will be compiled for assessing such changes and for testing climate models. This effort will be difficult because of human influence on the hydrologic system (e.g., dams and other diversions). However, without such data and an assessment of it's utility, testing the reliability of climate models and documenting change in the climate variables most important to agriculture will be difficult.

(4) The above data sets and subsequent analyses will be compared to climate-model results. This research will be closely coordinated with other research projects sponsored by the CDRP.

Results to Date: A revised set of global temperature data (station and gridded) has been prepared for the period 1851 to 1988. Precipitation data have been analyzed for southern-hemisphere continental regions. They show significant long-term changes in the distribution of rainfall in certain regions. A

CARBON DIOXIDE OCEAN RESEARCH

DOWNING, JOHN P.

PACIFIC NORTHWEST LABORATORY

FY 1989	180
FY 1988	165
FY 1987	40

10/01/88-09/30/89

Objective: To identify the ocean research needed to understand the differences among climate models, to improve their capabilities to estimate changes in global and regional climate likely to result from energy-related alterations to the radiative balance of the atmosphere, and to improve models of the global carbon cycle.

Product: A plan for ocean research in FY 1989 and 1990, technical coordination and oversight of ocean research in climate systems, a program of innovative research conducted by small businesses to develop new technologies for oceanographic sensors, and brief topical reports on new scientific developments responsive to the immediate interests of CO_2 program management.

Approach: The oceanic processes that contribute to the uncertainty about future atmospheric CO_2 concentrations and regional climate change will be identified and ranked according to their relative importance based upon the best information currently available. A Phase-I program of process studies, data analysis, and model development will be initiated to improve existing ocean simulation and prediction capabilities in anticipation of large, multi-agency ocean-observation programs to be conducted during the nineties. In a Phase-II program, DOE will support the development of an interactive global ocean data base tailored for the CO_2-climate research community. The first element of Phase II will be a global survey of ocean carbon chemistry to be conducted in conjunction with the World Ocean Circulation Experiment Hydrographic Program (WOCE).

Results to Date: A research plan for FY 1989 was implemented followed by the initiation of research in five new areas. The new projects include (1) laboratory investigations of the effects of wave breaking and whitecaps on CO_2 gas exchange, (2) an evaluation of surface layer models for climate studies, (3) a feasibility study of acoustic monitoring for changes in ocean temperature, (4) an investigation of deep-water formation in ice-free regions, and (5) a proof-of-concept study of expendable sensors for sampling remote regions of the ocean. A Phase I program of small-business innovative research (SBIR) was initiated to develop new in situ sensors for monitoring optical and chemical parameters of the ocean. Sensor technologies under development in Phase I have great potential for advancing sea truth capabilities during satellite observation programs during the nineties.

EXPENDABLE BOTTOM-LAUNCHED CTD PROFILER

DOWNING, JOHN P.

BATTELLE MARINE SCIENCES LABORATORY

FY 1989	100
FY 1988	0
FY 1987	0

02/16/89-09/30/89

Objective: To develop an expendable continuous temperature-depth (CTD) profiler with satellite telemetry capabilities for long-term hydrographic observations in remote areas of the ocean.

Product: A proof-of-concept study of an expendable CTD profiler with satellite data transmission and ground-positioning capabilities.

Approach: Existing methods for CTD profiling require ships or aircraft for surface support. Ship-of-opportunity observations are inexpensive but are restricted to routinely-traveled shipping lanes. Some regions of the ocean are far from shipping lanes, most of them south of 40° S, where profiles of temperature and salinity are infrequently made. At present, there are no off-the-shelf sensors well suited for making observations in these regions.

This research will develop a prototype sensor package for obtaining hydrographic data inexpensively. The sensor package will have microprocessor-controlled sampling and launch schedules, will have satellite telemetry, and will operate as a surface drifter that transmits sea-surface and air temperatures periodically to satellites with a ground-positioning capability like ARGOS.

THE INTERCOMPARISON OF RADIATION CODES IN CLIMATE MODELS (ICRCCM)

ELLINGSON, ROBERT G.

UNIVERSITY OF MARYLAND

FY 1989	69
FY 1988	67
FY 1987	0

04/01/89-03/31/90

Objective: To provide leadership, research, and analysis in the international Intercomparison of Radiation Codes in Climate Models (ICRCCM).

Product: Improved understanding from analyses of the longwave radiation model calculations for improving GCMs.

Approach: The ICRCCM is an international effort that is cosponsored by the World Meteorological Organization (WMO), the U.S. Department of Energy, and the International Association of Meteorology and Atmospheric Physics (IAMAP).

The ICRCCM calculations by different participants have produced significantly different results, not only in the radiation codes used in climate models but also in the more detailed narrow-band codes. The ICRCCM study will document these differences and, through the analyses of the calculations, will try to understand why the radiation codes give a large range of results.

Results to Date: Several papers have been submitted to the *Journal of Geophysical Research* for a special issue on ICRCCM early in 1990. The 1988 Paris Workshop Report has been completed; a draft has been submitted to the WCRP and the IRC, and the final version should be printed by the WMO early in fall 1989. A miniworkshop on the possibility of a Spectral Radiation Experiment (SPECTRE) was held at the University of Maryland in March 1989; discussions concentrated on the technology for simultaneously measuring radiance spectra and atmospheric properties. Arrangements were made with W.-C. Wang (Atmospheric and Environmental Research, Inc.) to initiate a comparison on calculations with CH_4, N_2O, and CFCs. An invited paper was presented at IAMAP89 in Reading, England.

CLOUD/RADIATION INTERACTIONS AND CLIMATE

ELLIS, JAMES S.

LAWRENCE LIVERMORE NATIONAL LABORATORY

FY 1989	250
FY 1988	250
FY 1987	275

10/01/88-09/30/89

Objective: To compare detailed radiation transfer models, to compare short- and longwave radiation transfer approximations used in GCMs and chemistry transport models, and to compare both sets of radiation models to satellite data and laboratory/atmospheric measurements to establish model and data uncertainty ranges.

Product: The comparison will establish the range of uncertainty among models and between models and the data. These results will contribute to development and validation requirements for cloud-radiation interactions in climate and chemistry models.

Approach: The research builds upon the existing ICRCCM longwave-radiation-model comparison study. The ICRCCM is an international effort cosponsored by the World Meteorological Organization, the U.S. Department of Energy, and the International Radiation Commission of the International Association of Meteorology

and Atmospheric Physics. Initial comparisons focused primarily on longwave calculations with clear-sky conditions (the exception being some GCM sensitivity calculations). Later comparisons were expanded to include prescribed clouds. Continuing investigations have been directed toward understanding and documenting the relative uncertainty of radiative-transfer calculations and the effects of such uncertainties on the results of GCMs and chemistry transport models. Subsets of the satellite data compiled through the First ISCCP Regional Experiment will be used to evaluate the models calculations.

Results to Date: We continue to support the co-leader of ICRCCM, Robert Ellingson, and to serve as a focus for the radiation-code validation process of the ICRCCM. The principal effort following the August 1988 ICRCCM workshop has been directed toward summarizing the results of the longwave intercomparisons and presenting early analyses of the results. A detailed report of the workshop has been written and submitted to the World Meteorological Organization for publication. A detailed paper and a summary paper on the results from the analyses of the longwave radiation calculations have been submitted for publication in a special issue of the *Journal of Geophysical Research.* Additional efforts have been made toward improving computationally efficient radiation approximations for chemistry transport models. Improvements in net heating rates calculated for the upper stratosphere are especially important for the calculation of dynamic processes and temperatures.

PROGRAM FOR CLIMATE MODEL DIAGNOSIS AND INTERCOMPARISON

GATES, W. LAWRENCE

LAWRENCE LIVERMORE NATIONAL LABORATORY

FY 1989	2000
FY 1988	220
FY 1987	0

10/01/88-09/30/89

Objective: To better understand (and eventually to reduce) differences among climate model estimates of the regional, CO_2-induced climate changes through a program of systematic model diagnosis and intercomparison.

Product: By concentrating on the diagnostic analysis of model simulations, by providing a vehicle for communication among modeling groups, and by exploring the sensitivity of models to different resolutions and numerical methods and to different representations of important processes, the PCMDI is intended to provide a systematic basis for the improvement of GCMs. The provision of a coordinated and centralized program in model diagnosis will also permit the study of a greater number of model attributes, including variables of particular interest to those conducting studies of the possible impacts of climate changes, thereby providing a needed bridge between modelers and the users of the model simulations.

Approach: One of the first major questions to be addressed by the PCMDI is the issue of model resolution. Models used for climate studies have generally been run at resolutions dictated by available computer memory and time; we have undoubtedly been paying a price for the limited resolution in our studies of regional climate change. The model with which we will initially study the resolution issue is the European Centre for Medium Range Weather Forecasts (ECMWF) operational model, which is recognized as the best in the world in weather forecasting and lends itself well to resolution studies. It can be run at T-21, T-42, T-63, T-106, and T-213 (spanning 6° to 1/2° latitude grids). Parallel with the resolution study, a preliminary diagnostics package will be implemented with the ECMWF model to estimate the structure and distribution of systematic efforts and their relationship to the model's parameterized physical processes. Particular attention will be given to the diagnosis of the models' surface heat and hydrologic balance, their cloud-radiative forcing, and their portrayal of low-frequency variability. A data bank for systematic model verification and a comprehensive model inventory will also be developed.

Results to Date: We have acquired 15 workstations and will receive 4100 computer resource units (CRAY-1 hours) for FY90.

MODEL INTERCOMPARISON

GATES, W. L., and POTTER, G.

LAWRENCE LIVERMORE NATIONAL LABORATORY and
OREGON STATE UNIVERSITY

FY 1989	61
FY 1988	75
FY 1987	75

02/01/89-01/31/90

Objective: To provide a basis for systematic diagnosis of the GCMs to accelerate the reduction of the uncertainties in the projection of the regional and seasonal distributions of future climate changes, particularly those caused by increased CO_2 concentrations. To estimate ranges and uncertainties imposing significant restraints on the use of model projections for assessing the potential impacts of climatic changes on resources and societal activities.

Product: The diagnostic analysis of model simulations is intended to provide a systematic basis for the improvement of GCMs. The provision of a coordinated and centralized program in model diagnostics will also permit the study of a greater number of model attributes, including variables of particular interest to those conducting studies of the possible impacts of climate changes, thereby providing a needed bridge between modelers and the users of the model simulations.

Approach: In cooperation with the climate modeling community, the specific work approach is expected to fall into several broad categories: (1) the performance of comparative model integrations, (2) the conduct of systematic sensitivity and predictability experiments, (3) the development of improved diagnostic and intercomparison techniques, (4) the documentation and identification of systematic simulation errors, (5) the participation in model improvement, and (6) the development and maintenance of model data banks.

Results to Date: A manuscript on the application of the coupled atmosphere/upper-ocean model to the estimation of the global climatic effects of increased CO_2 has been prepared and will be submitted for publication. The model has been found to achieve an average equilibrium warming of about 4.0°C for doubled CO_2 after approximately 25 years simulation.

A number of important diagnostic computer programs have been transferred from OSU to LLNL including a comprehensive graphics package and data base system that can be applied to any number of models.

A byproduct of the coupled atmosphere/upper-ocean model simulations being done in this project is a relatively long simulation for a control and a 2 x CO_2 simulation. The results from these simulations have produced unexpected benefit and have resulted in a better understanding of low-frequency variability in the atmosphere-ocean system.

GEOPHYSICAL MODELS OF THE FOSSIL-FUEL CARBON DIOXIDE PROBLEM

HOFFERT, MARTIN I.

NEW YORK UNIVERSITY

FY 1989	179
FY 1988	170
FY 1987	170

06/08/89-06/07/90

Objective: To develop and to apply a coupled 2-D ocean/atmosphere model.

Product: The 2-D coupled model will be used to address issues related to the role of the ocean in transient climate change and to ocean thermal delay of climate change.

Approach: The research will develop a latitude-depth-resolved bottom-water model based on previous research. The formation of bottom water is a key process in driving the circulation of the ocean and thus the transport of heat both horizontally and vertically in the ocean. Application of this model will bound the fluctuations in the bottom-water flow rates that may accompany CO_2-induced climate change. The results, in turn, will provide insights into the data requirements and model-development requirements necessary to incorporate bottom-water formation into the 3-D GCMs of the ocean/atmosphere system.

Currently, the climate experiments are conducted by comparing the model's representation of current climate with the model's estimation of the climate with doubled CO_2. These are called equilibrium experiments because the CO_2 is doubled instantaneously and the model is run until the output suggests that the model has reach a stable solution at doubled CO_2. The climate system, of course, would be responding to slowly increasing CO_2, not to an instantaneous doubling. This slowly increasing case is called a transient climate experiment. The further development of the NYU 2-D model and its application will be an important step in preparing for transient GCM experiments.

Results to Date: A more realistic version of our ocean/climate model has been developed and solved for the steady structure of the world ocean in the presence of stratification feedback on eddy diffusivity and upwelling feedback from changes in bottom water. Comparison of model-predicted and observed profile of oceanic properties indicate excellent agreement. The feedback on climate from ocean turbulence and bottom-water-formation changes is analogous to such atmospheric processes as cloud-radiative interactions insofar as they occur below the resolution scale of numerical models but profoundly affect climate predictions. Our approach, based on oceanographic turbulence microstructure data, predicts that eddy diffusivity will increase strongly with depth and will feed back on the thermal structure of the oceans to retard the penetration of heat and tracers as the surface warms. The new model is much more sensitive to changes in bottom-water temperature, where diffusivity is large, which implies a wide range of possible long-term sea-level changes from thermal expansion (or contraction) depending on how bottom-water formation is affected by climate change.

GCM-OBSERVATIONAL COMPARISONS: REGIONAL AND LOCAL CLIMATE

KARL, THOMAS R.

NATIONAL CLIMATIC DATA CENTER

FY 1989	25
FY 1988	50
FY 1987	0

03/01/89-09/30/89

Objective: To develop methods whereby the inexact specification of the surface-boundary effects in a GCM can be reduced or eliminated in model-to-observation comparisons and in projections of local and regional climate. To analyze the regional climate records of the United States and China as they relate to climate change and the greenhouse effect.

Product: (1) A method that allows for direct interpretation and comparison of GCM-simulated surface-based climate to the observed surface-based climate without undue influences from local boundary conditions, (2) an estimation of the effects of the urban heat island bias in China, and (3) a procedure to make better use of the Plum-Rain records to estimate summertime temperature in Beijing back to the 1700s.

Approach: A procedure that relates free-atmosphere variables to surface observations of daily temperature, precipitation, and cloud ceilings will be developed and applied to five locations across North America: Fairbanks, Alaska; Spokane, Wash.; Bismarck, N.D.; Topeka, Kan.; and Charleston, S.C. The method will use principal-component analysis and canonical correlation. The technique has been applied to GCM output and the results compared to observed surface observations.

The urban heat island bias in China will be investigated by comparing urban and rural stations in China with time-series methods and by comparisons of urban and rural annual average temperature differences as functions of temperature.

Earlier estimates of July mean temperatures in Beijing will be refined by using the number of hours of rainfall within each day as one of the predictors in place of a variable indicating whether precipitation has or has not occurred.

Results to Date: A paper has been submitted to the *Journal of Climate*. The paper describes the method of climatological prediction by model statistics and presents the results of one application of this method. Calculations for a second paper focusing on the ability of the GCM to handle transitions in weather or climate regimes have been completed. The results have been described in several scientific symposiums and will be submitted to a scientific journal next fiscal year.

The urban heat island bias in China has been described in the *WMO/UNEP Inter-Governmental Panel on Climate Change, Science Report.* A paper that describes the methods used to calculate Beijing summer temperatures since 1724 was coauthored in a textbook on *Climate Since 1500.*

UNITED STATES HISTORICAL CLIMATOLOGICAL DATA SET DEVELOPMENT

KARL, THOMAS R.

NATIONAL CLIMATIC DATA CENTER

FY 1989	125
FY 1988	125
FY 1987	0

03/01/89-09/30/89

Objective: To compile high-quality long-term data sets of monthly cloud cover, sunshine, vapor pressure, sea-level and station pressure, temperature, and precipitation and daily observations of snow depth, temperature, and precipitation for a reasonably dense network of stations across the United States.

Product: Computer readable data sets to be described by and made available through CDIAC along with supplementary metadata.

Approach: Manuscript meteorologic data will be keypunched and merged with existing machine-readable data sets. Both existing digital data and manuscript data will be edited for random errors as well as biases. Many of the stations span the period 1900 through at least 1987.

Results to Date: An updated (through 1987) monthly sunshine data set has been delivered to CDIAC for approximately 200 stations.

A data set of monthly average cloud cover for a network of approximately 200 stations has been delivered to CDIAC along with supporting documentation regarding data inhomogeneities and estimation processes used for missing data.

A data set of concomitant upper air and surface observations for long-term U.S. upper-air stations has been delivered to CDIAC. These data include calculation of monthly precipitable water and the height of any surface-based inversions. Other observed variables include the 1000-, 850-, 700-, 500-, and 300-hPa winds; temperatures; relative humidities; and heights. In addition, concomitant surface observations of snow cover, maximum and minimum temperature, precipitation, cloud ceilings, winds, and relative humidity are provided. This data set consists of approximately 50 stations.

A preliminary data set of daily snow depth has been delivered to CDIAC. At this time, these data have not been fully edited for errors. About 200 stations are included in this data set.

A data package of nearly 200 stations with monthly average water vapor pressures has been delivered to CDIAC. Included in this package is supporting documentation for inhomogeneities and the methods used to check for random errors. These data have been quality controlled for random errors using intra- and interstation edits.

A daily data set of 138 stations of temperature and precipitation has been keypunched back to 1900. These data are in the process of being edited for random errors. Stations were selected based on the quality of the monthly average data from the U.S. Historical Climatology Network.

Updates of the *Historical Climatology Series 4-5* (printed by the National Climatic Data Center) have been completed using updated and

adjusted data from the Historical Climatology Network. These data have been delivered to CDIAC along with supporting station histories.

Historical observations of monthly average sea-level and station pressures have been key-punched and are in the process of being edited for appropriate climatological elevations and corrections. A preliminary data set of about 200 stations has been delivered to CDIAC.

THE MULTIDIMENSIONAL ASPECTS OF RECENT CLIMATE CHANGE IN NORTH AMERICA

KUKLA, GEORGE

LAMONT-DOHERTY GEOLOGICAL OBSERVATORY

FY 1989	183
FY 1988	174
FY 1987	174

08/15/89-08/14/90

Objective: To analyze time-related changes in the properties and the frequency of individual air masses over North America and to determine the degree to which the observed climate changes agree with the predictions of climate models.

Product: A regional data base for first detection of CO_2-induced climate change. The information will be used for model validation.

Approach: Daily climate data sets from 91 stations for North America (Canada and the U.S.) will be combined with upper-air data sets. Temperature, precipitation, cloudiness, and derived information, such as air-mass type and diurnal range of temperature, will be developed. Changes in regional climate will be assessed with principal-component analysis and canonical correlation, and possible causal relationships will be posed. The data set and the derived information will be compared to GCM results (initially the OSU and the NCAR GCMs).

Results to Date: Daily data for both surface and upper-air elements have been examined for about 60 first-order stations for the recent four decades. The U.S. Historical Climate Network, which contains monthly data for high-quality stations whose records begin around 1900, has also been referenced.

Although the mean annual temperature of the Northern Hemisphere has increased by about 0.15°C during the past four decades, the average temperature of the contiguous United States shows practically no change. Autumns and winters cooled, while springs and summers warmed. Regionally, cooling dominates in the East, and warming in the West. We have found significant increases in cloud and precipitation amounts as well as a decrease in the temperature range and sunshine. A marked increase in the frequency of low-cloud observations is in qualitative agreement with model predictions; many features are not. The transient response of regional climates may not be proportional to the difference between the 1 x CO_2 and 2 x CO_2 equilibrium climates.

CARBON DIOXIDE EFFECTS RESEARCH

MacCRACKEN, MICHAEL C.

LAWRENCE LIVERMORE NATIONAL LABORATORY

FY 1989	970
FY 1988	978
FY 1987	925

10/01/88-09/30/89

TASK I: CLIMATE MODELING AND DATA ANALYSIS (K. E. Taylor)

Objective: To improve our understanding of climate models so that, when these models are used to make projections of future climate change, the reliability of the projections can also be evaluated. More specifically, (1) to establish the relative roles of the processes that contribute to the latitudinal and seasonal sensitivity of climate models to increasing CO_2 concentrations, (2) to examine the processes controlling the rate of change of climate, (3) to use a 2-D climate model and other simplified models to assist in analyzing and interpreting results from 3-D models, and (4) to update and improve the 2-D climate model to treat interactions between climate and atmospheric chemistry.

Product: An updated and improved model that will be an efficient tool for model diagnosis

and study of climate change. By establishing the relative roles of the processes that lead to climate-model sensitivity, the importance of uncertainties and limitations in representations of these processes can be assessed, and models improved. In cooperation with D. Wuebbles's project, a better understanding of the importance of feedbacks between atmospheric chemistry and climate change will be obtained.

Approach: To explore all components of the relationship between climate and CO_2 and trace gases, the complexity of climate models must be balanced against available computational capabilities. The approach taken here is to formulate and directly solve equations for the zonally averaged component of climate. The resulting 2-D climate model retains many of the essential characteristics of the climate system and has been used as an important tool for understanding the climate itself as well as the results obtained by 3-D climate models.

The weather systems that are explicitly simulated in 3-D models are accounted for by eddy parameterizations in 2-D models (or can be prescribed). The consequent reduction in "climatic noise" (along with the greatly reduced computational costs of 2-D simulations) makes it possible to carry out series of runs in which individual processes can be examined in detail. Because computational costs preclude such studies with 3-D climate models, the 2-D model is recognized as an essential tool. It will be used to address a number of important questions concerning the historical climate record and future climate change. A study is planned, for example, to determine how the pattern of climatic response to a stratospheric injection of volcanic aerosols depends on the latitude and season of the volcanic eruption. Another planned application is to use the 2-D model to explore the limitations of the GCM experiments undertaken as part of Task II of this project. In particular, the climate-model response to a doubling of atmospheric CO_2 concentration will be compared to its response to a prescribed increase in sea-surface temperature.

Results to Date: The hydrologic cycle, a realistic surface boundary layer, and eddy transport parameterizations were added to the 2-D climate model. These additions essentially complete the major developmental phase of that model. In formulating the numerical scheme used to solve the model equations, a time-split finite-difference method commonly used in solving fluid-dynamics problems was extensively analyzed to determine when it could be expected to provide accurate solutions and when it might fail.

A sea-ice model has also been prepared for coupling to the 2-D climate model. The linking of these two models should provide more-realistic climate simulations of the seasonal cycle and of climate change because the insulating and optical properties of sea-ice are known to be important in polar regions.

With a simplified, analytical model of atmospheric radiative properties, a climatic feedback involving oceanic production of dimethyl sulphide (DMS), cloud condensation nuclei, changes in clouds' optical properties and surface insolation was analyzed. This exploratory study extended previous work in that an empirical relationship between insolation and DMS production was applied, yielding a self-consistent model of the feedback. More-detailed studies of the link between cloud optical properties and climate were carried out with a 3-D model (GCM). Papers have been prepared for publication on this work, and presentations have been made at two international conferences.

TASK II: MODEL INTERCOMPARISON (G. Potter)

Objective: To develop a basis and strategy for intercomparing climate models so that the causes of different results from different models can be determined. Comparison of climate models' CO_2 sensitivities will be used to investigate the differences that can arise among models and the mechanisms that contribute to the differences.

Product: An understanding of the causes of the range of results that can be produced by different climate models will be analyzed in terms of the differences inherent in model structure and the effects caused by different parameterizations of the oceanic meridional transport and heat capacity. Such an understanding will provide a basis for model improvement.

Approach: The OSU GCM will be used to develop a strategy for model intercomparison that uses sea-surface-temperature perturbations as a surrogate for increasing CO_2.

Results to Date: In cooperation with R. Cess of SUNY Stony Brook, a useful methodology has been developed for understanding why different models produce different sensitivities to perturbations, such as increased CO_2. The procedure is relatively simple and can be used by a wide range of atmospheric modeling groups, including those that have not previously studied CO_2 climate change. Results of this analysis were published in *Science* and show that the models' sensitivity to perturbations is primarily dependent on cloud feedback. A more detailed paper is being prepared for the *Journal of Geophysical Research.*

The next step of the intercomparison includes a study to investigate similarities and differences among the CO_2 radiative forcing calculated by each model. The results of this study and the study on cloud forcing will enable us to more fully understand the primary causes of differences among models.

A third area of research is directed at using a forecast model for testing model produced cloud radiative forcing against ERBE satellite data. We will use the model of the European Center for Medium-Range Weather Forecasting (ECMWF) for this purpose. We are nearly ready to initiate an extremely fine grid test of cloud forcing.

TASK III: PROGRAM MANAGEMENT
(M. C. MacCracken)

Objective: To prepare technical reports and presentations providing state-of-the-art estimates of the climate effects of increasing CO_2 and the extent that such changes have started to occur and to assist in providing technical oversight of the climate research area and in integration of the research program.

Product: (1) A focal point for climate research undertaken by federal and international climate programs relevant to the CO_2-climate issue. (2) Technical coordination of DOE contract research. (3) Specific studies on timely CO_2-climate issues (e.g., small studies of immediate interest, such as an analysis of patterns of climatic change). (4) Statistical analysis support for activities, such as overviews of model/data comparisons.

Approach: To provide a source of intellectual stimulation and focus for DOE participation in the CO_2-climate issue and to help assure coordination of the research activities conducted by climate research groups sponsored by DOE.

Results to Date: The observed regional and seasonal distributions of surface air temperature and precipitation have been compared with model results from four U.S. general-circulation modeling groups investigating the effects of the increasing CO_2 concentration on climate. The results indicate that agreement with observations and among models deteriorates as the spatial scale of the comparison is refined, showing relatively little coherence of temperature and precipitation patterns on subcontinental and smaller scales. In simulations of the climate's sensitivity to a doubling of the CO_2 concentration, the various models show little agreement on the details of the latitudinal and longitudinal patterns of change, except that Northern Hemisphere winter-time temperature changes are increased in polar latitudes.

Additional activities have included (1) support for analyses to determine which climatic variables should be most susceptible to early detection and to evaluate the potential use of paleoclimates as analogs for CO_2-induced climate change, (2) presentation of results at scientific and agency meetings, and (3) working with other agencies in coordination of research activities.

REDUCE UNCERTAINTY IN PROJECTION OF FUTURE SEA-LEVEL CHANGE PRODUCED BY ICE WASTAGE

MEIER, MARK F. and
ILLANGASEKARE, T. H.

INSTITUTE OF ARCTIC AND
ALPINE RESEARCH

FY 1989	130
FY 1988	130
FY 1987	130

08/15/89-08/14/90

Objective: To understand better and predict how the runoff from the world's glacier ice, exclusive of Antarctica, will respond in the next century to a changed climate caused by increased atmospheric CO_2.

Product: (1) An understanding of the heat and mass flow into subfreezing snow and firn, making it possible to model the evolution of

the temperature distribution and the infiltration rates through the firn. (2) The relation of changes in climate, as given by GCM predictions, to changes in the surface mass and energy balances of glaciers. (3) The analysis of the effects of changes in surface mass and energy balances on the flow of meltwater through snow and firn and on runoff from these glaciers in a CO_2-affected climate.

Approach: The approach to Product (1) will involve laboratory investigations to obtain a qualitative understanding of the physical processes that are associated with the mass and heat transfer within the subzero snow mass and to develop a conceptual model based on these observations. It will also include a field experiment in which natural snow and firn will be carefully measured before, during, and after the melt season and a numerical analysis. The approach to Product (2) will require the compilation of results of GCMs to develop a consensus on how climate will likely change in the next century and then the development of simple mass and energy-balance models to translate the changes in climate into their effects on glacier surfaces for certain representative areas selected for this work. Product (3) will involve applying the mass and energy-balance models to GCM estimates of climatic environments for present-day conditions and checking the rsults against known data. Then the models will be applied to the changed environments caused by a doubled concentration of CO_2. The estimates of meltwater production will be routed through the snow and firn to estimate the runoff and its evolution with time. These results, when integrated for the major ice masses of the world exclusive of Antarctica can then be interpreted as the effect these glaciers will have on global sea-level rise.

Results to Date: Sea-level rise will be a major consequence of greenhouse warming, and current models suggest that wastage of land ice will be the major cause of this. Meltwater generated at the surface of a cold ice cap or glacier will not run off immediately but will refreeze until the snow is warmed and pathways are developed. The time scale of this process may be the largest uncertainty in predicting future sea-level change. Our artificial natural and artificial melt experiments on arctic ice caps show that a critical element is the development of ice layers that could permit more-rapid lateral runoff. Detailed field measurements (before and after) were made of snow temperature, structure, and hydraulic properties for use in computer models. An initial computer model of water flow in cold snow successfully simulated some aspects of this flow; but an advanced model, now under development, is needed to cope with the sharp discontinuities in snow that cause ice layers. This advanced model, which couples heat-flow and water-flow equations, links a meltwater-generating zone (at 0°C), a nonequilibrium zone with water flowing between subfreezing ice grains, and a cold zone with no liquid water present.

APPLICATIONS OF NONLINEAR DYNAMICS IN CLIMATE RESEARCH

PEARSON, ERIK W.

PACIFIC NORTHWEST LABORATORY

FY 1989	34
FY 1988	0
FY 1987	0

02/16/89-09/30/89

Objective: To evaluate the role of recent ideas in nonlinear dynamics, falling under the general heading of chaos, in climate research.

Product: A summary of recent research applying the ideas of nonlinear dynamics to climate problems in two areas: climate modeling and analysis of climate-related time series data. Recommendations as to fruitful areas of research will be included.

Approach: The project is carried out through a critical review of current literature. Subject areas include analysis of fractal time series and nonlinear energy balance and other simple climate models. Also included will be a summary of key ideas in nonlinear dynamics as they apply to climate research.

THE ROLE OF CLOUDS IN CO_2-INDUCED CLIMATE CHANGE

RANDALL, DAVID A.

COLORADO STATE UNIVERSITY

FY 1989	109
FY 1988	0
FY 1987	0

09/15/89-09/14/90

Objective: To develop a quantitative understanding of surface radiative forcings as related to clouds and cloud climate feedbacks on climate change and to develop an advanced ocean-atmosphere GCM.

Product: An understanding of the surface radiative forcings, relative to clouds, from the various GCMs; an understanding of how the models compare with the available observations and of their possible methodological shortcomings; and an improved GCM with fully coupled ocean and atmosphere.

Approach: The proposed research focuses on the radiative role of clouds in current climate and in a climate modified by increased atmospheric concentrations of CO_2. Specifically, the research will address the role of clouds through five related research tasks. The connecting theme is to diagnose the differences among the GCMs and to allow improved physical parameterization of clouds in the GCMs. In cooperation with LLNL and SUNY Stony Brook, 14 GCMs will be compared on surface fluxes (sensible, latent heat, infrared, and solar); precipitable water content; and precipitation and evaporation.

Also, differing cloudiness parameterizations will be studied as atmospheric CO_2 concentrations change in a simple coupled ocean/atmosphere model.

Cloud data from satellite, aircraft and balloons will be used to quantify cloud forcing and feedback processes as observed.

An ocean GCM will be added to the existing CSU atmospheric GCM (the Q-flux version of the ocean model) in a stepwise process. The mechanics are simple; however, coupled GCMs magnify the imperfections of the models being brought together. Understanding the physical and methodological problems and then making appropriate, physically based corrections is difficult. The primary concern will be the effect on clouds. For example, simple changes in ocean albedo can have dramatic impact on model cloudiness requiring modification of the cloud parameterizations.

ATMOSPHERIC METHANE: RESEARCH PROGRAM FOR A STUDY IN CHINA

RASMUSSEN, R. A.

OREGON GRADUATE CENTER

FY 1989	302
FY 1988	272
FY 1987	237

02/01/89-01/31/90

Objective: To measure the magnitude of the methane source from rice paddy fields and biogas generators including seasonal cycles.

Product: Rice growing and biogas generators are thought to be large sources of atmospheric methane and contributors to the seasonal cycles in the time series documenting methane trends. This project will provide new information on the magnitude of these sources and their seasonal characteristics. This research will provide major new information for understanding the time series documenting the increase in atmospheric methane.

Approach: The Oregon Graduate Center will cooperate with the P.R.C. to measure methane releases to the atmosphere from rice paddy fields, nonagricultural soils, and biogas generators. Standard techniques developed by OGC will be used. The measurements will be made in such a way that seasonal characteristics of the releases can be determined. These data will be used in analysis and modeling programs to understand the time series record of atmospheric methane.

Results to Date: Between 1985 and 1987, we conducted about 30 experiments and obtained some 900 measurements of trace gases emitted from rice fields and biogas generators around Chengdu in the Sichuan Province of China. The biogas generators were found not to be a significant source of methane on a global scale (<<1 Tg/year). Rice fields release CO, $CHCl_3$, and CO_2 at observable rates. The emission

rates of CO and $CHCl_3$ are too small to contribute significantly to the global cycles of these gases. The CO_2 emissions are very large, but because rice fields cycle carbon, there is probably no net flux of CO_2 into the atmosphere when integrated over a few years. Neither rice fields nor biogas generators contribute significantly to the local and regional CO and hydrocarbon pollution. There is evidence, although not beyond reasonable doubt, that the rice fields take up some man-made chlorocarbons, particulary CCl_3F_2, CCl_4, and CH_3CCl_3. These gases are implicated in the potential depletion of the ozone layer.

These experiments were not sufficient to determine the global or annual fluxes of methane. The continuation of the experiments in Tu-Zu in the Sichuan Province of China during 1988 and 1989 is providing the data from which global fluxes of methane may be estimated.

THERMOCLINE CIRCULATION AND ACOUSTIC MONITORING FOR CLIMATE CHANGE

SEMTNER, ALBERT J.

NAVAL POSTGRADUATE SCHOOL

FY 1989	75
FY 1988	0
FY 1987	0

02/16/89-09/30/89

Objective: To examine thermocline dynamics in a highly-resolved GCM basin-by-basin and to evaluate the feasibility of using ocean acoustics to monitor changes in ocean temperature and salinity over decadal time scales.

Product: An analysis of the exchange of mass, heat, and salt among ocean basins and subdomains of individual oceans resulting from the mean flow and eddy fluctuations and a model-based study of the feasibility of monitoring secular temperature changes by measuring the travel time of acoustic signals in the oceanic sound channel.

Approach: A global ocean study is now being carried out by the Naval Postgraduate School and the National Center for Atmospheric Research (NCAR). That study uses an eddy-resolving, primitive-equation ocean model. The model has a grid resolution of 1/2° x 1/2° with 20 levels to simulate ocean circulation and inherently unstable currents on a global basis.

An analysis will be performed with an archive of model-generated data that has been established at NCAR. The archive consists of 900 days of model history for years 19.5 to 22.0 of the integration and includes 900-day means, standard deviations, and eddy correlations. All of these data can be analyzed in diverse ways with a program developed by NCAR.

The analysis will be performed on 24 subdomains to determine the exchange of mass, heat, and salt across common vertical and horizontal boundaries. (1) Contour maps of key fields and (2) budgets of exchanges and net internal changes will be systematically assembled. The contributions of both the mean flow and the eddy fluctuations will be analyzed. Of particular importance will be a regional analysis of air-sea interaction of the coupled climate system.

The 24 subdomains of the global model will be determined by vertical division into the mixed layer (0 to 25 m), thermocline (25 to 710 m), and deep ocean (>710 m) and by division into eight geographic entities.

An additional analysis will be conducted to examine the feasibility of monitoring global ocean warming by measuring the travel time of acoustic signals in the oceanic sound channel. The feasibility of measuring the signal over the noise of the eddy variability in the model will be evaluated.

ANALYSIS OF DEEP CONVECTION IN AN EDDY-RESOLVING MODEL

SKYLLINGSTAD, ERIC

PACIFIC NORTHWEST LABORATORIES

FY 1989	90
FY 1988	0
FY 1987	0

2/16/89-09/30/89

Objective: To compare convective adjustment in the World Ocean Circulation Experiment community ocean general circulation (WOCE/CME) model with observations of deep convec-

tion in open water with existing ocean and climate data and to design numerical experiments to improve convection parameterizations in future ocean models.

Product: An analysis of observed and model ocean climatology in the Labrador Sea to test the overturn algorithm in an eddy-resolving ocean circulation model and new insight into the relative importance of oceanic versus atmospheric variability in forcing deep convection.

Approach: The WOCE/CME model resolves eddies over a 1/3° X 2/5° by 23-layer grid covering the North Atlantic. The general approach will be to synthesize model and observed climatologies for a subregion of the model domain where observation suggests convection regularly occurs. The subregion including the Labrador Sea and adjacent parts of the North Atlantic was chosen because (1) deep convection has been observed in ice-free regions of the Labrador Sea; (2) the basin can, for the present purpose, be considered closed at the northern boundary and relatively small adjustments to heat and salt fluxes are required; and (3) a general cyclonic circulation is driven by the West Greenland and Labrador currents causing at least two water masses (Labrador Sea water and subpolar mode water) to interact in the main basin.

The analysis will assemble a climatology of water characteristics, transports, vorticity, and tracer age from the CME integration (5 model years). Concurrently, a climatology will be assembled for the Labrador Sea from U.S. and Canadian observations to examine the annual cycle of convection and stratification. Finally, the differences between model and real-ocean convection will be interpreted, and numerical experiments for the next generation of ocean models will be developed.

SURFACE LAYER MODELS FOR SIMULATIONS OF LARGE-SCALE INTERACTIONS

SLINN, G. W. N., and EMERSON, S. R.

BATTELLE MARINE SCIENCES LABORATORY
AND UNIVERSITY OF WASHINGTON

FY 1989	85
FY 1988	0
FY 1987	0

02/16/89-09/30/89

Objective: To evaluate and test recently developed 1-D surface layer models for the analysis of time-series of chemical fluxes in the upper ocean and for the next generation of 3-D ocean models.

Product: (1) An assessment of the strengths and weaknesses of parameterizations for simulating surface-ocean processes currently used in ocean GCMs for studies of climate and (2) an intercomparison of newly developed, process-oriented, one-dimensional surface-layer models for applications in future climate studies.

Approach: Long time-series measurements of biogeochemically important materials will be made at several sites for the GOFS program. Because the fluxes of many important species (nutrients for example) cannot be measured directly, the fluxes must be calculated from profile data with mixing models. Accurate flux calculations are essential for balancing the budgets of biologically reactive dissolved constituents in the surface layer. Several recent developments in the mixed-layer models will be evaluated in this project and tested for inclusion in an improved model for flux calculations.

A RESEARCH PROGRAM ON NATURAL AND ANTHROPOGENIC CLIMATE CHANGE

WANG, WEI-CHYUNG

ATMOSPHERIC AND ENVIRONMENTAL RESEARCH, INC.

FY 1989	394
FY 1988	273
FY 1987	210

03/01/89-02/28/90

Objective: To compare climate data and climate-model results to improve the understanding of local and regional climate changes in relationship to large-scale climate, particularly desertification.

Product: Possible cause-and-effect physical mechanisms between local or regional climate and large-scale climate.

Approach: The atmospheric energy budget components associated with atmospheric moisture and clouds will be analyzed. This analysis will include the horizontal and vertical latent- and sensible-heat fluxes, thermal and solar radiation, and heat storage. The results will be combined with the previous surface energy budget analysis to assist in identifying the physical processes that cause the model differences.

The causes for the differences between the spectral and grid-point numerical formulations will be sought. An initial hypothesis is that the moisture field and the moisture fluxes are different for the two formulations. If one numerical technique is superior to another, these results will provide the basis for expanded experiments on more-detailed GCMs.

The effect of resolution on regional results will be examined. The objective will be to assess the ability to use GCM results as the boundary conditions for a mesoscale model to further improve the representation of regional climate.

Climate data will be analyzed, and the climate model statistics will be evaluated against the observed climate. This research will draw upon previous results obtained under the DOE's agreement with the P.R.C. The new effort will begin with the statistical analysis of paleoclimate data for 6,000 years B.P. A major area of interest is the fact that the U.S. climate is essentially monsoon free and the Chinese climate is dominated by the monsoon. This distinction is important for model validation because the timing of the monsoon is known to within a few days in the historical record and can therefore be used as a climate parameter to test models. The same statistical analyses conducted on the data will be conducted on the model results, and the observed climate will be compared to that predicted by models.

Research will continue on the physical causes of arid and semiarid climate in the U.S. and China and how the areas defined as arid or semiarid may change as CO_2-induced climate change progresses.

We will assist in the scientific coordination of the USDOE and P.R.C. Chinese Academy of Sciences joint research project on CO_2-induced climate change.

Results to Date: We have developed a methodology to compare the statistics between GCM simulations and observations. The method can be viewed as a generalization of the Model Output Statistics and Perfect Prog procedure used in numerical weather-prediction models. The method has been tested with the Oregon State University GCM and the observations from the Historical Climate Network. The method is particularly useful in relating the free-atmosphere variable to surface observed variables. As part of the GCM intercomparison, we examined the surface energy balances simulated by three general circulation models for current climatic boundary conditions and for an atmosphere with twice the current level of CO_2. The surface energy balance allows diagnosis of the radiative and thermodynamic processes that control surface temperature.

We have been participating in the U.S.-China joint research on the greenhouse effect. The focus has been on the preparation and analysis of climate data. For Beijing, the sun-rain records span the period 1724 to 1904. These records consist of visual observations of cloudiness, precipitation, and wind direction. We have used the duration of precipitation events to reconstruct the Beijing May, June, and July monthly mean temperatures. The instrumental precipitation data in the semi-arid

region of northern China has been used to study precipitation fluctuations and their relationship to the El Nino/Southern Oscillation. In recent years, this region has shown signs of desertification.

RADIATIVE, CHEMICAL, AND DYNAMICAL FEEDBACK PROCESSES INFLUENCING THE CO_2 TRACE GASES' CLIMATE EFFECTS

WANG, WEI-CHYUNG

ATMOSPHERIC AND ENVIRONMENTAL RESEARCH, INC.

FY 1989	199
FY 1988	255
FY 1987	170

09/01/89-08/31/90

Objective: To develop and improve the radiative transfer codes for climate studies and to incorporate trace gases' radiative effects into the NCAR GCM.

Product: Advanced radiative codes with particular focus on the water vapor continuum and a radiative transfer code for the NCAR GCM that includes additional trace gases.

Approach: Radiative transfer models will be developed and/or improved with a focus on the water vapor continuum in the context of the ICRCCM. Surface radiation measurements before, during, and after a dust event in China together with the ERBE satellite data will be used to test the quantitative connection between the dust event and aerosol-induced changes and regional meteorological responses.

How the other trace gases may modify the initial radiative heating/cooling profile in the atmosphere from that of CO_2 alone will be examined. Such differences may lead to significantly different climate feedbacks (e.g., clouds). The combined effects in a GCM experiment will assist in understanding and defining the predicted climate response, suggesting detection strategies as well as improving the predictive capabilities of the GCMs. To assist in the analysis of the GCM experiment and to examine meridional heat transport feedback mechanism, the development and application of the seasonal energy balance model will continue. Adding a stratospheric photochemical model will expand the research to include the effect of stratospheric temperature changes on surface temperature.

Results to Date: We have used a seasonal energy balance model together with a photochemical model to study the climatic effects of increasing the atmospheric trace gases CO_2, CH_4, N_2O, CFC-11, and CFC-12 and their associated changes in atmospheric O_3. Using projected trends of these gases, our calculations have showed that the annual and global mean surface temperature could warm by as much as 2.5°C with larger warming at high latitudes by the middle of next century. The calculations also suggest that the warming in the lower stratosphere and upper troposphere will be much larger than that of the surface, especially during the summertime. Large stratospheric cooling is calculated at an altitude around 45 km, where O_3 depletion caused by increases of trace gases contributes substantially to the total cooling. However, the effects of O_3 changes on the temperature below 40 km appear to be small because of small changes calculated in O_3 distribution.

We have also incorporated the radiative effects of CH_4, N_2O, CFC-11, and CFC-12 into the NCAR CCM1. This development is intended for using the CCM1 to calculate explicitly the combined greenhouse effect of increasing atmospheric CO_2 and these trace gases.

ENHANCED RESEARCH PROGRAM ON THE LONG-RANGE CLIMATIC EFFECTS OF INCREASING ATMOSPHERIC CARBON DIOXIDE

WASHINGTON, W. M., and MEEHL, G.

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

FY 1989	324
FY 1988	263
FY 1987	250

05/01/89-04/30/90

Objective: To improve and to apply the NCAR coupled ocean-atmosphere GCM to study the climatic effects of increasing CO_2 concentrations, with emphasis on seasonal, regional, and oceanic aspects of the change.

Product: Estimates of the pattern of regional and seasonal changes in climate caused by increasing CO_2 and of possible changes in ocean circulation and temperatures. Because this model is global, is seasonal, and contains interactive prescriptions for ocean dynamics, clouds, and sea ice, the results will add significantly to the available set of results of such cases, thereby allowing a preliminary estimate of uncertainties. Later studies will refine these results for use in first-detection analyses by providing initial estimates of climatic effects for the case of slowly increasing CO_2 concentrations.

Approach: The NCAR coupled ocean-atmosphere general circulation model will be updated to include a diurnal cycle, a full ocean cycle, increased horizontal resolution, and improved cloud representation. The model will be used to simulate the regional and seasonal sensitivity of the climate to increasing CO_2 concentrations. Detailed diagnostics will be conducted comparing observations and the control experiment. These diagnostics will be used to aid interpretation of 2 x CO_2 experiments. The model will include a hierarchy of ocean parameterizations ranging from a swamp model to a fully dynamic ocean model. Sea ice parameterizations will be included in all versions, and the atmosphere will also be well treated, including interactive cloud cover. The old and new models will be used in the GCM comparison to see the changes wrought.

Results to Date: During the past year, we published several articles dealing with coupled GCMs of the atmosphere, ocean, and sea ice. These experiments seem to indicate that the climate system evolves in different ways depending on whether carbon dioxide is instantaneously doubled or slowly increased.

An unexpected finding in our experiments is that the climate system simulates many realistic aspects of the El Nino/Southern Oscillation (ENSO) warm and cold events, even the responses of extratropical regional patterns.

We have revised and updated the atmosphere and ocean models. Our multitasked atmospheric model has better cumulus parameterization, improved surface albedos, snow and soil moisture diagnostics, and a highly vectorized and efficient code. Our four-layer, 5° latitude-longitude ocean model has been replaced by a multitasked and highly vectorized 20-layer, 1° latitude-longitude model (derived from the Semtner-Chervin global eddy-resolving ocean model). These models are in the testing stage and will soon be coupled.

MODEL VALIDATION RESEARCH: COMPARISON OF SIMULATED AND OBSERVED CLIMATE PATTERNS FOR THE PAST 18,000 YEARS

WEBB, THOMPSON, III

BROWN UNIVERSITY

FY 1989	420
FY 1988	409
FY 1987	489

02/01/89-01/31/90

Objective: To attempt to validate the NCAR GCM against paleoclimate data.

Product: An initial quantitative comparison between paleoclimate data and the NCAR GCM.

Approach: The proposed research will focus on (1) using GCMs to simulate a series of climatic changes from the past, (2) assembling paleoclimatic data from large areas of the tropics and the northern hemisphere mid-to-high latitudes for the comparison of model simulations and observations, (3) developing methods and procedures for improving the comparability of the observed and simulated data, and (4) comparing the model results with the paleoclimatic data. The third set of tasks is required because preliminary work has shown that both the simulated and observed data require transformation and averaging before telling quantitative comparisons are possible.

Results to Date: We are continuing to refine our simulations of past climates by including in our climate models additional processes beyond those used in our initial experiments for the period 18,000 BP to present. We have run experiments for 9000 BP with a low-resolution climate model that includes a mixed-layer ocean, sea ice, soil moisture, and snow cover. These new simulations have provided new estimates of past climates for comparison with paleoclimatic data. We are also using a high-resolution climate model (the NCAR GCM) to complete a simulation for 6000 BP that exactly parallels a 6000 BP simulation with the climate

model of the U.K. Meteorological Office. This experiment will allow us to make both model-to-model comparisons and data-to-model comparisons.

We have generated new estimates of climate values from pollen and lake-level data in eastern North America. These add precision to previous data-to-model comparisons. We have also run experiments with the NCAR OGCM to simulate ocean circulation during the last glacial maximum (18,000 years). These experiments have led to several improvements in the model to give a more realistic circulation both for the present and for 18,000 years ago. Comparison of foraminiferal and radialarian indicators of water masses and circulation features with the two simulations is underway.

DETECTION OF CO2-INDUCED CLIMATE CHANGE

WIGLEY, T. M. L., and JONES, P. D.

UNIVERSITY OF EAST ANGLIA

FY 1989	121
FY 1988	113
FY 1987	120

12/01/88-11/30/89

Objective: To assemble and analyze present and past instrumental climate data as a basis for detecting CO_2-induced climatic change and validating climate models.

Product: Global surface temperature and mean sea-level pressure data bases that amalgamate satellite, marine, and land-based data for use with appropriate statistical techniques for signal detection and pattern recognition and with specially developed energy balance climate models.

Approach: In addition to variations in CO_2 and trace gas (CTG) concentrations, climate responds to a number of other forcing factors: changes in ocean circulation, volcanic activity, solar irradiance, etc. To detect CTG effects, their signal must be isolated from the noise of natural climatic variability, a significant part of which is caused by these other factors. A high-quality, spatially extensive data base is required to define the noise and its spatial characteristics. Available land and marine data bases will be amalgamated, and satellite data will be used to fill in gaps in coverage. Land and marine data differences will be reconciled where possible. The data will be analyzed to determine the potential effects on climate of CTG variations and other factors. Analyses will be guided by simple energy-balance climate models that allow the transient response effects and interhemispheric differences to be quantified. A homogenized mean sea level pressure data set will be developed, and both pressure and temperature data will be used for regional-scale GCM evaluation. These analyses are primarily oriented towards obtaining early evidence of CTG-induced climatic change that would lead either to confirmation, rejection, or modification of model projections.

Results to Date: A gridded data set on a 5° x 5° resolution incorporating land and corrected sea surface temperature (SST) data has been produced for each month back to 1854. SST corrections are based on a model of the evaporative cooling that takes place while a temperature reading is being made with a canvas or similar bucket. This is the first combined data set of gridded SST and land data. 1988 was the warmest year on record. Cooling associated with the 1988/89 La Nina event will mean that 1989 will be a relatively cool year, but still above the 1950 to 1979 reference period average. Upwelling-diffusion modeling studies have been made to simulate future temperature changes produced by greenhouse-gas forcings and to study the possible cooling effect of SO_2-derived cloud condensation nuclei changes. The model has also been used to estimate the natural variability of the climate system on the century time scale, a crucial parameter in detection work. Various statistical packages have been developed for GCM validation, testing the differences in means, variances, and spatial patterns between observed and simulated climate data. The techniques are also used to intercompare GCM results and for multivariate detection studies.

TRACE-GAS INTERACTIONS IN THE GLOBAL ATMOSPHERE

WUEBBLES, DONALD J.

LAWRENCE LIVERMORE NATIONAL LABORATORY

FY 1989	250
FY 1988	275
FY 1987	285

10/01/88-09/30/89

Objective: (1) To understand the effects that increasing atmospheric concentrations of CO_2 and other trace gases may be having on global atmospheric chemistry and climate; (2) to understand the interactions among climate, chemical, and radiative processes; and (3) to establish clear relationships between theoretical models and the measurements of atmospheric constituents being made in the troposphere and stratosphere.

Product: A better understanding of the processes relating to global atmospheric chemistry and climate, insights into the mechanisms and processes by which trace gases affect the global environment, and an understanding of what measurements are required to further develop and validate global atmospheric models.

Approach: (1) Information will be developed on past trends and potential future trends of the various trace species in coordination with studies of trace species histories and economic analyses being done at PNL. (2) The budgets of relevant trace gases will be examined to better establish which uncertainties require consideration in developing scenarios of future emissions. (3) Existing capabilities for modeling global atmospheric chemical, radiative, and physical processes will be extended. (4) Model sensitivity analyses will be performed to better define the mechanisms, key parameters, and overall uncertainties of potential trace-gas influences on the atmosphere. (5) A clearer relationship will be established between theoretical models and the measurements of atmospheric constituents being made in the troposphere and stratosphere with the purpose of defining and reducing existing uncertainties in the determination of trace-gas effects.

To accomplish this evaluation, LLNL is extending present modeling capabilities and developing new models to allow coordinated treatment of chemical and climatic effects. The LLNL 1-D atmospheric chemistry-transport models have been reference models for past assessments. The LLNL 2-D model of tropospheric and stratospheric chemical, radiative, and dynamic processes is rapidly becoming the new standard for such assessments. Results of atmospheric-chemistry-perturbation studies with the 2-D model can be used to determine radiative perturbations, the climatic significance of which can be evaluated with climate models. Efforts are also underway to develop a 1-D radiative-convective chemistry model and to couple our 2-D chemistry and climate models for use in interactive simulations.

Results to Date: Research studies in FY-89 primarily centered on determining the relative roles of CO_2 and other trace gases contributing to climate change and on examining the interactions among chemical, climatic, radiative, and dynamic processes in the global atmosphere. A journal article was published on the role of atmospheric chemistry in determining climate change. Another research study examined the effects of anthropogenic emissions (CO_2, CFC, CH_4, N_2O, etc.) and natural solar variations in determining trends in stratospheric ozone and temperature. Several papers were published that examine the roles of non-CO_2 greenhouse gases in influencing future climate and evaluate some of the difficulties in mitigating the effects of these gases.

As part of the re-evaluation of the Montreal Protocol by the United Nations Environmental Programme, we helped develop and provide analyses of scenarios of future trace-gas emissions and their corresponding effects on ozone and temperature. An evaluation of potential replacement compounds for CFCs was also made for the report, which is being published by the World Meterological Organization. Significant contributions were also made to other major reports on global change for DOE, for IPCC (Intergovernmental Panel on Climate Change), and for the *U.S.-U.S.S.R. Special Report on Future Climate.*

We continued to improve the 1-D and 2-D models of the troposphere and stratosphere. Emphasis was on further refinements and improvements in the treatment of radiative-transfer processes, including an improved treatment of cloud processes.

VEGETATION RESEARCH

The thrust of this research is to provide information about the effects of CO_2 and climate on vegetation. The research strategy is to determine primary effects for representative systems and to explore ways of extrapolating the basic process information to other plant systems. An important requirement is to acquire new experimental data and to develop and validate models for improving predictions from altered CO_2 and climate conditions. Once developed and tested, the models would be applied to different types of vegetation (e.g., forests and rangelands) and at larger geographic scales.

Emphasis is placed on changes produced in system-level properties, such as productivity, yield, structure and function (including compositional changes), and plant-animal-microbial relationships (the effects of pests, nutrition, and disease). In addition, effects of CO_2 and climate change on system-level hydrologic conditions will be considered.

Primary products are data and models about changes in processes and properties of crops and ecosystems. These products will aid estimates of changes of primary productivity. These estimates, in turn, will aid investigation of secondary responses of plants and animals including some of the intricate relationships with microorganisms and with nutritional requirements of systems. As a general requirement, the research products would represent a system-level effect of CO_2 and climate change, and would have to be a meaningful parameter for examining consequences on renewable resources.

Research Objectives The first objective is to improve the capability of predicting effects on vegetation of increased CO_2 and climate change. The thrust here is to determine the extent that representative systems might be modified by rising atmospheric CO_2 and climate change and to develop a modeling capability for predicting such effects. The second objective is to search for existing evidence of biological response to the atmospheric CO_2 increase and climate change of the past few centuries. Intuitively, the historical 25% increase of CO_2 should be registered in changes of plant growth rate. The third objective is to provide the biological information needed for improving climate-model sensitivity and predictions of climate response to CO_2. The fourth objective is to provide information about the direction, rate, and magnitude of change in such system-level properties as productivity and yield for the analysis of the availability of food, fiber, and other resources. The fifth objective is to assure the compatibility of information across a range of time and space scales.

Research Questions Examples of questions to be addressed are:

- How much do plant productivity and yield change in relation to more CO_2 and associated climate changes? At the fundamental level, what are the interactive effects of simultaneous changes of these and other variables on photosynthesis and transpiration?
- How will functional and structural properties of ecosystems change with different CO_2 and climate regimes, and will such changes lead to different geographic distributions of forest, rangeland, wetlands, and deserts?
- What historical or paleo records would be useful for detection of changes in plant and ecosystem responses to variable CO_2 and climate? Specifically, is it possible to determine the magnitude of growth response produced by CO_2 enrichment and climate change from tree-ring chronologies?
- What are the information requirements for resource analysis?

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SIMULATION MODELING OF CROP RESPONSE TO CO_2 ENRICHMENT

ACOCK, BASIL

SYSTEMS RESEARCH LABORATORY

FY 1989	100
FY 1988	100
FY 1987	0

09/01/89-08/31/90

Objective: (1) To define a generic modular structure for models of plant growth and then to develop and test modules needed as components of modular crop models. (2) To validate the soybean crop model GLYCIM for a wide range of environmental and crop conditions at ambient CO_2 and, where unused data exist, to validate and evaluate model performance at elevated CO_2. (3) To make yield predictions of the response to CO_2 for large areas with a scaled-up version of GLYCIM.

Product: A validated, mechanistically based plant-growth simulation model that can treat CO_2-dependent physiological processes in the framework of the whole plant and the associated environmental factors affecting growth.

Approach: The generic approach will incorporate essential CO_2-dependent processes and interactions as well as physiology and growth processes that are common to many plant species. Modular concepts will be employed in this phase of the research. Modifications of routines or adjustments of code to treat basic processes will account for unique plant properties [e.g., the pathway of CO_2 fixation (C_3 vs C_4), carbohydrate source-sink dependencies, relative patterns of root or shoot growth, etc.]. The effects of these types of adjustments on model performance will be investigated. This research will also explore ways to aggregate plant processes to represent generic functions with analytical approaches described for large-area forecasts.

The 2-D soil model SOILSIM will be used to study the movement of water and solutes in both the unsaturated (rooted) and saturated portions of the soil.

SOILSIM will be incorporated into GLYCIM and will be validated with data sets collected from all over the U.S. under the sponsorship of the American Soybean Association. Finally, the model will be used to make large-area predictions to test the proposed method. That method involves using the model to predict yields for sites representative of the area as determined by the National Agricultural Statistics Service, weighting and aggregating the yields over the area, and comparing the prediction with reported yields.

Results to Date: Early in the year, analysis of the soybean-crop simulator GLYCIM with the uncertainty-analysis program PRISM revealed how insensitive the soil model RHIZOS is to soil-input variables and parameters. As a result, the 2-D soil model SOILSIM was purchased from a commercial company along with the rights to distribute a modified version. As purchased, SOILSIM contained algorithms to predict correctly the movement of water and solutes through a heterogeneous medium. It had simple empirical equations to simulate boundary conditions, no dictionary, and few comments in the code. SOILSIM was adapted for use in crop models by inserting comments in the code, preparing a dictionary of variable and parameter names and units, and replacing the empirical boundary-condition equations with equations that link to crop models. For instance, equations estimating transpiration as a function of time and year were replaced with equations that use estimates of transpiration produced by the crop models. This work was done in collaboration with soil modelers across the U.S. and in Israel to try to ensure that the product contains the best available knowledge of the processes. Finally, subroutines were written to interface SOILSIM and GLYCIM.

ASSESSMENT OF CROP RESPONSE TO INCREASED ATMOSPHERIC CARBON DIOXIDE: RISING CO_2 EFFECTS ON RICE

ALLEN, L. H.

PLANT STRESS AND PROTECTION RESEARCH UNIT

FY 1989	250
FY 1988	250
FY 1987	0

09/01/89-08/31/90

Objective: To determine the direct effects of CO_2 and the interactive effects of temperature, water management, and nutrition on rice photosynthesis, growth, water use, and yield. To develop and/or adapt process-level crop model(s) for prediction of rice growth and yield responses to elevated CO_2 and to environmental and germplasm variables.

Product: Primary information on physiology, growth, and yield of rice in relation to increasing atmospheric CO_2. The physiology and growth data will be used to modify a plant-simulation model for another C_3 grain, winter wheat. The research will also produce data on how interactions of CO_2 enrichment, variable temperature, and nutrient and water stress affect rice growth and productivity in a higher-CO_2 world with climate regimes different from today's.

Approach: The Plant Stress and Protection Research Unit is conducting a 6-year study on the effects of increased atmospheric carbon dioxide on physiology, growth, and yield of rice at both optimal and stress levels of temperature, water, and nutrients. Rice is an important food-grain for much of the world's population; it provides half the diet for 1.6 billion people, and by the end of the century two-thirds of the people will depend on rice for food.

The initial experiment will derive response functions to CO_2 concentration under nonlimiting conditions of water and nutrients and near-optimum temperatures. These results will be used to determine coefficients for specific rate equations to modify and adapt an existing plant-simulation model. This experiment is aimed primarily at determining process rates for the module PNET of the simulation model. At the same time, the structure and equations of an existing plant-simulation model will be adjusted to the plant properties of rice. This adjustment will be an initial test of the concept of adapting existing modules rather than developing new ones to simulate responses of new and different plants to CO_2 and climate changes. Subsequent experiments will investigate temperature interactions with CO_2 enrichment, interactive effects of CO_2 and nitrogen fertilization, and interactive effects of CO_2 and water management practice. An independent model validation experiment is also planned.

Results to Date: An indica (tropical) type of rice (*Oryza sativa*, L., cultivar IR-30) was grown under paddy-culture conditions in six outdoor, sunlit, controlled-environment chambers from October 1988 to February 1989 at Gainesville, Fla. Paddy-water depth was maintained at about 5 cm. Three chambers each were maintained at CO_2 concentrations of 330 and 660 ppm. Within each CO_2 treatment, a high, intermediate, and low set of temperatures (daytime air, nighttime air, and constant paddy water) were maintained: 40/33/37°C, 34/27/31°C, and 28/21/25°C, respectively.

The highest-temperature treatment failed to produce seed and produced little biomass following the mid-stem-extension phase.

The lowest and intermediate temperature treatments produced grain yields calculated to be 7.9 and 4.2 metric tons per hectare, respectively, with the 330-ppm-CO_2 treatment and 8.4 and 4.8 metric tons per hectare with the 660-ppm-CO_2 treatment.

With both CO_2 treatments, yields decreased about 0.6 metric tons per hectare per °C rise in temperature. These yield decreases may be larger than would be experienced under field conditions, where yields may be lower to begin with.

If these controlled-environment growth chamber data can be linearly interpolated and extrapolated to real-world field conditions, then tropical paddy rice-grain production of current cultivars could decline about 7 or 8% for each 1°C rise in temperature, seriously affecting world food supply.

INTEGRATION OF EXPERIMENTAL AND MODELING APPROACHES TO STUDY COMPETITIVE INTERACTIONS AMONG PLANTS UNDER ELEVATED CO_2

BAZZAZ, F. A.

HARVARD UNIVERSITY

FY 1989	229
FY 1988	213
FY 1987	0

11/01/88-10/31/89

Objective: To obtain data for predicting effects of CO_2 and physical influences (e.g., light and moisture) on plant communities based on knowledge of component species and their growth, productivity response, and resource use. Experimental studies will test the hypothesis that CO_2 affects competitive outcome primarily through its influence on the utilization of other resources. *A priori* knowledge of species response to resource ayailability and of the mechanism of response will aid model formulation and the development of a predictive capability.

Product: Data on growth and physiology of individuals and mixtures of species will be produced at several levels of CO_2, parameterizations of the responses of individuals and mixtures, and modeling descriptions of CO_2's effect on plant competition.

Approach: Experiments will be carried out with mixtures of species representing annual communities and native grasslands. With CO_2-controlled growth chambers, the designs will examine relative responses at three CO_2 levels; two light intensities; and variable water, nutrient, and temperature conditions. Companion data on physiology will provide insight on causes of differential responses to CO_2.

The resulting data will be used in a plant-competition model to simulate CO_2 effects on community growth and composition change. The initial phase of the research will develop a data base for annuals for which a mechanistic model of interspecific competition will be formulated. Because the model represents general physiological features, it can be tested with other assemblages of species and/or communities (e.g., the general model structure will serve as a basis for application to mixtures of perennial plants subjected to different levels of CO_2 and different physical environments).

A supplemental task of the research is to obtain specific data for modeling community response to CO_2, temperature, and light. Specifically, experiments will characterize the physiological properties of individual leaves throughout the canopy and the life cycle of co-occurring plant species. Growth and resource deployment will be examined as well as the CO_2 and light conditions associated with photosynthesis.

Results to Date: None reported.

INTERACTIONS OF CARBON DIOXIDE ENRICHMENT WITH WATER AND NUTRIENT STRESS IN CROPS: TOWARDS THE DEVELOPMENT OF A UNIVERSAL CROP SIMULATOR

BISWAS, P. K.

TUSKEGEE INSTITUTE

FY 1989	150
FY 1988	150
FY 1987	100

09/15/89-09/14/90

Objective: To develop a system for measuring canopy photosynthesis in a cotton field, to make measurements of canopy and leaf photosynthesis in cotton growing at elevated CO_2 controlled by the Free Air CO_2 Experiment (FACE) system, and to develop techniques for measuring tissue water potential with a thermocouple psychrometer.

Product: New data from field studies with cotton, including interactive effects of CO_2 and water or nutrient stress.

Approach: The bulk of the research involves characterization of the field site, field experiments with cotton, and studies of the physical environment of exposed chambers. Physiological and growth measurements will be made of plants cultivated in the FACE CO_2 regime. Canopy photosynthesis and transpiration validation data will be gathered with pop-

on chambers for a growth simulation model, COTCO2. In addition, fundamental measures of leaf photosynthesis and stomatal conductance will be determined with leaf cuvettes. Leaf tissue water potential will be determined by psychrometry, and those measurements will be compared with pressure-bomb results. These observations, when combined with biological data from other cooperators, will provide the basis for evaluating plant response for the elevated CO_2 conditions provided by the FACE system.

Results to Date: In 1989 we measured both leaf and canopy photosynthesis to provide validation data for COTCO2, a cotton growth model that incorporates CO_2 effects. COTCO2 is being developed by the U.S. Water Conservation Laboratory. We also took preliminary water potential measurements with a custom-made thermocouple psychrometer and nondestructive leaf-area measurements. Early in the growing season, canopy photosynthesis was much greater in the FACE plots than in the control plots. Later in the season, the difference in canopy photosynthesis became smaller as the size of the control canopy caught up to the size of the FACE canopy.

PHOTOSYNTHETIC ACCLIMATION TO ELEVATED CARBON DIOXIDE: BASIS FOR VARIABILITY AMONG PLANTS

CURE, JENNIFER D.

DUKE UNIVERSITY

FY 1989	139
FY 1988	161
FY 1987	0

09/01/89-08/31/90

Objective: To examine the rate or extent of acclimation to photosynthesis (the shift in the $A:C_i$ curve) upon extended exposure to elevated CO_2 and in the presence of internal and external constraints on growth. To describe the time course of acclimation, biochemically (as well as with $A:C_i$ curves) (i.e., in terms of changes in RuBisCo activity, activation state, and concentration; concentrations of RuBP, total protein, and chlorophyll; starch and soluble sugar accumulation and export rates; and SPS activity per unit area). To survey leaf tissues, significant changes in leaf structure, and changes in cell properties among the various photosynthetic tissues of the leaf.

Product: This research will produce experimental data on the effects of CO_2 enrichment on causes and variability in photosynthetic (P_s) acclimation response to CO_2. Data and insights will be obtained for the time course of changes in gas-exchange patterns that are simultaneous with changes in carbon allocation and RuBisCo activity. The proportional contribution of leaf morphological adaptations to the overall acclimation process will be evaluated.

Approach: Experiments will test the hypothesis that plants of low genetic growth potential will rapidly lose photosynthetic capacity even in optimal growing conditions when exposed to high CO_2 environments, whereas plants with high growth potential will maintain photosynthetic capacity to the extent that growth is not limited by one or more external factors. Limiting external conditions will take the form of low light and low temperature. Impact of altered mesophyll structure on photosynthetic capacity will also be examined.

Results to Date: High-intensity light systems were installed in Phytotron C chambers; a gas-exchange system was assembled for measurement of photosynthetic parameters under controlled conditions; methods were developed for sample handling and measurement of protein, chlorophyll, initial and activated RuBP carboxylase activities, and active-site concentration; the effect of light intensity on the photosynthetic acclimation of a fast-growing species to elevated CO_2 was studied. And a DDG portable photosynthesis system has been scaled up into a full laboratory system.

Morning glory, cotton, sunflower, and kudzu were considered as subjects for the light studies. Based on a preliminary experiment and previous work in the Duke Phytotron, kudzu was selected because it has a high growth rate and apparently showed both a gas-exchange response and an anatomical response to elevated CO_2. The biochemical assays have been worked out for kudzu with the exception of the determination of the RuBP carboxylase active site, and work is underway in this area.

The real-time components of two experiments with kudzu have recently been completed at two light intensities. Gas-exchange measure-

ments were made, and tissue samples were collected 10 to 12 days after beginning of high CO_2 treatments. Tissues in liquid nitrogen are currently being analyzed for protein, chlorophyll, and a number of enzymes, and the gas-exchange data are under study. Even with large numbers of replicates, little or no significant change in photosynthesis occurred in kudzu leaves exposed to 700 ppm CO_2 at relatively high light intensities. We are currently ascertaining whether the variability in our data is real (i.e., genetic) or introduced with the gas-exchange system. We are also extending the experimental period to a month and using very low light intensities in some of the treatments in an effort to induce the acclimation response.

DEVELOPMENT OF METHODS FOR ASSESSING THE IMPACTS OF CO_2-INDUCED CLIMATE CHANGE ON AGRICULTURAL PRODUCTION

DECKER, WAYNE L.

UNIVERSITY OF MISSOURI, COLUMBIA

FY 1989	73
FY 1988	0
FY 1987	93

01/15/89-01/14/90

Objective: To examine existing statistical models of climate impact for evaluating effects of climate change on agricultural production. Specifically, to examine the technical merit of statistical-empirical methods for estimating regional-scale agricultural productivity in relation to climate change, CO_2 enrichment, and soil productivity; to define the critical linkages between climate and crop models that will be required for meaningful and accurate estimates; and to identify data requirements for a regional-scale assessment of agricultural response to changing CO_2 and climate.

Product: An evaluation of top-down empirical-statistical models for doing an assessment of the effects of climate and CO_2 change on regional agricultural productivity. Questions of scientific feasibility, potential general utility, and data requirements of this approach will be addressed.

Approach: The areas in which the outputs from the climate models (GCM) match or mismatch the outputs from the crop process models will be determined, and the data requirements for inputs into regional assessments will be identified. The approach builds on empirical crop models that have been developed for other purposes. Existing statistically determined equations as well as mechanistic approaches for estimating plant growth and yield response to CO_2 and climate change will be examined.

Requirements and capabilities of statistical crop climate models will be evaluated in relation to the kinds of output data expected from GCMs. Conventional statistical methods, which can estimate effects from altered temperature and water supply and from direct CO_2 enrichment, will be evaluated. Relative accuracy and sensitivity of different methods will be identified. Recommendations will be prepared for changes, if appropriate, in the outputs from the climatic scenarios.

Results to Date: With data from the Northwest Crop Reporting District of Missouri, the impact of CO_2 increases on corn production has been estimated. A statistical model was used to simulate the impact of climate change on corn production. The climate change scenarios included average temperature increases of 1, 2, and 3°C and precipitation decreases of 0 and 10%. The increases in yields produced by CO_2 fertilization were estimated to be 10 and 29%.

When the fertilization effect from doubled CO_2 was a positive 29%, an increase in production occurred with a 1°C increase in temperature with and without a decrease in precipitation. The break-even point occurred (1) with a 2°C increase in temperature and a 10% decline in precipitation and (2) with a 3°C increase in temperature and no change in precipitation. For a CO_2 direct effect of 10%, the break-even point occurred at a 1°C increase in temperature.

A comparison of the direct and indirect effects from a doubling of CO_2 for different regions has also been made. A district in central Iowa was compared with the northwest and southeast districts in Missouri. In general, the greatest decline in production occured in the

southeast Missouri district while the least effect is noted in central Iowa. This difference is thought to be caused by the higher water-retention properties of the soils of central Iowa.

A FIELD STUDY OF THE EFFECTS OF ELEVATED AMBIENT CO_2 ON ECOSYSTEM PROCESSES IN CHESAPEAKE BAY WETLANDS

DRAKE, BERT G.

SMITHSONIAN INSTITUTION

FY 1989	206
FY 1988	208
FY 1987	184

09/20/89-09/19/90

Objective: To determine whether elevated ambient CO_2 concentration as well as higher temperature will increase photosynthesis and net ecosystem production, alter species composition, alter relative partitioning of biomass between aboveground and belowground structures, change carbon and nitrogen concentration in plant tissue, alter decomposition rates, and/or change the water balance in plants and plant communities of a mesohaline salt marsh on Chesapeake Bay.

Product: Mechanistic biophysical information on the response of a wetland plant community when continuously exposed to elevated CO_2. This information will include experimental data on ecosystem-level photosynthesis, respiration, net productivity, and carbon storage; change of species composition in plant communities; partitioning of biomass between aboveground and belowground components; changes of carbon:nitrogen ratios of tissue; decomposition rates; and change of water balance of tissues. In addition, the research will produce a data base for modeling the effects of CO_2 enrichment on ecosystem processes, specifically community photosynthesis, carbon accumulation, and change in species composition.

Approach: Long-term research will be continued at the Smithsonian Environmental Research Center, a salt-marsh research site near Edgewater, Md. Three community types will be investigated in the field. There, elevated CO_2 levels will be controlled by small, replicated open-top chambers. Several year-long and unique data sets have been obtained, and the experimental research will continue to investigate photosynthesis, respiration, net productivity, compositional change, carbon storage, and nutrient cycling of an ecosystem treated with variable CO_2 and different temperature and water conditions. A data base will be obtained for modeling effects of CO_2 enrichment on ecosystem processes.

Results to Date: Experiments with open-top chambersat more than thirty sites divided equally among three plant communities on a brackish wetland on Chesapeake Bay have shown that elevated CO_2 reduces evapotranspiration in all three communities approximately equally producing a net savings of water throughout the season of approximately 25%.

It also reduces ecosystem nighttime respiration. The amount of reduction varies with species but on average is about 30% of respiration in the sites exposed to normal ambient CO_2 concentration.

Elevated CO_2 increases photosynthesis. The increase is greatest in the communities dominated by C3 species but occurs to a lesser degree in the C4-dominated communities. Measurements on detached tissues showed that the effect of elevated CO_2 increased quantum yield and reduced diurnal photoinhibition. There is no evidence of down regulation of photosynthetic efficiency with respect to light.

And elevated CO_2 increases above- and belowground production in the C3-dominated plant community. Root production increased approximately 80% in the C3 plant community.

The main significance of these findings is that they suggest a much greater impact of rising CO_2 on carbon accumulation and on water loss in terrestrial biota than has been estimated from studies of crops and wild species in controlled environments.

FREE-AIR CARBON DIOXIDE FIELD ENRICHMENT (FACE) FACILITY DEVELOPMENT

HENDREY, GEORGE

BROOKHAVEN NATIONAL LABORATORY

FY 1989	830
FY 1988	808
FY 1987	790

10/01/88-09/30/89

Objective: To develop and test a free-air gas-delivery system for enriching a field crop to specified levels of CO_2; to characterize physical and biological conditions of the Maricopa, Ariz., Field site prior to field experiments with cotton at specified levels of CO_2; and to obtain physiology, growth, and yield data for validating a plant-simulation model, COTCO2.

Product: (1) An experimental facility for maintaining specified levels of CO_2 in the canopy of a cotton crop throughout a growing season and (2) a field data set on plant response to CO_2 enrichment. A monoculture of cotton is a representative stand of plants for testing system performance, and the research is carried out in cooperation with Agricultural Research Service modeling and experimental research groups. Once performance tested, the system will be able to be deployed with various vegetation types and natural systems.

Approach: Open-field gaseous exposure facilities currently used for air-pollution research will be adapted for enriching plants in the open air with CO_2. After initial field studies, several devices, including CO_2 control and data processing systems, will be tested at BNL, Mississippi, and Arizona. Field tests will include characterization of the atmospheric and soil environments, local hydrology, and overall system performance. The general research strategy and experimental design for obtaining systematic data on the CO_2 and climate effect on plant growth will be determined. The feasibility of research on water use efficiency in a full-field FACE experiment will also be examined. Additional CO_2 delivery and control systems will then be constructed and used by the research consortium to produce validation data for evaluating CO_2 effects with native and agricultural species.

Results to Date: In 1988, four FACE arrays were tested in 1000 h of operation. Less than 7% of the 1-min average-CO_2 concentrations exceeded 20% of the set points (550 ppm). One array, which was operated for 93% of the experimental period, was within 10% of the set point 93% of the time. The FACE arrays were moved to Maricopa, Ariz., in April 1989 and are now operating in a cotton field equipped with subsurface irrigation. For 12 h each day, 550-ppm CO_2 will be applied to four treatment plots throughout the growing season. Results will be compared to four control plots located in the same field but away from the influence of the CO_2 treatment.

A gas-sampling array consisting of 63 intake ports arranged as three planes of 21 ports at each of three levels (near ground, mid-height of the plants, top of the canopy) draws samples from within one of the FACE arrays. Data from this multi-port system will be used to evaluate the spatial and temporal distribution of CO_2 and the effectiveness of the control achieved by the FACE system. Preliminary observations indicated that CO_2 control is similar to that achieved in the 1988 studies. As of August 1989, a treatment effect is clearly visible, with CO_2-enriched plots appearing morphologically different, entering the "cutout" stage earlier, developing significantly more bolls, and having a greater degree of mite infestation than control plots.

RANGELAND-PLANT RESPONSE TO ELEVATED CO2

KANEMASU, E. T., KIRKHAM, M. B., and OWENSBY, C.

KANSAS STATE UNIVERSITY

FY 1989	250
FY 1988	100
FY 1987	150

08/15/88-01/31/90

Objective: To identify the response of plants and grazing animals (sheep) on a native grassland in central Kansas to different soil-moisture conditions and atmospheric CO_2 concentrations. Specific objectives are to determine the effect of elevated concentrations of CO_2 on the photosynthetic rate, water use, and growth of prairie plants and on the diet quality of ruminants.

Product: Data on the physiology and plant growth of representative species of the grassland, including changes in forage quality. At the end of each season, data sets will be provided, which can be used for evaluating and modeling the effects of different CO_2 concentrations and climatic conditions on a grassland ecosystem.

Approach: Sixteen round, plastic, closed-top chambers (1.52 m in diameter) will be placed over plots of grassland, and CO_2 will be injected. Two watering regimes will be used: the soil in half of the plots will be kept at field capacity (the "well-watered" plots), and the soil in the other half will be kept at half field capacity (the "drought-stressed" plots). Similarly, two CO_2 levels will be used: ambient (350 ppm) and two times ambient (700 ppm). Twice weekly throughout the growing season, measurements of photosynthesis, transpiration, leaf temperature, stomatal resistance, plant-water potential, and plant height will be taken at midday. Soil moisture will be monitored weekly with a neutron probe, and that data will be used to determine the amount of water lost from the plots.

In addition, six round, plastic, open-top chambers (4.5 m in diameter) will be built and placed over plots of grassland, and CO_2 injected. Three chambers are kept at the ambient level of CO_2, and three chambers are maintained at the ambient level + 350 ppm CO_2. Every two weeks throughout the growing season, esophageally fistulated sheep will graze in the chambers to determine how the level of CO_2 affects diet quality. Biomass accumulation and species composition will also be determined.

Results to Date: The photosynthetic rate of the major species on the rangeland, big bluestem (*Andropogon gerardii* Vitman), a C_4 plant, has not, in general, been affected by the elevated CO_2. Under well-watered conditions, the average photosynthetic rate between 22 June and 12 July at 350 and 700 ppm CO_2 was 42.8 and 39.3 micromoles m^{-2} s^{-1}, respectively. Under drought-stressed conditions, these values were 36.1 and 39.7 micromoles m^{-2} s^{-1}, respectively. However, elevated CO_2 has decreased transpiration and increased stomatal resistance. Under well-watered conditions, the average transpiration rate between 22 June and 12 July at 350 and 700 ppm CO_2 was 0.020 and 0.025 mol m^{-2} s^{-1}, respectively. Under drought-stressed conditions, these values were 0.017 and 0.036 mol m^{-2} s^{-1}. For the nonstressed plants, the average stomatal resistance between 22 June and 12 July for the elevated and ambient level of CO_2 was 1.41 and 0.81 s/cm, respectively. For the drought-stressed plants, these values were 1.90 and 0.99 s/cm, respectively. These results for the rangeland grass (big bluestem) agree with those obtained by Drake for the C_4 salt-marsh grass *Spartina patens*.

Six esophageally fistulated sheep have been grazing in the chambers. Partially digested grass samples are being taken from the sheep and transported to the laboratory for analysis. Analyses of the samples are now in progress.

ELEVATED CO_2 AND TEMPERATURE: MODELING COTTON RESPONSE, EFFECTS ON INSECT-POPULATION DYNAMICS, AND LONG-TERM EFFECTS ON TREES

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WATER CONSERVATION LABORATORY and WESTERN COTTON RESEARCH LABORATORY

FY 1989	176
FY 1988	191
FY 1987	0

09/01/89-08/31/90

Objective: (1) To assemble data for use in modifying a plant-growth simulation model that incorporates CO_2 level and other climate variables with physiological processes affecting plant growth. (2) To determine the effects of elevated CO_2 on the growth and physiology of trees (*Citrus aurantium* L.). (3) To determine the effects of environmental factors, particularly CO_2 and elevated temperature, on the feedback inhibition of photosynthesis and on the rates of development and growth of plant organs. (4) To determine effects of temperature on growth, development time, and survival of beet armyworm and pink bollworm reared on plants grown at elevated CO_2 and to determine if these insects are affected by CO_2-altered tissue of plants. (5) To develop a database of virtually all the available data about the effects of CO_2 on important plant processes.

Product: Primary information on physiology, growth, and yield of plants, trees, and annual species subjected to increasing atmospheric CO_2. The physiology and growth data will be used to improve equations of the simulation model COTCO2, and yield information will be used to test the validity of the model. Controlled-environment experiments will produce data on interactive effects of CO_2 and temperature on feedback inhibition of photosynthesis and enhancement of growth at elevated temperatures.

Approach: A comprehensive data base of the quantitative information available in the literature about the effects of carbon dioxide on several important plant processes or parameters will be assembled. The processes or parameters will include yield, biomass, leaf stomatal conductance, leaf transpiration, harvest index, short- and long-term carbon-exchange rates, short- and long-term net-assimilation rates, root-to-shoot ratio, and carbon-to-nitrogen ratio. Classification variables (such as species, crop type, photosynthetic type, and carbon dioxide exposure method) will be included in the data base as well as experimental conditions, such as carbon dioxide concentration, light intensity level, temperature, humidity, irrigation level, salinity, nutrient level, and air pollutants. The data base will be implemented on an IBM-compatible personal computer with a popular program so that it is easily transported to other users.

The open-top CO_2-enrichment chamber technique will be used with ambient and 650-ppm levels of CO_2. Plant physiology and growth will be determined for different temperature conditions. Measurements will be made of leaf area, biomass, yield, foliage temperatures, net photosynthesis, stomatal conductance, photosynthetic response to CO_2, leaf carbohydrate content, stomatal response at variable soil moisture content, and susceptibility to insects. Insect studies will be done inside mesh enclosures under field conditions where CO_2 concentration is controlled by open-top chambers.

Beet armyworm larvae will be fed cotton plants that have been grown at elevated carbon dioxide in a greenhouse. The beet armyworms themselves will be in incubators in the laboratory where their survival, development, and growth can be closely observed. The experiment will be conducted at various temperatures so that the interactive effects between carbon dioxide and temperature can also be observed.

Results to Date: Cotton was grown in open-top field CO_2-enrichment (ambient and 650-ppm) chambers as in prior years, except the tops were covered with screens to isolate insect populations. Starting with nearly identical beet armyworm (BAW) populations in the spring, population counts were made through the course of the growing season. Larval populations of BAW were five- to six-fold higher in the enriched chambers, but the adult populations were inordinately low, compared to the ambient control chambers. Furthermore, significant increases in plant damage occurred.

No long-term CO_2-enrichment studies had been conducted on woody tree species, so a long-term study was initiated in 1988 on sour orange trees. Eight trees were planted in four open-top CO_2-enrichment chambers, two trees per chamber. Two of the chambers were enriched to 300 ppm above ambient. During the first year, the enriched trees grew to be about 26% taller in height and about 50% wider in trunk cross-sectional area, with most of the CO_2 effect coming during the hot summer months.

Ancillary experiments in the orange tree chambers showed 58% increases in growth of agave (a CAM plant), while sorghum (a C4 plant) showed an 11% increase in net leaf photosynthesis and a 27% decrease in stomatal conductance with CO_2-enrichment.

HERBIVORE RESPONSES TO PLANTS GROWN IN ENRICHED CO_2 ATMOSPHERE

LINCOLN, DAVID E.

UNIVERSITY OF SOUTH CAROLINA

FY 1989	51
FY 1988	46
FY 1987	50

07/01/89-06/30/90

Objective: To determine the biochemical basis for the altered nutritional value of leaves produced with elevated CO_2, the demographic and consumption responses of an herbivore to CO_2 regimes, the relationships plants with the C_4 photosynthetic pathway will have with herbivores, the impact of defoliation under enriched CO_2 conditions, and the response of specialist feeding herbivores to host-plant CO_2 enrichment.

Product: Experimental data on insect feeding rates as affected by plant tissue produced at different CO_2 levels. Changes in secondary biochemicals will be documented, and feeding rates will be determined in relation to CO_2-altered nutritive and biochemical properties. Along with other data on physiology and systems properties, the plant-insect information will contribute to a study of animal effects in a rangeland ecosystem.

Approach: While plants are exposed continuously to CO_2, insects will be allowed to feed on live plant material, and feeding rates will be determined on plants growing at different levels of CO_2. Effects of CO_2 on plant nutrition and biochemical properties will be determined simultaneously, and feeding rates will be correlated with the changed plant properties. Five experiments will be carried out at the Duke University Phytotron.

Experiments will be carried out with *Artemisia* plants and *Melanoplus* grasshoppers to investigate the mechanisms for the CO_2-induced increase in feeding by individual herbivores.

Grasshoppers will be used in feeding trials with *Bromus*, an annual grass of western ranges to study the influence of CO_2-induced changes in plants on growth, development, reproduction and populations size of grasshoppers.

Responses to C_3 and C_4 plants will be tested with *Bromus tectorum*, a C_3 annual, and with *Eleusine indico*, a C_4 grass, to determine the herbivore response to CO_2-induced changes of plants with C_3 and C_4 photosynthetic pathways.

The response of a specialist herbivore to CO_2-induced changes will be studied in its host plant. In this case the specialist insect (cabbage butterfly) will be tested with two different species of mustards; one is a crop type and another a widespread weed. The CO_2 effect on glucosinolate, the cueing biochemical for insect attack on the plant, will be examined.

The effect of herbivory on defoliation will be investigated in different CO_2 environments.

Results to Date: None reported.

ELEVATED CARBON DIOXIDE EFFECTS ON WOODY PLANT SOIL SYSTEMS

NORBY, RICHARD J., LUXMOORE, ROBERT J., and O'NEILL, ROBERT V.

OAK RIDGE NATIONAL LABORATORY

FY 1989	265
FY 1988	256
FY 1987	182

10/01/88-09/30/89

Objective: To determine whether temperate-forest trees increase in growth and carbon storage as the concentration of carbon dioxide in the atmosphere increases and to investigate mechanisms of nutrient cycling in relation to tree-growth change as influenced by atmospheric CO_2 concentration.

Product: Data on the effects of CO_2 on tree growth under field conditions. A data base on growth and physiological responses will be produced for small white oak and tulip poplar trees. The field experiment will also test the hypothesis that elevated atmospheric CO_2 levels will increase nutrient uptake and growth of woody plants in nutrient-poor soils with emphasis on root-rhizosphere-mycorrhizal responses to elevated CO_2.

Approach: Leaf litter from white oak seedlings after two growth cycles in elevated CO_2 will be analyzed for components of litter quality. An experiment will be conducted on the effect of CO_2 enrichment on the uptake of ^{32}P by mycorrhizal tulip poplar. Techniques of mathematical growth analysis and nutrient analysis of plant tissue will be used to determine the interactive effects of nutrient supply and CO_2 enrichment on tulip poplar seedlings.

Nine open-top field chambers will be added to the existing Controlled Exposure Facility at ORNL. The field chambers will be tested for temperature, light, and CO_2 gradients, and the computerized CO_2 dispensing system will be tested for maintenance of appropriate CO_2 concentrations.

White oak and tulip poplar seedlings will be planted in the field chambers. The chambers

will be maintained at ambient CO_2, ambient + 150 ppm, or ambient + 300 ppm, with three replicate chambers for each treatment level. The treatments will be maintained during daylight hours for four growing seasons. Aboveground growth, leaf production, and mycorrhizal infection of roots will be characterized. Physiological measurements will include analysis of photosynthetic characteristics, instantaneous and seasonal water-use efficiency, water relations during drought periods, and key metabolites in harvested material.

Leaf litter collected in the fall will be analyzed for lignin, cellulose, carbohydrates, phenolic compounds, and inorganic nutrients. The data will be used in empirical relationships that predict the decomposability of the litter and total nutrient return. Litter and fine-root decomposition will be measured directly with fine-mesh litter bags placed in the chambers after the second growing season. Microbial populations associated with litter will be quantified. Internal nitrogen cycling will be followed with a budget approach and with the use of ^{15}N. In the second year, ^{15}N-enriched organic matter will be added to the system, and the release of nitrogen to soil solution and its appearance in the plant will be monitored.

Results to Date: The chemical composition of senescent leaves of white oak (*Quercus alba*) seedlings was determined to estimate the effect of elevated CO_2 on the decomposability of leaf litter. The leaf litter of plants grown in elevated CO_2 had a lower concentration of nitrogen (higher C:N ratio) but a higher concentration of tannins compared to leaves of ambient-grown plants. These results would suggest slower decomposition. The response of lignin and the lignin-to-nitrogen ratio to CO_2, however, was inconsistent.

The assembly of the open-topped field chamber facility for CO_2-enrichment studies was completed. Dormant white oak and yellow poplar (*Liriodendron tulipifera*) seedlings were planted in the chambers in May. Estimated relative aboveground growth rates increased with increasing CO_2 concentration in both species. Photosynthetic rates measured in August increased linearly with CO_2 in both species. The relative increase in photosynthesis exceeded the relative increase in CO_2 concentration by 30% in yellow poplar and by 14% in white oak. Stomatal conductance was not affected by CO_2 concentration, but transpiration efficiency increased dramatically in the +150- and +300-ppm treatments, especially in white oak. The dark respiration rate of leaves was not significantly affected by the CO_2 treatments.

RESPONSE OF TUNDRA ECOSYSTEMS TO ELEVATED ATMOSPHERIC CARBON DIOXIDE

OECHEL, WALTER C.

SAN DIEGO STATE UNIVERSITY

FY 1989	244
FY 1988	135
FY 1987	170

09/15/89-09/14/90

Objective: To determine current patterns of CO_2 flux from tussock and wet coastal tundras along environmental gradients on the north slope of Alaska at sites representing a range of vegetation types and environmental conditions, to evaluate recent patterns of peat accumulation in tussock and wet coastal tundras, and to determine the methane content of permafrost and the current rates of methane release as a function of vegetation and environment.

Product: Definitive statement of what is known and unknown about tundra response to varying CO_2 and climate conditions. This includes documentation of the logic and supporting data, including measurements of CO_2 and CH_4 exchange across tundra ecosystems.

Approach: The research will evaluate current rates of CO_2 and CH_4 flux along a latitudinal gradient from the foothills of the Brooks Range to the coast of the Arctic Ocean. Measurements will be made along the transect formed by the Haul Road and at other sites where permafrost temperature research has been done on the North Slope. Peat profile dating will be performed at the same sites as the CO_2 and CH_4 flux measurements to compare past and current rates of carbon accumulation or loss.

Field research will be carried out with small pop-on chambers to measure the CO_2 and CH_4 fluxes of different ecosystems across the North Slope of Alaska. Simultaneously, environmental

parameters (air temperature, radiation, relative humidity, soil moisture, and temperature) will be determined during the short-term gas-exchange experiments. In addition, continuous monitoring of the physical environment will be done at the three sites. Ecosystem data (leaf area, aboveground biomass, carbon content of thaw layer, and depth to permafrost) will be determined simultaneously with the flux measurements. Initial interpretations will relate CO_2 and CH_4 fluxes to environmental and biotic properties of the systems under observation.

Results to Date: Recent activities emphasized data reduction and analysis of previous results. That data came from the experimental manipulation of atmospheric CO_2 and temperature in the tussock tundra at Toolik Lake, Alaska. Contrary to previous thinking, which indicated carbon accumulation in tussock tundra, these recent analyses illustrate that carbon is currently being lost from the tussock tundra in this region. If carbon losses at Toolik Lake are representative of all circumpolar tussock tundra, carbon loss from tussock tundra may be on the order of 0.1 to 0.2 Gty^{-1}, and net carbon sequestering of all arctic tundra may be 0.2 to 0.3 Gty^{-1} less than previously thought.

The tussock tundra may have recently changed from a carbon sink to a carbon source as the result of increases in surface temperature during the past century and concomitant climate change. Warmer, drier soil conditions should cause an increase in soil decomposition. This trend, if general and continuing, could result in massive amounts of carbon being liberated from soil organic matter as CO_2.

THE DEVELOPMENT OF A GENERIC ECOSYSTEM MODEL FOR ASSESSING THE EFFECTS OF ELEVATED CO_2 ON ECOSYSTEMS

REYNOLDS, JAMES F.

SAN DIEGO STATE UNIVERSITY

FY 1989	350
FY 1988	253
FY 1987	231

09/01/89-08/31/90

Objective: (1) To predict primary, secondary, and tertiary effects of elevated CO_2 and climate change on individual plants; (2) to develop the capability of simulating plant growth at conditions beyond those used to calibrate the model; (3) to incorporate individual and aggregated plant response into an ecosystem framework to predict primary effects of global change (i.e., different physical conditions); (4) to validate system-level response with various ecosystem field studies of elevated CO_2 and different climate conditions; and (5) to use a validated ecosystem model to test hypotheses and make predictions about ecosystem response to global change.

Product: A capability to model and to predict plant and ecosystem response to anticipated changes of the future physical environment (e.g., rising CO_2, warmer temperature, and more or less moisture or light).

Approach: The leaf model will simulate primary effects at the leaf level, including photosynthesis, respiration, stomatal conductance, the processes controlling CO_2 diffusion, and biochemical fixation. A supply-demand structure will be formulated, and the model will incorporate feedbacks on photosynthesis involving acclimation and carbon and nitrogen allocation patterns. Effects of light, temperature, water stress, and leaf age will be accounted for by the model.

The canopy model will integrate leaf-level processes, characterize the microenvironment of the plant canopy, and produce calculations of gas exchange and response to a variable light and temperature environment. The model will simulate the daily time-course of plant photosynthesis and transpiration and describe the aggregate behavior of a population of leaves with known properties. Further work needs to incorporate the effects of altered photosynthesis and morphology due to elevated CO_2.

The whole-plant model will combine the canopy and partitioning models into an overall carbon and nitrogen balance for predicting root, stem, leaf, and reproductive growth to understand and simulate the growth of whole plants in response to CO_2, temperature, light, nitrogen, and water as well as other variables. The modeling approach is to consider resource availability (e.g., photosynthate, nitrogen, and water) and determine the potential for the growth of organs; this approach also requires knowledge of allocation and biomass partitioning. Patterns of resource availability and

allocation will determine actual growth; by considering supply-demand relationships, actual growth will be estimated relative to potential.

Modeling the plant community or population response is an intermediate step that links the plant to the ecosystem. The community models will examine ways in which species interaction might change as resources (e.g., CO_2) or other environmental variables (e.g., temperature) are modified, resulting in a mechanistic plant community model for examining multispecies response to CO_2 subsidy and to nitrogen, water, and temperature stress. Properties proposed for modeling studies include interspecific competition, nearest-neighbor effects, and resource abundance.

Modeling ecosystem response requires the integration of results from whole-plant and community models coupled with ecosystem processes, such as nutrient cycling, water dynamics, microbial activity, and herbivory. The development of such linkages among modules and hierarchical relationships for representing interactions will require that considerable attention be paid to the scaling problem (i.e., how to represent processes at the hectare and larger scale when the bulk of knowledge comes from detailed physiology and small-plot studies).

Results to Date: The development of several core models has progressed. Our mechanistic leaf photosynthesis and conductance model was included in a canopy-energy and gas-exchange model. The photosynthesis model has been validated under current CO_2 levels and responds realistically to short-term increases in CO_2. Work with the canopy model has focused on the interactive effects among canopy acclimation to growth at high CO_2 (e.g., increased leaf area), leaf acclimation (reduced photosynthetic capacity because of changes in leaf nitrogen), and whole-plant photosynthesis.

The conclusions of this work are that (1) canopy gas exchange is sensitive to the nature of the acclimation to elevated CO_2, (2) leaf acclimation reduces canopy photosynthesis and transpiration beyond that expected from elevated CO_2 alone, and (3) canopy acclimation partially offsets this adjustment. The leaf model has been incorporated into a whole-plant growth model, and a new resource allocation submodel was developed that allows variable allocation of nitrogen to leaf proteins as well as leaf and root biomass. This significantly increases generality and the ability to predict long-term responses of plants to CO_2 and climate change.

We have developed a generic plant-community model based on resource availability and interspecific competition by way of resource preemption. It includes plant responses to temperature, water, nitrogen, and CO_2. This model is being parameterized and validated for both annual species and perennial grasses. At the ecosystem level, we are identifying how the effects of elevated CO_2 and changing climate may be translated through the ecosystem to different hierarchical levels. We used the SPUR ecosystem model to test the effects of elevated CO_2 and climate change on species composition, productivity, and nutrient cycling in grassland ecosystems. Preliminary results suggest that warmer temperatures and reduced precipitation may enhance the growth of C4 plants over that of C3 plants, but no overall change in productivity or nutrient cycling need occur. However, ecosystem response is very sensitive to regional weather patterns and the timing of precipitation.

INFLUENCE OF ATMOSPHERIC CO_2 ENRICHMENT ON RANGELAND FORAGE QUALITY AND ANIMAL GRAZING

SIONIT, NASSER

SAN DIEGO STATE UNIVERSITY

FY 1989	124
FY 1988	0
FY 1987	0

09/15/89-09/14/90

Objective: To examine the effect of CO_2 enrichment on plant requirements for nitrogen, the relationship of atmospheric CO_2 concentration on the carbon-to-nitrogen ratio in plant leaves, and the effects on forage quality and animal consumption.

To determine if there are differences among species' responses to elevated CO_2 and nutrient supply.

Product: A more complete understanding of the effects of elevated levels of CO_2 and nutrient supply in a tall grass prairie ecosystem as indicated by photosynthesis, plant growth,

species composition, nutrient concentration in forage, and animal selectivity of rangeland grasses.

Approach: Open-top chambers will be used to grow plants at two CO_2 levels and two nutrient levels. Plant physiology and growth will be measured. The effect of CO_2 and nutrient variation on tissue quality will be determined from biochemical analysis and by feeding trials with grazing animals, which are expected to select herbage of different qualities as they graze in the treated plots. Conventional field techniques will be employed to assay the grazing selectivity. Phenology and species composition will be determined periodically throughout the experiment.

INTEGRATION OF EXPERIMENTAL AND MODELING APPROACHES IN THE UNMANAGED ECOSYSTEM RESEARCH PLAN

STRAIN, BOYD R.

DUKE UNIVERSITY

FY 1989	350
FY 1988	353
FY 1987	188

09/15/89-09/14/90

Objective: (1) To improve the empirical data base on the effects of CO_2 and climate variables on plants and ecosystems with special attention to mechanisms of photosynthetic decline and physiological controls of whole-plant growth when some plants are continuously exposed to elevated CO_2. (2) To investigate possible mechanisms of CO_2 suppression of plant respiration. (3) To contribute new information to an integrated modeling approach for examining the effects of different CO_2 and climate regimes on whole plants and ecosystems. The data needs of PRECO- and SERECO-type models will be addressed.

Product: Data for modeling and predicting changes of plant physiology and growth as a function of different future CO_2 and climate conditions. These data include new experimental information on physiological and ecological controls of whole-plant and whole-system functions. The research will develop data on the physiology of whole-plant systems and competitive plant-to-plant interactions.

Approach: As a function of different CO_2 and physical conditions (e.g., temperature and moisture), the research will examine mechanisms of net photosynthesis, photorespiration, starch and sugar changes, stomatal conductance and transpiration rate, and growth characteristics with graminoid and shrub species representative of tundra and rangeland ecosystems.

The Duke University Phytotron will be used for experiments that will focus on an apparent decline in photosynthetic potential, observed with some plants as CO_2 concentration increases. Data will be obtained for testing and modifying the Farquhar equation of CO_2-dependent photosynthesis response. At the biochemical level, the phosphate translocation-recycle hypothesis (i.e., that phosphate movement between cytoplasm and chloroplast regulates ATP and NADPH concentrations and thus controls the CO_2 fixation rates of 3-phosphoglyceric acid of the C_3 pathway) will be tested. An alternative hypothesis is that phosphorous availability regulates transport of sucrose from cytoplasm to phloem tissue, thereby controlling the availability of sugars in other plant tissues. Either or both mechanisms may limit CO_2 fixation and growth at elevated CO_2 concentrations. New data will determine the applicable mechanisms, if terms of the basic CO_2-dependent equation need to be modified, and if so, how.

In addition to carrying out physiological studies, the research will also synthesize and integrate existing information about carbon fixation and allocation in plants, ecosystem productivity and stability in relation to CO_2 and climate variables, nutrient availability and cycling, properties of the ecosystem likely to be affected by CO_2-altered growth (e.g., plant-animal interactions, plant-microbial interactions, and water fluxes). This information will be used in reexamining the Farquhar equation and to formulate generic models (e.g., PRECO and SERECO) of whole-plant and whole-system responses to CO_2 and climate.

Results to Date: After 20 days of growth in 650-ppm CO_2, net photosynthesis decreased by 50% in cotton plants with restricted root growth but only by 18% in plants with unrestricted root growth. Reduced carboxylation

efficiency and RuBP-regenerating capacity correlated with decreased net photosynthesis. Photosynthetic reduction in elevated CO_2 seems to be a source-sink phenomenon in which environmental restrictions on growth feed back to reduce photosynthesis.

Studies were continued on the effects of elevated CO_2, soil water stress, and atmospheric humidity deficit on growth and net photosynthesis of C-3 and C-4 weedy plants. C-3 plants acclimated in response to dry air, maintaining higher photosynthesis than the plants grown in humid air. C-3 plants decreased in cell-wall elasticity, causing increased turgor pressure and improved plant-water relations.

Sugar maple and beech trees were grown under different levels of CO_2, nitrogen, and irradiance. Reparation rate decreased with CO_2 enrichment (64% in beech and 13% in sugar maple). On the other hand, beech increased 13% in canopy photosynthesis at high CO_2. Decreased respiratory cost and increased photosynthesis enhanced the net carbon balance of beech more than that of sugar maple.

RESOURCE ANALYSIS

Changes in climate and vegetation caused by increasing atmospheric CO_2 may have significant consequences for human health and welfare. Many important resources, such as agriculture, forests, fisheries, human populations, and water resources, could be affected by the interactive effects of changing CO_2 and climate. Some of these resources will be affected primarily by climate, while for others the direct effect of CO_2 may be significant. Additionally, coastal resources may be sensitive to rising sea level and related factors, such as changes in tidal regime. Effects on such resources as these could have important implications for industrial productivity, land use, and energy use.

Research Objectives The objectives of resource analysis are (1) to provide integrated quantitative analyses of the effects of changes in CO_2 and climate on key resources on a regional basis and (2) to develop useful responses to possible problems and develop mechanisms to take advantage of possible benefits introduced by changes in CO_2 and climate. The effects of both CO_2 and climate will be considered, and important inter-resource connections will be accounted for.

Research Questions To fulfill these objectives, the following questions must be answered:

- What are the most important resource areas and resource issues for analysis?
- What are the most important inter-resource connections?
- What are the best definitions of regions to be used in these analyses?
- What analytical approach is best to develop solutions?
- How satisfactory is our understanding of the response of resources both to changes in CO_2 and climate and to other important factors, such as technology or government-economic actions, and what additional analytical methods need to be developed?
- How much of the required data base is available, and what additional data need to be developed for the analyses?

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CARBON DIOXIDE INFORMATION AND ANALYSIS RESEARCH PROGRAM: RESOURCE ANALYSIS

CUSHMAN, ROBERT

OAK RIDGE NATIONAL LABORATORY

FY 1989	450
FY 1988	367
FY 1987	0

10/01/88-09/30/89

Objective: To plan and monitor analyses to allow anticipation of the consequences of changing CO_2 and climate on natural and societal resources.

Product: (1) Evaluations of the current issues concerning the responses of natural and societal resources to changing CO_2 and climate, including responses to climate-induced rising sea level. (2) Assembly of data bases useful for analyses of the responses of resources to changing CO_2 and climate.

Approach: Current issues concerning the responses of resources to changing CO_2 and climate will be analyzed based on critical reviews of the literature. Methods for the analysis of the response of resources to changing CO_2 and climate will be investigated, including the definition of regions for use in regional resource analyses and the application of climate-model output in resource analyses. A global coastal hazards data base will be further developed to identify those coastal areas that are especially susceptible to erosion and inundation, based on geology, geomorphology, terrain, tidal range, wave heights, trends in relative sea level, and other variables. Other data bases will be developed as needed for specific resource analyses. Geographic information systems will be applied to the analyses of this subtask, where appropriate.

Results to Date: An analysis of the potential responses of ecosystems to changing CO_2 and climate was completed; a manuscript based on this analysis is being prepared for publication. A DOE report, *Workshop on Sea Level Rise and Coastal Processes* (DOE/NBB-0086), was published; in this report, current knowledge concerning the role of such factors as sediment transport, storm surge, and tides in shaping the response of the rising sea level is analyzed. In association with the Global Coastal Hazards Data Base project (V. M. Gornitz, Columbia University, Lamont-Doherty Geological Observatory), data on geology, geomorphology, elevation, tidal range, wave height, erosion/accretion trends, and relative-sea-level trends were prepared for analysis and display in a geographic information system. Additional data on coastal storms were also collected and prepared.

In collaboration with Pacific Northwest Laboratory, Resources for the Future, and Sigma Xi, environmental data for the Missouri-Iowa-Nebraska-Kansas region were collected, quality assured, and displayed; these data will be used in a project to evaluate the regional response of agriculture, water resources, and forestry to climate change.

CO_2 RESOURCE ANALYSIS RESEARCH

EDMONDS, J. A., and SCOTT, M.

PACIFIC NORTHWEST LABORATORY

FY 1989	700
FY 1988	0
FY 1987	0

10/01/88-09/30/89

Objective: To develop the scientific information base and analytic tools needed to describe the nature and kind of consequences of increasing atmospheric CO_2 and climate change on human and natural systems and the timing, magnitude, and uncertainty associated with those consequences. This objective includes describing direct and indirect effects at the regional level and how regional responses interact with each other.

Product: Coordination for the Precursor to a Methodology Project; a research plan for methodology development; the design and initial development of a baseline description of resources and interactions for today's climate and resources; identification of the most important research issues to be addressed by the Resources Analysis Program; and the acquisition of the knowledge needed by the Project.

Approach: PNL will coordinate research efforts at PNL, ORNL, and other participating institutions to ensure the integrity, continuity,

and focus of efforts. A quantitative analysis of the current relationship between the regional resource base and the economic and social viability of the selected region will be conducted. This analysis will provide the baseline description of the region. This analysis will link physical plant productivity models, expert systems describing firm-level economic responses, and input-output models of regional economies. Knowledge transfer will proceed through the conduct of and participation in workshops and meetings and the publication of papers and reports.

Results to Date: The program has been organized, and a region of study (Missouri, Iowa, Nebraska, and Kansas) has been chosen. Program participants have held four program coordination meetings, and all participants have been linked with the Carbon Dioxide Research Program's communication system. The program presented its approach to the joint BESAC/HERAC global-change committee. Three interim progress reports were presented to the Carbon Dioxide Research Program. Oak Ridge National Laboratory climate and resource data bases were integrated into the project's information systems with SAS software.

The initial analysis, which calibrates the region and examines the effects of imposing a historical analog climate change on the region without any adaption and with and without considering CO_2 fertilization effects, was completed.

Papers were presented at the annual meeting of the Air and Waste Management Association, and personnel participated in the Forum on Global Change and Our Common Future and in the IIASA Workshop on Energy Futures. Workshops were conducted to identify the most important issues in resource analysis and to identify ways of incorporating uncertainty analysis into the project.

DEVELOPMENT OF A GLOBAL COASTAL HAZARD DATA BASE

GORNITZ, VIVIEN M.

LAMONT-DOHERTY GEOLOGICAL OBSERVATORY

FY 1989	50
FY 1988	35
FY 1987	50

12/01/88-09/30/89

Objective: To develop a single data base that incorporates all of the information needed to consistently predict on a global basis which coastal segments are at greatest risk from a rise in sea level.

Product: A global coastal hazards data base for coastal managers and engineers at national and international levels.

Approach: A coastal data base will be compiled that contains relevant topographic, geologic, geomorphologic, erosional and subsidence information. These data will be integrated into a geographic information system (GIS), and high-risk shorelines (areas characterized by low coastal relief, an erodible substrate like sand or unconsolidated sediment, present and past evidence of subsidence, extensive shoreline retreat, and/or high wave or tide energies) will be identified.

Information on seven variables relating to the coastal zone [elevation (relief), bedrock geology, geomorphology (coastal landforms), vertical movements (relative sea level changes), horizontal shoreline movements (erosion or accretion), tidal ranges, and wave heights] will be compiled and entered into the ORNL ARC/INFO GIS. The ARC/INFO GIS is an integrated software package that includes a number of

associated modules that can relate numerical data with spatial data and can display statistical information in the form of maps.

Results to Date: Data compilation for the U.S. has been completed for the seven variables and currently is being extended to Canada and Mexico. Classification schemes for coastal geology and geomorphology have been especially adapted for this project. Statistical summaries of the coastal variables have been prepared. Mean differences in these coastal properties between the east and west coasts of the U.S. can be largely attributed to fundamental differences in plate-tectonic settings. Mean elevations, even at the relatively coarse spatial resolution of 0.25° latitude-longitude, vary sufficiently to distinguish among geomorphologic/geologic environments.

Data entry into the ARC/INFO GIS has been completed for the entire U.S. east coast for four variables. A preliminary version of the coastal vulnerability index (CVI) has been tested for the that area. It defines criteria for high- and very-high-risk coastal segments, using the four variables currently in the GIS, elevation, geology, geomorphology, and shoreline displacement. Maps have been produced on which high- and very-high-risk segments are identified; they are (from north to south) Nantucket and Martha's Vineyard in Massachusetts, Fire Island in New York, parts of the mid-New Jersey coast, parts of the Delaware and Chesapeake bays, the Atlantic coast of the southern Delmarva Peninsula, Cape Hatteras in North Carolina, and the Cape Canaveral area in Florida. Further testing of the CVI is in progress, and methods of averaging or smoothing data are being implemented.

Finally, a questionnaire has been mailed internationally to about 350 government marine and coastal management agencies, research institutes, and university departments requesting additional information on coastal conditions in individual countries.

SCIENTIFIC INTERFACE

Knowledge is of little use if the persons needing it are not aware of it or cannot obtain it. In a program such as the CDR Program, which must explore scientific issues that are often both comprehensive and complex, the need for effective communication among scientists, policy makers, and the interested public is vital.

Objectives The scientific interface component of the CDR Program provides (1) mechanisms through which scientific information can be obtained, evaluated, and subjected to quality-control procedures; (2) the exchange of data; and (3) high-quality analyses of complex data to synthesize information used in evaluating environmental issues. Specific objectives include preparing numerous scientific and informational reports, sponsoring scientific conferences, and providing scientists access to current scientific material and data on CO_2 through the Carbon Dioxide Information Analysis Center.

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CARBON DIOXIDE INFORMATION ANALYSIS CENTER

KANCIRUK, PAUL

OAK RIDGE NATIONAL LABORATORY

FY 1989	1130
FY 1988	1055
FY 1987	1000

10/01/88-09/30/89

Objective: To acquire or compile, quality assure, document, archive, and distribute CO_2-related information in support of DOE's Carbon Dioxide Research Program (CDRP).

Product: A fully integrated information analysis center needed to support CDRP's research program and to provide CO_2-related information to the research and policy-making communities.

Approach: The Carbon Dioxide Information Analysis Center identifies users' needs by working closely with the research community, the Carbon Dioxide Research Program, and policy makers by attending workshops, reviewing the literature, and maintaining personal contacts. Data, models, and other products and services are evaluated as to usefulness and acquired if available or compiled at CDIAC if not in a usable form. These products undergo extensive quality assurance and complete documentation in full coordination with the original supplier of the information. They are then made available to the research and policy making communities. CDIAC works with other data centers and individual researchers to promote the compilation and exchange of data. CDIAC's activities and approaches are evolving with changing research needs and technology, and future emphasis will be placed on using new methods of communication (electronic bulletin boards), new media for archiving and distribution (CD ROMs), and new data products (geographic information systems and fully registered and projected cartographic data packages). These new approaches to information management will complement the suite of CDIAC tools.

CDIAC's research activities will reflect any new programmatic directions of CDRP. CDIAC's activities will include information support for the evaluation of complex environmental issues associated with elevated levels of atmospheric CO_2, including the technical-management aspects of the national CO_2 program.

Results to Date: CDIAC has provided technical support for CDRP and the general research and policy making communities by serving as CDRP's information-gathering and distribution center. Activities included obtaining and evaluating data, articles, and reports; producing numeric data packages (NDPs) and computer model packages (CMPs); distributing CO_2-related reports; compiling bibliographies, and producing the semiannual newsletter CDIAC Communications. Near the end of FY 1989, there were 33 numeric data packages and 2 versions of a computer model available; 11 issues of CDIAC Communications had been distributed (our distribution is currently to 4614 people, including 103 foreign embassies and 1390 people in 146 foreign countries). We provided 483 copies of NDPs and CMPs to researchers in 18 countries (a 20% increase over FY 1988), bringing our total since 1985 to 5076 copies of data sets and models.

CDIAC has filled 4240 requests for information through mid-August (an increase of 39% over FY 1988), bringing our total to 13,423 requests from users in 70 countries since 1985. We have added 236 references to our Bibliographic Information System, bringing our total reference listing to 10,189. We performed 17 custom literature searches for users in FY 1989.

INSTITUTIONAL AND INTERNATIONAL SYSTEMS

The potential cause of global climate change is directly related to increased usage of energy (fossil fuels) for humankind's well being. It is recognition of the global nature and therefore the potential effects of global climate change that requires and expanded coordination with and cooperation between the international science community and the development of mechanisms by which to discuss research findings and potential response options with institutional organizations.

The four state-of-the-art reports on carbon dioxide research with the two companion volumes were definitive scientific statements about what is known and is not known. They identified the uncertainties surrounding the data and recommended research. It is necessary to build upon these findings and recommendations and to expand our international outreach as well as our outreach to key institutional elements, such as the utility industry, the producers of fossil fuels, and environmental groups.

Objectives The objective of this portion of the work is to bring together the various strands of research that must be consolidated into a coherent and reinforcing set of findings, to define possible response options, and to establish an effective mechanism for dialogue between the interested groups.

Numerous potential modification and adaption strategies will undoubtedly be identified. These strategies will have different impacts on various institutional segments and regions of the world. Therefore, contact must be extended to institutional and international systems to transfer knowledge so decision-making can be based on the best information available from the world's scientific research.

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SUPPORT FOR ACTIVITIES OF THE POLAR RESEARCH BOARD, NAS

HUSHEN, W. TIMOTHY

NATIONAL ACADEMY OF SCIENCES

FY 1989	25
FY 1988	25
FY 1987	25

03/01/89-02/28/90

Objective: To advise on U.S. and international policies and on research of the Arctic and Antarctic, to represent the U.S. within the Scientific Committee on Antarctic Research (SCAR), and to develop plans for a strategy for the conduct of polar research during the decades ahead.

Product: Advice, guidelines, and recommendations on polar research resulting from interaction during the semiannual meetings of the Board and the meetings of its subgroups and from special studies organized by the Board to respond to particular problems or to develop long-range plans and priorities.

Approach: The Board is a multidisciplinary body with representation from marine and terrestrial biology, earth sciences, engineering, medicine, physical sciences, and social sciences. Members are drawn from academic institutions, industry, and national laboratories. In addition, the Board always has one member representing Canadian research activities. Federal agencies, such as the Department of Energy, with programs in the arctic or the antarctic have liaison representation on the Board and brief the Board periodically at its meetings on these activities.

The Board will continue to provide advice to federal agencies on the development and implementation of national initiatives in global processes and coordination with the ICSU global-change program.

The Board will serve as liaison between the Academy's National Committee for the International Geosphere-Biosphere Program and other federal agencies to assure that the importance of research in the polar regions on climatic and other global environmental processes receives attention as the program evolves.

The Board will ensure that polar processes and programs are integrated into global initiatives under consideration by other NRC activities in the oceans, earth, and atmospheric sciences and is developing an interdisciplinary research plan for both polar regions that addresses the problems of global change.

The Committee on Glaciology will continue to provide advice on the role of snow and ice research to global geoscience programs. For example, the Committee has prepared material to aid the Board in the preparation of its document *The role of Antarctica in Global Change*. This report outlines top-priority research themes that could serve as an antarctic component of large global-change research programs, highlighting antarctic processes that have a global impact.

The Committee on Glaciology is also planning a December 1989 forum on ice sheets and sea-level change to examine progress made in this area since the publication of the Committee's 1984 workshop that led to the publication of the report *Glaciers, Ice Sheets, and Sea Level: Effects of a CO_2-Induced Climate Change*, prepared for the Department of Energy. Discussions during this forum should provide a foundation for planning a major workshop on this topic in the future.

PARTIAL SUPPORT FOR THE NAS BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE

PERRY, JOHN S.

NATIONAL ACADEMY OF SCIENCES

FY 1989	35
FY 1988	35
FY 1987	35

09/15/89-09/14/90

Objective: To provide scientific leadership and guidance to the government on important national and international issues in the atmospheric sciences and climate, including the National Climate Program and U.S. participation in the World Climate Research Program.

Product: Regularly scheduled board, committee, and panel meetings that will review current national and international issues and provide advice and assistance to the government as needed.

Approach: Scientific leadership and guidance will be provided to the government on important national and international issues in the atmospheric sciences and climate.

The activities of the Climate Research Committee and the Tropical Ocean-Global Atmosphere Program and International Satellite Cloud Climatology Project advisory panels will be continued in providing guidance on U.S. participation in the World Climate Research Program and on related national climate research efforts.

The activities of the Committee on Atmospheric Chemistry will be continued with efforts focused on such issues as increases in greenhouse gases, stratospheric ozone depletion, and acid deposition.

A capability to respond to needs for evaluation, guidance, recommendations, and support to the federal agencies and the Congress in the areas of atmospheric sciences and climate will be maintained.

PARTIAL SUPPORT FOR THE FORUM ON GLOBAL CHANGE AND OUR COMMON FUTURE

PERRY, JOHN S.

NATIONAL ACADEMY OF SCIENCES

FY 1989	14
FY 1988	0
FY 1987	0

04/15/89-04/14/90

Objective: To communicate to the public a scientifically balanced view of what changes are occurring in the global environment, what these changes mean for society, and what kind of policies for mitigation or adaptation may be needed.

Product: An assessment of the state of science intended for the interested public and the broader scientific community.

Approach: The National Academy of Sciences' National Research Council (NRC), the Smithsonian Institution, the American Association for the Advancement of Science, and Sigma Xi, the Scientific Research Society will cosponsor and organize a major public Forum on Global Change and Our Common Future, to be held May 1-3, 1989, immediately following the annual National Science and Technology Week.

The scientific program of the Forum will address:

The elements of global change, emphasizing that we must understand the earth as a total system

The human causes of global change

What global change means for society, including the impacts on water resources, agriculture, coastal areas, biodiversity, and industry

Global change and global life-support systems, including the carrying capacity of the earth and sustainable development

Policy implications of global change, including energy and industrial policies, the political aspects of policy options, and implications for international cooperation

PARTIAL SUPPORT FOR THE NATIONAL ACADEMY OF SCIENCES-NATIONAL RESEARCH COUNCIL COMMITTEE ON GLOBAL CHANGE

PERRY, JOHN S.

NATIONAL ACADEMY OF SCIENCES

FY 1989	15
FY 1988	15
FY 1987	10

09/01/89-08/31/90

Objective: To provide partial support to the NAS/NRC Committee on Global Change so that effects from energy research and development are accurately reflected in global studies of earth-system processes.

Product: The Committee on Global Change, a focal point for plans and communications related to the emerging International Geosphere-Biosphere Program (IGBP), will provide scientific guidance and leadership to the government on important national and international and multidisciplinary problems involving the earth system (ocean, biota, space, and solid earth).

Approach: The Committee will participate in the development of an IGBP by reviewing initiatives, proposals, and plans developed by the international community and by providing recommendations to U.S. federal agencies. This work involves bilateral or multilateral scientific initiatives in support of the IGBP for the consideration of the U.S. sponsoring agencies and international planning bodies.

The Committee will advise governmental departments and agencies about progress related to the IGBP in terms of intrinsic scientific merits and technological approaches.

The Committee will provide background information and advice to U.S. delegations and individual participants of international planning activities, such as meetings of the ICSU Special Committee on the Geosphere-Biosphere Program and its working groups.

The Committee will devise and carry out symposia, workshops, etc. to foster involvement of U.S. scientists in IGBP activities.

The Committee will provide nongovernmental scientific liaison with the international governance of the program.

In coordination with the departments and agencies supporting the IGBP, the Committee will provide them assistance in their executive and congressional analyses of the program and its progress toward implementation.

SYMPOSIUM ON ICE AND CLIMATE PROCEEDINGS

RAYMOND, CHARLES F.

UNIVERSITY OF WASHINGTON

FY 1989	10
FY 1988	0
FY 1987	0

04/01/89-03/31/90

Objective: To publish papers presented at the Symposium on Ice and Climate, which are intended to express the most current knowledge about information obtained from ice about climate processes and past climates, physical processes by which ice influences climate change, and practical means by which ice effects can be incorporated into large-scale climate models.

Product: The International Glaciological Society will publish the proceedings of the Symposium on Ice and Climate scheduled for August 21-25, 1989, at the University of Washington, Seattle, Wash.

Approach: The meeting is being organized by the International Glaciological Society and is being cosponsored by them and the American Geophysical Union and the American Meteorological Society. It will bring together scientists involved with the study of snow, land and sea ice, and climate with the intention of providing the most recent information on climate reconstruction from ice data and the active role of snow and ice in climate processes.

CHAPMAN CONFERENCE ON THE CAUSES AND CONSEQUENCES OF LONG-TERM SEA LEVEL CHANGES

SPILHAUS, A. F., Jr.

AMERICAN GEOPHYSICAL UNION

FY 1989	5
FY 1988	0
FY 1987	0

04/10/89-04/09/90

Objective: To set the stage for determining past sea levels, the mechanisms responsible for each major change in sea level, and the consequences of sea-level change through interaction with geologic systems, ocean chemistry, temperature, climate, etc.

Product: A more complete picture of sea level in the framework of the planetary geologic systems.

Approach: The American Geophysical Union will convene a Chapman Conference on long-term sea-level changes with regard to measurements, causes, and consequences of sea-level change so that approaches, techniques, and results can be discussed and compared.

APPENDIX A

ADDRESSES OF PRINCIPAL INVESTIGATORS

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APPENDIX B

CARBON DIOXIDE AND CLIMATE WORK BREAKDOWN STRUCTURE

I. GLOBAL CARBON RESEARCH
- A. Carbon Cycle
  - 1. Atmospheric Observations
    - a. Contemporary Atmospheric Observations
    - b. Past Atmospheric Observations
    - c. Standards
  - 2. Oceans
    - a. CO_2 Absorption and Exchange
    - b. Carbon Removed to Deep Ocean
    - c. Biotic Effects
  - 3. Biosphere
    - a. Contemporary Carbon Change of Vegetation and Soil
    - b. Historical Record of Terrestrial Carbon
  - 4. Other Sources, Sinks, and Fluxes for Atmospheric CO_2
- B. Energy Emissions
  - 1. Record of Fossil-Fuel Emission
  - 2. Projections
  - 3. Uncertainty Analysis
  - 4. Other Emissions
- C. Energy Technology
  - 1. Emissions Reduction
  - 2. Emissions Abatement
- D. Modeling of the Global Carbon Cycle
  - 1. Subsystem Models
    - a. Atmospheric Circulation Models
    - b. Ocean Carbon Models
    - c. Biosphere Carbon Models
  - 2. Coupled Atmospheric/Ocean, Atmosphere/Biosphere Models
  - 3. Global Carbon Cycle Models
  - 4. Sensitivity/Uncertainty Analysis
  - 5. Estimates of Future Atmospheric CO_2
- E. Management

II. CLIMATE RESEARCH
- A. Modeling the Atmospheric/Oceanic Climate System
  - 1. One-Dimensional Atmospheric/Oceanic Climate Models
  - 2. Two-Dimensional Atmospheric/Oceanic Climate Models
  - 3. Three-Dimensional Atmospheric/Oceanic Climate Models
  - 4. Model Intercomparison and Analysis
- B. Supporting Atmospheric and Oceanic Data and Analyses
  - 1. Atmospheric and Oceanic Climate Record
  - 2. Other Geophysical and Chemical Data
- C. First Detection of CO_2-Induced Climate Change
  - 1. Data Analysis
  - 2. Experimental Observations
  - 3. Monitoring
- D. Analysis and Estimated Climate Change
  - 1. Analysis
  - 2. Estimated CO_2-Induced Climate Change
- E. Management

III. VEGETATION RESEARCH
- A. Capability for Predicting CO_2 and Climate Effects
  - 1. Experimental Data Base on Productivity, Growth, and System-Level Change
  - 2. Modeling Combined CO_2 and Climate Effects
  - 3. Interactions of CO_2, Climate, and Other Variables at the System Level
  - 4. CO_2- and Climate-Induced Effects with Hydrologic Budgets
- B. Evidence of CO_2 and Climate Effects
  - 1. Historical/Paleo Detection of CO_2 and Climate Effects
  - 2. Data Bases for Model Validation
- C. Biological Information for Climate Models
  - 1. Reflectivity Feedback from Altered Surface Properties
  - 2. Water Vapor Feedback from Altered Transpiration
  - 3. Vegetation Systems' Influence on Rate of Exchange of Radiatively Active Gases (CO_2, CH_4, and N_2O)
- D. Information for Resource Analysis
  - 1. Productivity and Yield of Vegetation Systems
  - 2. Ecosystem Structure, Composition, and Distribution
  - 3. Altered Water Budget of Vegetation Systems
  - 4. Altered Plant-Animal-Microbial Relationships
- E. Compatibility of Information Across Time and Space Scales
  - 1. Temporal and Spacial Information Requirements
  - 2. Extrapolation
  - 3. Basic Research
- F. Management

IV. RESOURCE ANALYSIS
- A. Resource and Issue Identification
- B. Regional Definition
- C. Data Base Development
- D. Methodology Development
- E. Integrated Response Analyses (includes effects of non-CO_2-climate factors)
- F. Evaluation of Corrective and Adaptive Actions
- G. Management

V. SCIENTIFIC INTERFACE
- A. Carbon Dioxide Information Analysis Center
- B. Management

VI. INSTITUTIONAL & INTERNATIONAL SYSTEMS
- A. Coordination and Cooperation with International Organizations
- B. Coordination and Cooperation with Industrial and Professional Organizations

VII. DECISIONS

SUBJECT INDEX

(Continued)

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